Section 2

ANTENNAS, TOWERS, AND WAVE PROPAGATION

Part 1

WAVE PROPAGATION, RADIATION, AND ABSORPTION *

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THE NATURE OF RADIO-WAVE PROPAGATION

Radio waves are a part of a larger spectrum of electromagnetic radiation or wave motion extending from the very low frequencies which are now employed in servomechanisms, up through the extremely high frequencies and short wavelengths found in cosmic rays. Between these two extremes lie several ranges of frequencies which are related by reason of their being portions of a common spectrum but which exhibit such different characteristics under normal experience that their kinship may not be readily recognized. However, under certain conditions, analogies are useful for describing the characteristics of one range in terms of another. These other ranges include the frequencies used for electric-power systems; the audio frequencies used in systems for the transmission, amplification, or recording of audible sounds; the radio frequencies; radiant heat; light; and the X rays.

The portions of the spectrum occupied by these frequency ranges are shown in Fig. 1-1*a*. The limits of each frequency range are not defined sharply, but each range overlaps slightly into the ranges above and below. The frequency ranges are marked in terms of the frequency F in cycles per second and are also marked in terms of the wavelength λ in space in centimeters. The wavelength λ is related to the frequency F by the formula $C = F\lambda$, where C is the velocity of light and other electromagnetic radiation in space and is approximately equal to 3×10^{10} cm/sec ($2.99795 \pm 0.00003 \times 10^{10}$).

The range comprising the presently recognized limits of the radio spectrum has been expanded in Fig. 1-1*b*. The portions of the radio spectrum to which television broadcasting and television relay stations are allocated have been further expanded in Fig. 1-1*c*. The following discussion and methods apply particularly to these portions of the spectrum. †

The television broadcast allocations in the United States are: Channels 2 to 4 and 54 to 72 Mc, Channels 5 to 6 and 76 and 88 Mc, Channels 7 to 13 and 174 to 216 Mc, Channels 14 to 83 and 470 to 890 Mc. The television relay allocations are: 1,990 to 2,110 Mc, 6,875 to 7,125 Mc, and 12,700 to 13,200 Mc. The allocations for common carrier channels over which television programs are carried between cities are 3,700 to 4,200 Mc, 5,925 to 6,425 Mc, and 10,700 to 11,700 Mc. These allocations may change from time to time as the relative needs of various services for radio frequencies change, so that the allocations included herein should be considered to be merely illustrative. Current information should be obtained, when necessary, by consulting the Rules of the FCC.

* Reprinted from "Television Engineering Handbook," edited by Donald G. Fink, McGraw-Hill Book Company, Inc., 1957.

† The recently concluded Administrative Radio Conference (ITU, Geneva, 1959) extended their consideration of the radio spectrum to 40,000 Mc.

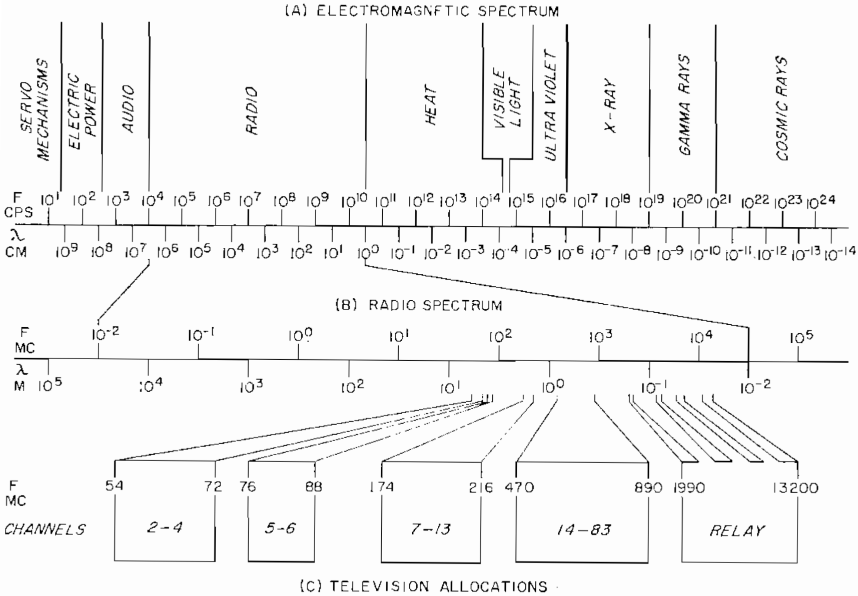


FIG. 1-1. (*a*) Electromagnetic spectrum; (*b*) radio spectrum; (*c*) television allocations.

PROPAGATION IN FREE SPACE

For simplicity and ease of explanation, propagation in space and under certain conditions involving simple geometry, in which the wavefronts remain coherent, may be treated as ray propagation. It should be kept in mind that this assumption may not hold in the presence of obstructions, surface roughness, and other conditions which may be encountered in practice.

For the simplest case of propagation in space, namely that of uniform radiation in all directions from a point source, or isotropic radiator, it is useful to consider the analogy to a point source of light. The radiant energy passes with uniform intensity through all portions of an imaginary spherical surface located at a radius r from the source. The area of such a surface is $4\pi r^2$, and the power flow per unit area $W = P_t/4\pi r^2$, where P_t is the total power radiated by the source. In the engineering of broadcasting and of some other radio services, it is conventional to measure the intensity of radiation in terms of the strength of the electric field E_o rather than in terms of power density W. The power density is equal to the square of the field strength divided by the impedance of the medium, so for free space $W = E_o^2/120\pi$, and $P_t = 4\pi r^2 E_o^2/120\pi$, or

$$P_t = \frac{r^2 E_o^2}{30} \tag{1-1}$$

where P_t is in watts radiated, W is in watts per square meter, E_o is the free-space field in volts per meter, and r is the radius in meters. A more conventional and useful form of this equation, which applies also to antennas other than isotropic radiators, is

$$E_o = \frac{\sqrt{30 g_t P_t}}{r} \tag{1-2}$$

where g_t is the power gain of the antenna in the pertinent direction compared with an isotropic radiator.

An isotropic antenna is useful as a reference for specifying the radiation patterns for more complex antennas but does not in fact exist. The simplest forms of practical antennas are the electric doublet and the magnetic doublet, the former a straight conductor which is short compared with the wavelength and the latter a conducting loop of short radius compared with the wavelength. For the doublet radiator the gain is 1.5 and the field strength in the equatorial plane is

$$E_o = \frac{\sqrt{45P_t}}{r} \tag{1-2a}$$

For a half-wave dipole, namely, a straight conductor one-half wave in length, the power gain is 1.64 and

$$E_o = \frac{7\sqrt{P_t}}{r} \tag{1-2b}$$

From the above formulas it can be seen that for free space (1) the radiation intensity in watts per square meter is proportional to the radiated power and inversely proportional to the square of the radius or distance from the radiator, (2) the electric field strength is proportional to the square root of the radiated power and inversely proportional to the distance from the radiator.

Typical Antennas in Free Space

The formulas for the free-space patterns, power gains, and effective areas of the fundamental doublet antennas and of a few typical antennas which are used frequently in television broadcast and relay systems are shown in Fig. 1-2. For purposes of pattern calculation, the element spacings S are measured in electrical angles $S^\circ = 2\pi S/\lambda$. For the turnstile and loop arrays the length $L = nS$, and for $S = \lambda/2$, $n = 2L/\lambda$.

The effective area B is related to the power gain g by the formula $B = g\lambda^2/4\pi$. The physical dimensions of the antennas, their effective areas, the wavelength, etc., should be expressed in the same units. The values given for power gain and effective area are for optimum conditions, and departures will result in lesser values of power gain and effective area.[1,2,*]

Transmission Loss between Antennas in Free Space [9]

The maximum useful power P_r that can be delivered to a matched receiver is given by

$$P_r = \left(\frac{E\lambda}{2\pi}\right)^2 \frac{g_r}{120} \text{ watts} \tag{1-3}$$

where E = received field strength in volts per meter
λ = wavelength in meters, $300/F$
F = frequency in megacycles per second
g_r = receiving antenna power gain over an isotropic radiator

This relation between received power and the received field strength is shown by scales 2, 3, and 4 in Fig. 1-3 for a half-wave dipole. For example, the maximum useful power at 100 mc that can be delivered by a half-wave dipole in a field of 50 db above 1 μv per meter is 95 db below 1 watt. A general relation for the ratio of the received power to the radiated power obtained from Eqs. (1-2) and (1-3) is

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi r}\right)^2 g_t g_r \left(\frac{E}{E_o}\right)^2 \tag{1-4}$$

* Superscript numbers refer to References at end of part.

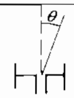
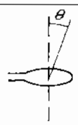
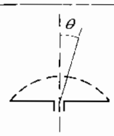
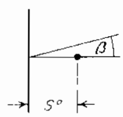
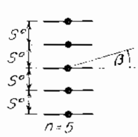
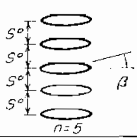
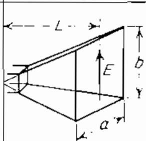
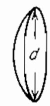
TYPE	CONFIGURATION	PATTERN	POWER GAIN OVER ISOTROPIC	EFFECTIVE AREA
ELECTRIC DOUBLET		$\cos\theta$	1.5	$1.5\,\frac{\lambda^2}{4\pi}$
MAGNETIC DOUBLET OR LOOP		$\sin\theta$	1.5	$1.5\,\frac{\lambda^2}{4\pi}$
HALF WAVE DIPOLE		$\frac{\cos(\frac{\pi}{2}\sin\theta)}{\cos\theta}$	1.64	$1.64\,\frac{\lambda^2}{4\pi}$
HALF WAVE DIPOLE AND SCREEN		$2\sin(S^\circ\cos\beta)$	6.5	$1.64\,\lambda^2/\pi$
TURNSTILE ARRAY		$\frac{\sin(n\frac{S^\circ}{2}\sin\beta)}{n\sin(\frac{S^\circ}{2}\sin\beta)}$	n OR $2L/\lambda$	$n\lambda^2/4\pi$ OR $L\lambda/2\pi$
LOOP ARRAY		$\frac{\cos\beta\sin(n\frac{S^\circ}{2}\sin\beta)}{n\sin(\frac{S^\circ}{2}\sin\beta)}$	n OR $2L/\lambda$	$n\lambda^2/4\pi$ OR $L\lambda/2\pi$
OPTIMUM HORN $L \geq a^2/\lambda$		HALF POWER WIDTH $70\,\lambda/a$ DEGREES (H PLANE) $51\,\lambda/b$ DEGREES (E PLANE)	$10\,ab/\lambda^2$	$0.81\,ab$
PARABOLA		HALF POWER WIDTH $70\,\lambda/d$ DEGREES	$2\pi d^2/\lambda^2$	$d^2/2$

FIG. 1-2. Patterns, gains, and areas of typical antennas.

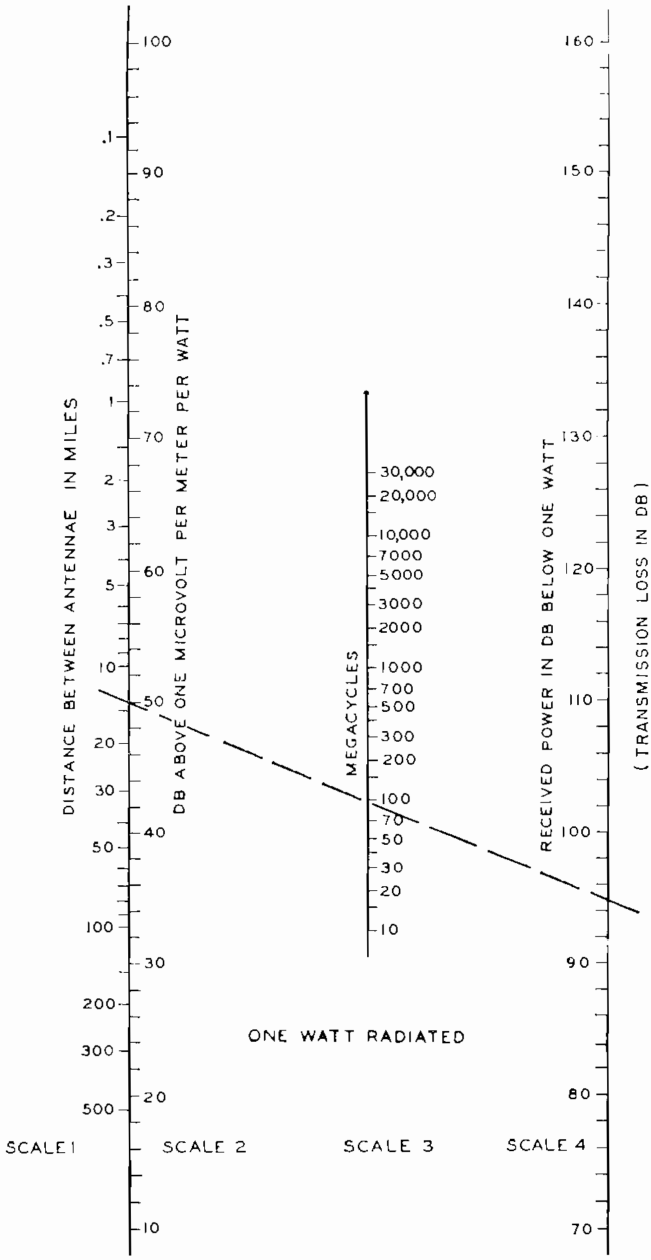


Fig. 1-3. Free-space field intensity and received power between half-wave dipoles.

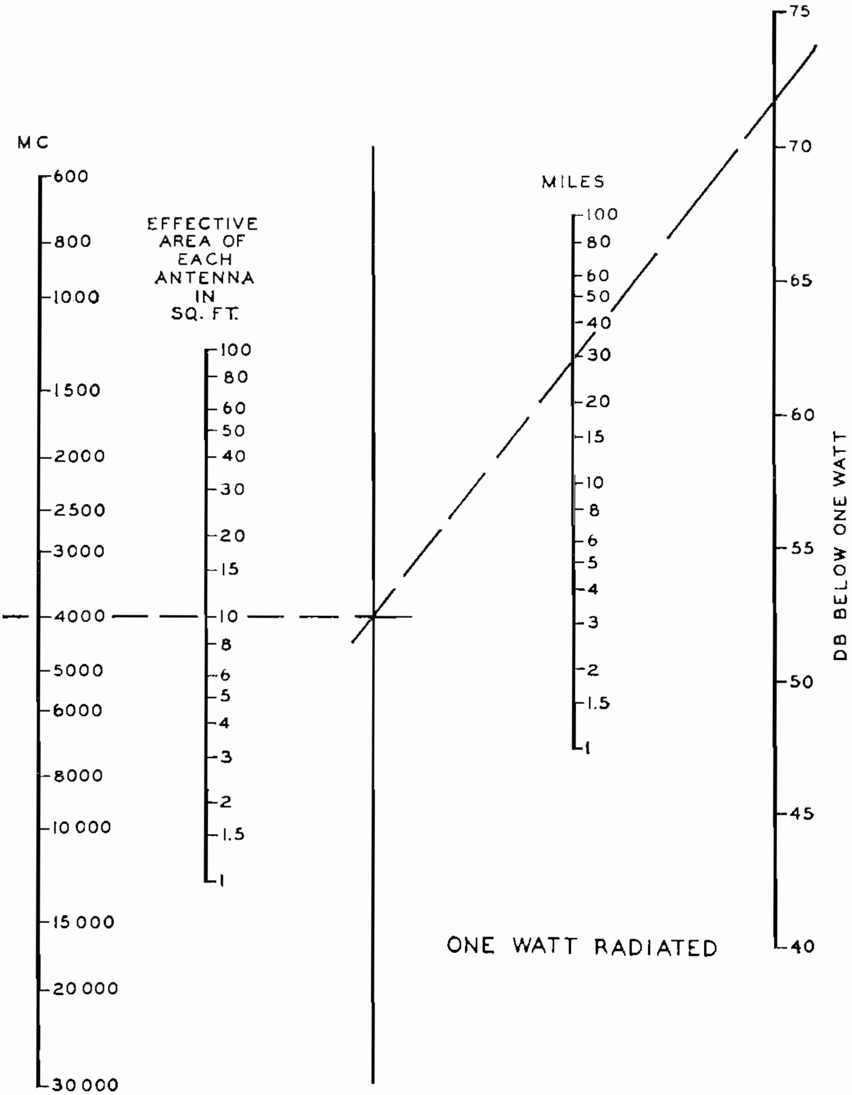


FIG. 1-4. Received power in free space between two antennas of equal effective areas.

When both antennas are half-wave dipoles, the power-transfer ratio is

$$\frac{P_r}{P_t} = \left(\frac{1.64\lambda}{4\pi r}\right)^2 \left(\frac{E}{E_o}\right)^2 = \left(\frac{0.13\lambda}{r}\right)^2 \left(\frac{E}{E_o}\right)^2 \tag{1-4a}$$

and is shown on scales 1 to 4 of Fig. 1-3. For free-space transmission $E/E_o = 1$.

When the antennas are horns, paraboloids, or multielement arrays, a more convenient expression for the ratio of the received power to the radiated power is given by

$$\frac{P_r}{P_t} = \frac{B_t B_r}{(\lambda r)^2} \left(\frac{E}{E_o}\right)^2 \tag{1-4b}$$

where B_t and B_r are the effective areas of the transmitting and receiving antennas, respectively. This relation is obtained from Eq. (1-4) by substituting $g = 4\pi B/\lambda^2$, and is shown in Fig. 1-4 for free-space transmission when $B_t = B_r$. For example, the free-space loss at 4,000 Mc between two antennas of 10 sq ft effective area is about 72 db for a distance of 30 miles.

PROPAGATION OVER PLANE EARTH[3, 7]

The presence of the ground modifies the generation and the propagation of the radio waves so that the received field strength is ordinarily different than would be expected in free space. The ground acts as a partial reflector and as a partial absorber, and both of these properties affect the distribution of energy in the region above the earth.

Field Strengths Over Plane Earth

The geometry of the simple case of propagation between two antennas each placed several wavelengths above a plane earth is shown in Fig. 1-5. For isotropic antennas, for simple magnetic-doublet antennas with vertical polarization, or for simple electric-doublet antennas with horizontal polarization the resultant received field is[5, 7]

$$E = \frac{E_o d}{r_1} + \frac{E_o d R e^{j\Delta}}{r_2} = E_o(\cos\theta_1 + R\cos\theta_2 e^{j\Delta}) \tag{1-5}$$

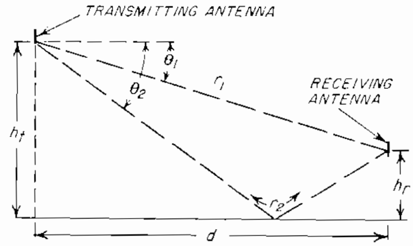


FIG. 1-5. Ray paths for antennas above plane earth.

For simple magnetic-doublet antennas with horizontal polarization or electric-doublet antennas with vertical polarization at both transmitter and receiver, it is necessary to correct for the cosine radiation and absorption patterns in the plane of propagation. The received field is

$$E = E_o(\cos^3\theta_1 + R\cos^3\theta_2 e^{j\Delta}) \tag{1-5a}$$

where E_o is the free-space field at distance d in the equatorial plane of the doublet, R is the complex reflection coefficient of the earth, $j = \sqrt{-1}$; $e^{j\Delta} = \cos\Delta + j\sin\Delta$, and Δ is the phase difference between the direct wave received over path r_1 and the ground-reflected wave received over path r_2, which is due to the difference in path lengths.

For distances such that θ is small and the differences between d and r_1 and r_2 can be neglected, Eqs. (1-5) and (1-5a) become

$$E = E_o(1 + Re^{j\Delta}) \tag{1-6}$$

When the angle θ is very small, R is approximately equal to -1. For the case of two antennas, one or both of which may be relatively close to the earth, a surface-wave term must be added[3, 4] and Eq. (1-6) becomes

$$E = E_o[1 + Re^{j\Delta} + (1 - R)Ae^{j\Delta}] \tag{1-7}$$

The quantity A is the surface-wave attenuation factor which depends upon the frequency, ground constants, and type of polarization. It is never greater than unity and decreases with increasing distance and frequency, as indicated by the following approximate equation:[9]

$$A \simeq \frac{-1}{1 + j(2\pi d/\lambda)(\sin\theta + z)^2} \tag{1-7a}$$

This approximate expression is sufficiently accurate as long as $A < 0.1$, and it gives the magnitude of A within about 2 db for all values of A. However, as A approaches unity, the error in phase approaches 180°. More accurate values are given by Norton[7] where, in his nomenclature, $A = f(P,B)e^{i\phi}$.

The equation (1-7) for the absolute value of field strength has been developed from the successive consideration of the various components which make up the ground wave, but the following equivalent expressions may be found more convenient for rapid calculation:

$$E = E_o\left\{2\sin\frac{\Delta}{2} + j[(1 + R) + (1 - R)A]e^{j\Delta/2}\right\} \tag{1-8}$$

When the distance d between antennas is greater than about five times the sum of the two antenna heights h_t and h_r, the phase difference angle Δ is equal to $4\pi h_t h_r/\lambda d$ radians. Also when the angle Δ is greater than about 0.5 radian the terms inside the brackets, which include the surface wave, are usually negligible, and a sufficiently accurate expression is given by

$$E = E_o\left(2\sin\frac{2\pi h_t h_r}{\lambda d}\right) \tag{1-8a}$$

In this case the principal effect of the ground is to produce interference fringes or lobes, so that the field strength oscillates about the free-space field as the distance between antennas or the height of either antenna is varied.

When the angle Δ is less than about 0.5 radian, there is a region in which the surface wave may be important but not controlling. In this region $\sin\Delta/2$ is approximately equal to $\Delta/2$ and

$$E = E_o\frac{4\pi h_t' h_r'}{\lambda d} \tag{1-8b}$$

In this equation $h' = h + jh_o$, where h is the actual antenna height and $h_o = \lambda/2\pi z$ has been designated as the minimum effective antenna height. The magnitude of the minimum effective height h_o is shown in Fig. 1-6 for sea water and for "good" and "poor" soil. "Good" soil corresponds roughly to clay, loam, marsh, or swamp, while "poor" soil means rocky or sandy ground.[9]

The surface wave is controlling for antenna heights less than the minimum effective height, and in this region the received field or power is not affected appreciably by changes in the antenna height. For antenna heights that are greater than the minimum effective height, the received field or power is increased approximately 6 db every time the antenna height is doubled, until free-space transmission is reached. It is ordinarily sufficiently accurate to assume that h' is equal to the actual antenna height or the minimum effective antenna height, whichever is the larger.

When translated into terms of antenna heights in feet, distance in miles, effective power in kilowatts radiated from a half-wave dipole, and frequency F in megacycles per second, Eq. (1-8b) becomes the following very useful formula for the rapid calculation of approximate values of field strength for purposes of prediction or for comparison with measured values:

$$E \simeq F\frac{h_t' h_r'\sqrt{P_t}}{3d^2} \tag{1-8c}$$

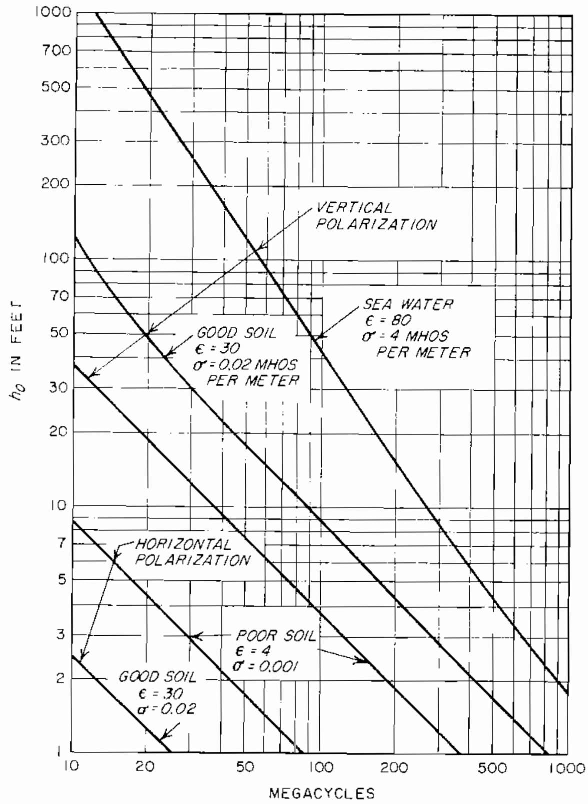


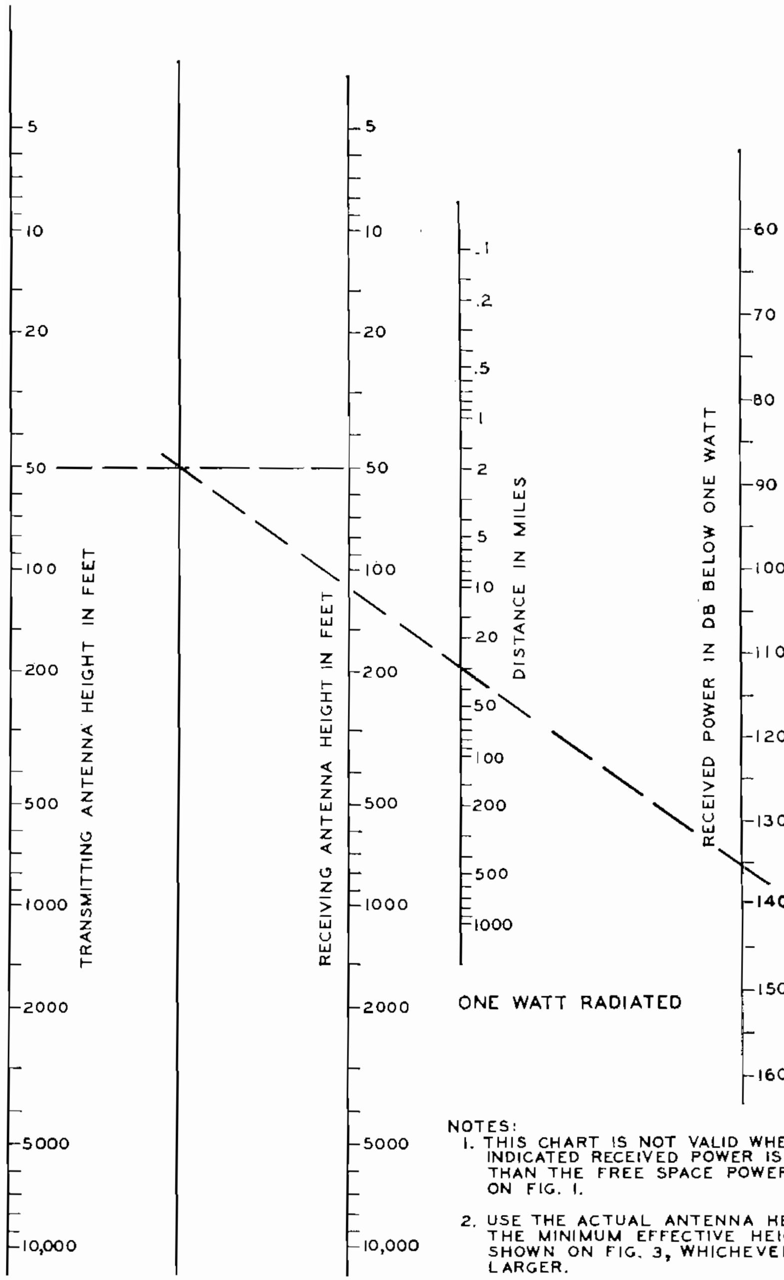
FIG. 1-6. Minimum effective antenna height.

Transmission Loss between Antennas Over Plane Earth

The ratio of the received power to the radiated power for transmission over plane earth is obtained by substituting Eq. (1-8*b*) into (1-4), resulting in

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi d}\right)^2 g_t g_r \left(\frac{4\pi h_t' h_r'}{\lambda d}\right)^2 = \left(\frac{h_t' h_r'}{d^2}\right)^2 g_t g_r \tag{1-9}$$

This relation is independent of frequency, and is shown on Fig. 1-7 for half-wave dipoles ($g_t = g_r = 1.64$). A line through the two scales of antenna height determines a point on the unlabeled scale between them, and a second line through this point and the distance scale determines the received power for 1 watt radiated. When the received field strength is desired, the power indicated on Fig. 1-7 can be transferred to scale 4 of Fig. 1-3, and a line through the frequency on scale 3 indicates the received field strength on scale 2. The results shown on Fig. 1-7 are valid as long as the value of received power indicated is lower than that shown on Fig. 1-3 for free-space transmission. When this condition is not met, it means that the angle Δ is too large for Eq. (1-8*b*) to be accurate and that the received field strength or power oscillates around the free-spaee value as indicated by Eq. (1-8*a*).[9]



NOTES:
1. THIS CHART IS NOT VALID WHEN THE INDICATED RECEIVED POWER IS GREATER THAN THE FREE SPACE POWER SHOWN ON FIG. 1.
2. USE THE ACTUAL ANTENNA HEIGHT OR THE MINIMUM EFFECTIVE HEIGHT SHOWN ON FIG. 3, WHICHEVER IS THE LARGER.

Fig. 1-7. Received power over plane earth between half-wave dipoles.

PROPAGATION OVER SMOOTH SPHERICAL EARTH

Propagation within the Line of Sight

The curvature of the earth has three effects on the propagation of radio waves at points within the line of sight. First, the reflection coefficient of the ground-reflected wave differs for the curved surface of the earth from that for a plane surface. This effect is of little importance, however, under the circumstances normally encountered in practice. Second, since the ground-reflected wave is reflected against the curved surface of the earth, its energy diverges more than would be indicated by the inverse distance-squared law and the ground-reflected wave must be multiplied by a divergence factor D. Finally, the heights of the transmitting and receiving antennas h_t' and h_r', above the plane which is tangent to the surface of the earth at the point of reflection of the ground-reflected wave, are less than the antenna heights h_t and h_r, above the surface of the earth, as shown in Fig. 1-8.

Under these conditions Eq. (1-6), which applies to larger distances within the line of sight and to antennas of sufficient height that the surface component can be neglected, becomes

$$E = E_o(1 + DR'e^{j\Delta}) \tag{1-10}$$

Similar substitutions of the values which correspond in Figs. 1-5 and 1-8 may be made in Eqs. (1-7) through (1-9). However, under practical conditions, it is generally

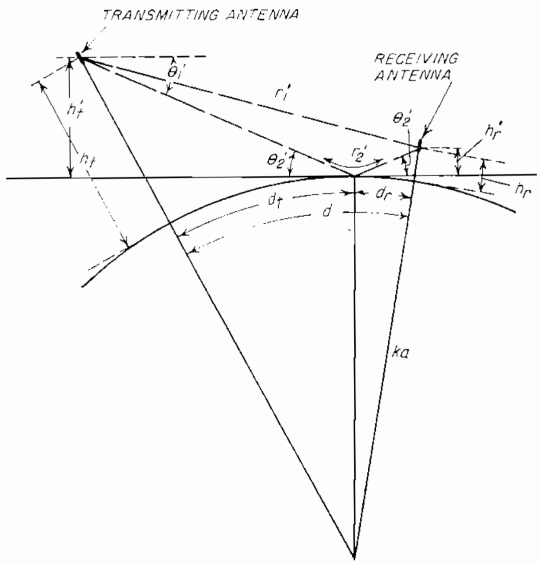


FIG. 1-8. Ray paths for antennas above spherical earth.

satisfactory to use the plane-earth formulas for the purpose of calculating smooth-earth values. An exception to this is usually made in the preparation of standard reference curves, which are generally calculated by the use of the more exact formulas.[4–10]

Propagation beyond the Line of Sight

Radio waves are bent around the earth by the phenomenon of diffraction, with the ease of bending decreasing as the frequency increases. Diffraction is a fundamental property of wave motion, and in optics it is the correction to apply to geometrical optics

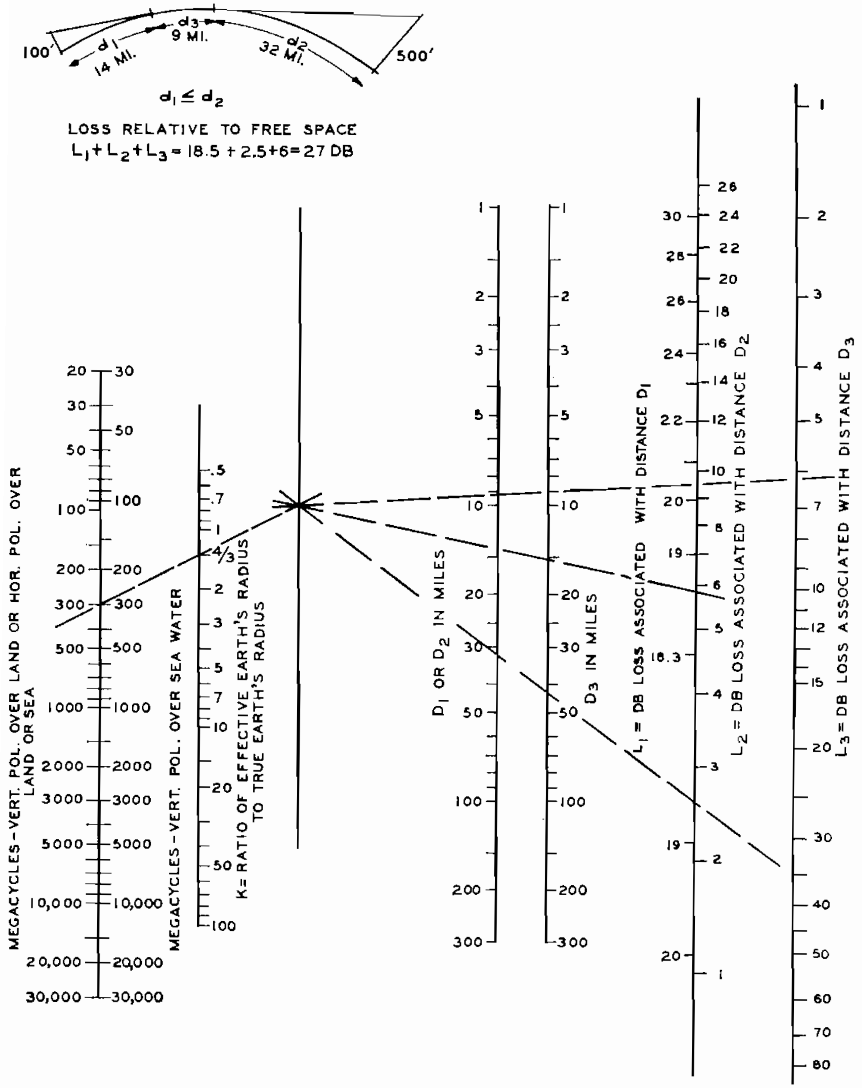


FIG. 1-9. Decibel loss beyond line of sight.

(ray theory) to obtain the more accurate wave optics. In wave optics, each point on the wavefront is considered to act as a radiating source. When the wavefront is coherent or undisturbed, the resultant is a progression of the front in a direction perpendicular thereto, along a path which constitutes the ray. When the front is disturbed, the resultant front may be changed in both magnitude and direction with resulting attenuation and bending of the ray. Thus all shadows are somewhat "fuzzy" on the edges and the transition from "light" to "dark" areas is gradual, rather than infinitely sharp.

The effect of diffraction around the earth's curvature is to make possible transmission beyond the line of sight, with somewhat greater loss than is incurred in free space or

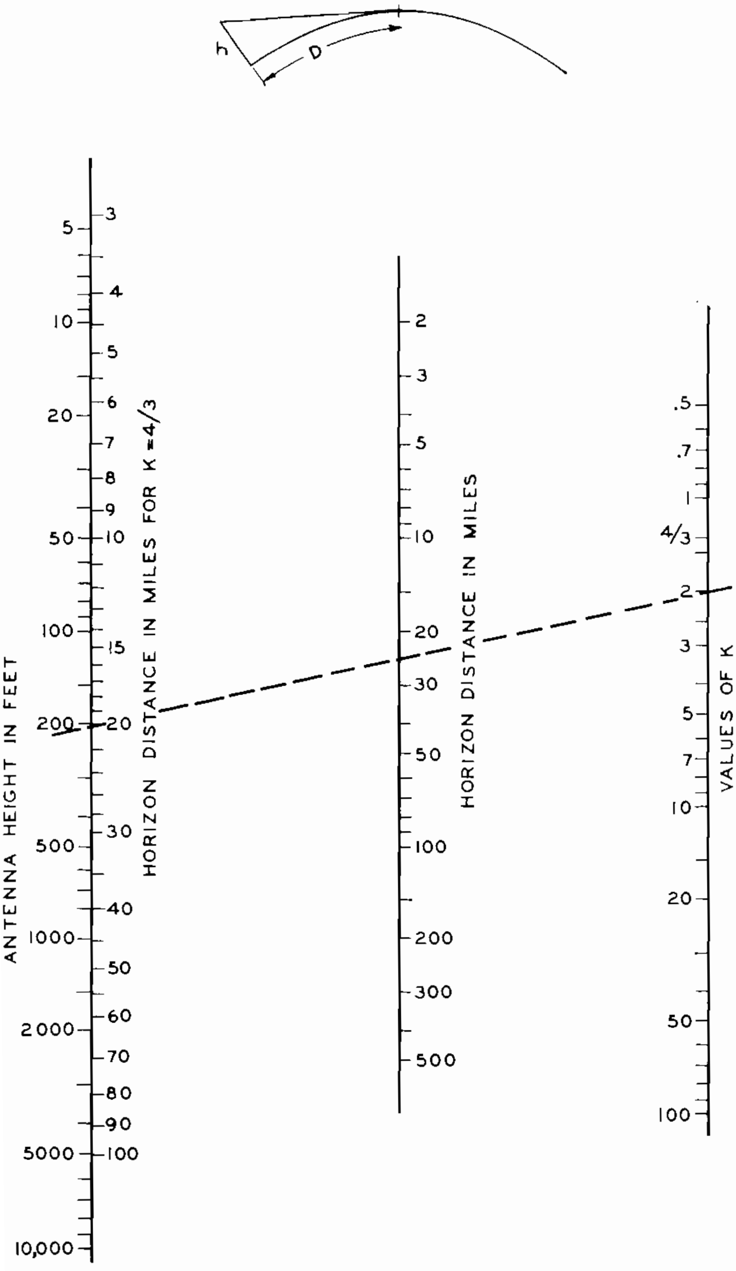


FIG. 1-10. Distance to horizon.

over plane earth. The magnitude of this loss increases as either the distance or the frequency is increased, and it depends to some extent on the antenna height.

The calculation of the field strength to be expected at any particular point in space beyond the line of sight around a spherical earth is rather complex, so that individual calculations are seldom made. Rather, nomograms or families of curves are usually prepared for general application to large numbers of cases. The original wave equations of Van der Pol and Bremmer [4] have been modified by Burrows [6] and by Norton [5,7] so as to make them more readily usable and particularly adaptable to the production of families of curves. Such curves have been prepared. These curves have not been included herein, in view of the large number of curves which are required to satisfy the possible variations in frequency, electrical characteristics of the earth, polarization, and antenna height. Also, the values of field strength indicated by smooth-earth curves are subject to considerable modification under actual conditions found in practice. For VHF and UHF broadcast purposes, the smooth-earth curves have been to a great extent superseded by curves modified to reflect average conditions of terrain.

Figure 1-9 is a nomogram to determine the additional loss caused by the curvature of the earth.[9] This loss must be added to the free-space loss found from Fig. 1-3. A scale is included to provide for the effect of changes in the effective radius of the earth, caused by atmospheric refraction. Figure 1-9 gives the loss relative to free space as a function of three distances; d_1 is the distance to the horizon from the lower antenna, d_2 is the distance to the horizon from the higher antenna, and d_3 is the distance between the horizons. The total distance between antennas is $d = d_1 + d_2 + d_3$.

The horizon distances d_1 and d_2 for the respective antenna heights h_1 and h_2 and for any assumed value of the earth's radius factor k can be determined from Fig. 1-10.

EFFECTS OF HILLS, BUILDINGS, VEGETATION, AND THE ATMOSPHERE

The preceding discussion assumes that the earth is a perfectly smooth sphere with a uniform or a simple atmosphere, for which condition calculations of expected field strengths or transmission losses can be computed for the regions within the line of sight and regions well beyond the line of sight, and interpolations can be made for intermediate distances. The presence of hills, buildings, and trees has such complex effects on propagation that it is impossible to compute in detail the field strengths to be expected at discrete points in the immediate vicinity of such obstructions or even the median values over very small areas. However, by the examination of the earth profile over the path of propagation and by the use of certain simplifying assumptions, predictions which are more accurate than smooth-earth calculations can be made of the median values to be expected over areas representative of the gross features of terrain.

Effects of Hills

The profile of the earth between the transmitting and receiving points is taken from available topographic maps * and is plotted on a special chart which provides for average air refraction by the use of a four-thirds earth radius, as shown in Fig. 1-11. The vertical scale is greatly exaggerated for convenience in displaying significant angles and path differences. Under these conditions vertical dimensions are measured along vertical parallel lines rather than along radii normal to the curved surface, and the propagation paths appear as straight lines. The field to be expected at a low receiving antenna at A from a high transmitting antenna at B can be predicted by plane-earth methods, by drawing a tangent to the profile at the point at which reflection appears to occur with equal incident and reflection angles. The heights of the transmitting and receiving antennas above the tangent are used in conjunction with Fig. 1-7 to compute the transmission loss or with Eq. (1-8c) to compute the field strength. A similar procedure can be used for more distantly spaced high antennas when the line of sight does not clear the profile by at least the first Fresnel zone.[11]

* Available from the U.S. Geological Survey, Department of the Interior, Washington, D.C.

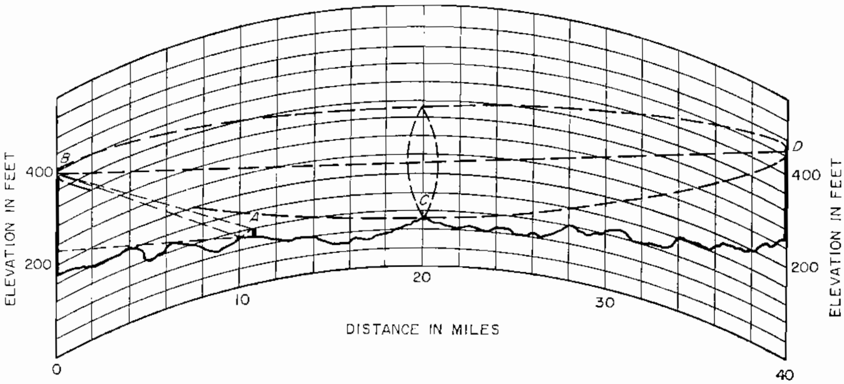


FIG. 1-11. Ray paths for antennas over rough terrain.

Propagation over a sharp ridge or over a hill when both the transmitting and receiving antenna locations are distant from the hill may be treated as diffraction over a knife edge, shown schematically in Fig. 1-12*a*.[9-15] The height of the obstruction H is measured from the line joining the centers of the two antennas to the top of the ridge. As shown in Fig. 1-13, the shadow loss approaches 6 db as H approaches 0, grazing incidence, and it increases with increasing positive values of H. When the direct ray clears the obstruction, H is negative, and the shadow loss approaches 0 db in an oscillatory manner as the clearance is increased. Thus, a substantial clearance is required over line-of-sight paths in order to obtain free-space transmission. There is an optimum clearance, called the first Fresnel-zone clearance, for which the transmission is theoretically 1.2 db better than in free space. Physically, this clearance is of such magnitude that the phase shift along a line from the antenna to the top of the obstruction and from there to the second antenna is about one-half wavelength greater than the phase shift of the direct path between antennas.

The locations of the first three Fresnel zones are indicated on the right-hand scale on Fig. 1-13, and by means of this chart the required clearances can be obtained. At 3,000 Mc, for example, the direct ray should clear all obstructions in the center of a 40-mile path by about 120 ft, to obtain full first-zone clearance, as shown at C in Fig. 1-11. The corresponding clearance for a ridge 100 ft in front of either antenna is 4 ft. The locus of all points which satisfy this condition for all distances is an ellipsoid of revolution with foci at the two antennas.

When there are two or more knife-edge obstructions or hills between the transmitting and receiving antennas, an equivalent knife edge may be represented by drawing a line from each antenna through the top of the peak that blocks the line of sight, as in Fig. 1-12*b*.

Alternatively, the transmission loss may be computed by adding the losses incurred when passing over each of the successive hills, as in Fig. 1-12*c*. The height H_1 is measured from the top of hill 1 to the line connecting antenna 1 and the top of hill 2. Similarly, H_2 is measured from the top of hill 2 to the line connecting antenna 2 and the top of hill 1. The nomogram in Fig. 1-13 is used for calculating the losses for terrain conditions represented by Fig. 1-12*a*, *b*, and *c*.

The above procedure applies to conditions for which the earth-reflected wave can be neglected, such as the presence of rough earth, trees, or structures at locations along the profile at points where earth reflection would otherwise take place at the frequency under consideration or where first Fresnel-zone clearance is obtained in the foreground of each antenna and the geometry is such that reflected components do not contribute to the field within the first Fresnel zone above the obstruction. If conditions are favorable to earth reflection, the base line of the diffraction triangle should not be drawn through the antennas, but through the points of earth reflection, as in Fig. 1-12*d*. H is

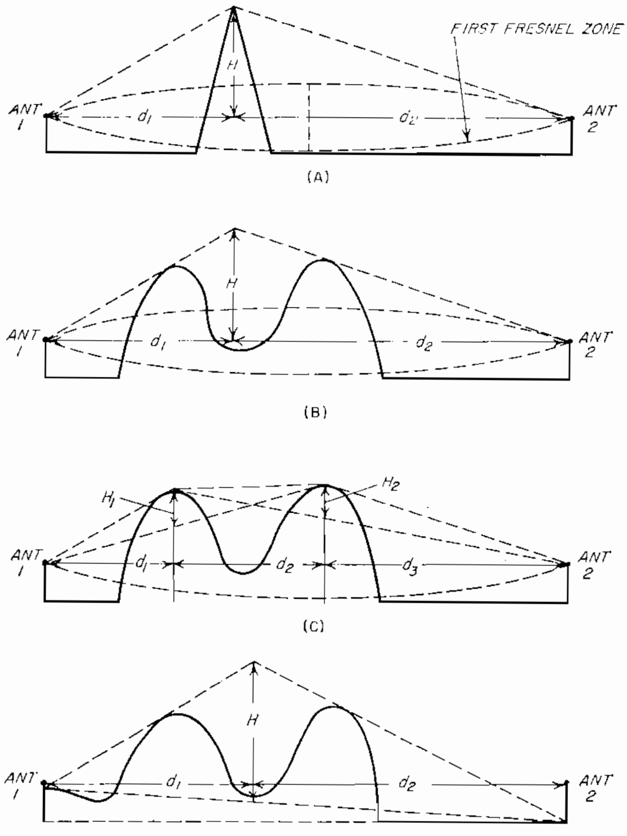


FIG. 1-12. Ray path for antennas behind hills.

measured vertically from this base line to the top of the hill, while d_1 and d_2 are measured to the antennas as before. In this case Fig. 1-14 is used to estimate the shadow loss to be added to the plane-earth attenuation.[9]

Under conditions where the earth-reflected components reinforce the direct components at the transmitting and receiving antenna locations, paths may be found for which the transmission loss over an obstacle is less than the loss over spherical earth. This effect may be useful in establishing VHF relay circuits where line-of-sight operation is not practical. Little utility may be expected for mobile or broadcast services.[15]

An alternate method for predicting the median value for all measurements in a completely shadowed area is as follows:[16] (1) The roughness of the terrain is assumed to be represented by height H, shown on the profile at the top of Fig. 1-15. (2) This height is the difference in elevation between the bottom of the valley and the elevation necessary to obtain line of sight with the transmitting antenna. (3) The difference between the measured value of field intensity and the value to be expected over plane earth is computed for each point of measurement within the shadowed area. (4) The median value for each of several such locations is plotted as a function of $\sqrt{H/\lambda}$.

These empirical relationships are summarized in the nomogram shown in Fig. 1-15. The scales on the right-hand line indicate the median value of shadow loss, compared

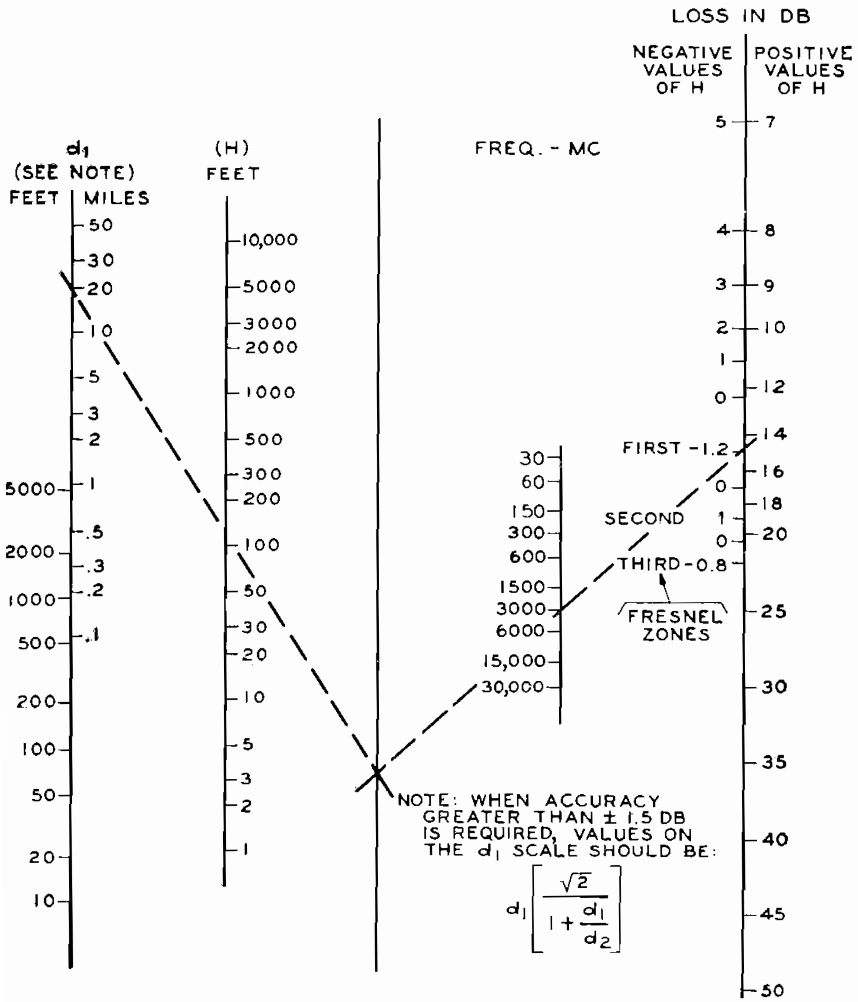
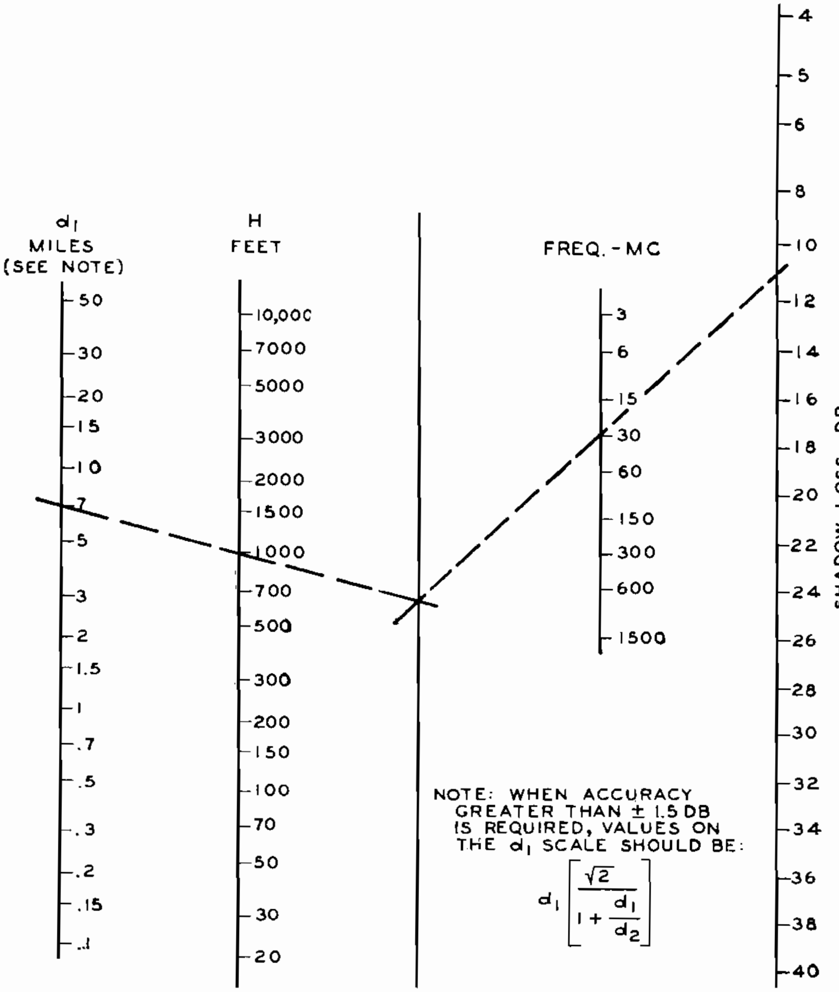


FIG. 1-13. Shadow loss relative to free space.

with plane-earth values, and the difference in shadow loss to be expected between the median and the 90 per cent values. For example, with variations in terrain of 500 ft, the estimated median shadow loss at 4,500 Mc is about 20 db and the shadow loss exceeded in 90 per cent of the possible locations is about 20 + 15 = 35 db. This analysis is based on large-scale variations in field intensity and does not include the standing-wave effects which sometimes cause the field intensity to vary considerably in a matter of a few feet.

Effects of Buildings

Built-up areas have little effect on radio transmission at frequencies below a few megacycles, since the size of any obstruction is usually small compared with the wavelength and the shadows caused by steel buildings and bridges are not noticeable except



$$d_1\left[\frac{\sqrt{2}}{1+\frac{d_1}{d_2}}\right]$$

FIG. 1-14. Shadow loss relative to plane earth.

immediately behind these obstructions. However, at 30 Mc and above, the absorption of a radio wave in going through an obstruction and the shadow loss in going over it are not negligible, and both types of losses tend to increase as the frequency increases. The attenuation through a brick wall, for example, may vary from 2 to 5 db at 30 Mc and from 10 to 40 db at 3,000 Mc, depending on whether the wall is dry or wet. Consequently, most building are rather opaque at frequencies of the order of thousands of megacycles.

For radio-relay purposes, it is the usual practice to select clear sites, but where this is not feasible the expected fields behind large buildings may be predicted by the preceding diffraction methods. In the engineering of mobile- and broadcast-radio systems it has not been found practical in general to relate measurements made in built-up areas to the particular geometry of buildings, so that it is conventional to treat them statistically. However, measurements have been divided according to general categories into

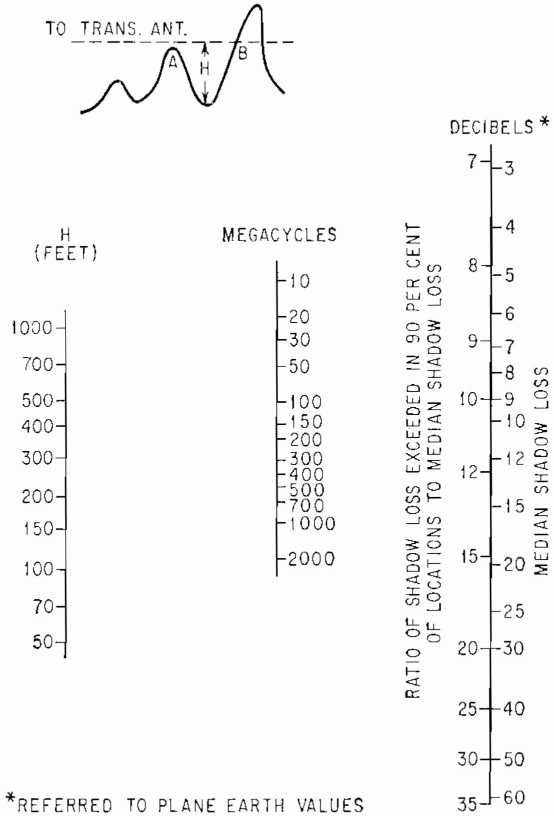


FIG. 1-15. Estimated distribution of shadow loss for random locations.

which buildings can readily be classified, namely, the tall buildings typical of the centers of cities on the one hand, and typical two-story residential areas on the other.

Buildings are more transparent to radio waves than the solid earth, and there is ordinarily much more back scatter in the city than in the open country. Both of these factors tend to reduce the shadow losses caused by the buildings. On the other hand, the angles of diffraction over or around the buildings are usually greater than for natural terrain, and this factor tends to increase the loss resulting from the presence of buildings. The quantitative data on the effects of buildings indicate that in the range of 40 to 450 Mc there is no significant change with frequency, or at least the variation with frequency is somewhat less than the square-root relationship noted in the case of hills. The median field strength at street level for random locations in Manhattan (New York City) is about 25 db below the corresponding plane-earth value. The corresponding values for the 10 and 90 per cent points are about −15 and −35 db, respectively.[9,16]

Measurements in congested residential areas indicate somewhat less attenuation than among large buildings. In the Report of the Ad Hoc Committee[19] measurements between 4 and 10 miles from the transmitter, which include some large building areas and some open areas but are made up principally of residential areas, shown median values of 4 to 6 db below plane earth for frequencies below 100 Mc and about 10 db for frequencies near 200 Mc. More recent measurements at 850 Mc[20] show values of 15 to 26 db below free space, which appear to be about 10 to 15 db below plane earth. These measurements were not random, however, but were the maximum values of field between 10 and 30 ft above the earth. The average effects for measurements taken in built-up areas have been accounted for in the preparation of the modified propagation curves of Figs. 1-19 and 1-20.

Effects of Trees and Other Vegetation

When an antenna is surrounded by moderately thick trees and below treetop level, the average loss at 30 Mc resulting from the trees is usually 2 or 3 db for vertical polarization and negligible with horizontal polarization. However, large and rapid variations in the received field strength may exist within a small area, resulting from the standing-wave pattern set up by reflections from trees located at a distance of as much as 100 ft or more from the antenna. Consequently, several nearby locations should be investigated for best results. At 100 Mc the average loss from surrounding trees may be 5 to 10 db for vertical polarization and 2 or 3 db for horizontal polarization. The tree losses continue to increase as the frequency increases, and above 300 to 500 Mc they tend to be independent of the type of polarization. Above 1,000 Mc trees that are thick enough to block vision present an almost solid obstruction, and the diffraction loss over or around these obstructions can be obtained from Fig. 1-13 or 1-14.[9,10]

There is a pronounced seasonal effect in the case of deciduous trees, with less shadowing and absorption in the winter months when the leaves have fallen. However, when the path of travel through the trees is sufficiently long that it is obscured, losses of the above magnitudes may be incurred, and the principal mode of propagation may be by diffraction over the trees.

When the antenna is raised above trees and other forms of vegetation, the prediction of field strengths again depends upon the proper estimation of the height of the antenna above the areas of reflection and of the applicable reflection coefficients. For growth of fairly uniform height and for angles near grazing incidence, reflection coefficients will approach -1 at frequencies near 30 Mc. As indicated by Rayleigh's criterion of roughness, the apparent roughness for given conditions of geometry increases with frequency so that near 1,000 Mc even such low and relatively uniform growth as farm crops or tall grass may have reflection coefficients of about -0.3 for small angles of reflection.[20]

The distribution of losses in the immediate vicinity of trees does not follow normal probability law but is more accurately represented by Rayleigh's law, which is the distribution of the sum of a large number of equal vectors having random phases. This distribution is shown by the graph R of Fig. 1-23.

Effects of the Lower Atmosphere, or Troposphere

The dielectric constant of the air is slightly greater than 1 and is variable. It depends on the pressure and temperature of the air and on the amount of water vapor present, so that it varies with weather conditions and with the height above the earth. Whenever the dielectric constant varies with height, a horizontally traveling wave will be refracted and the path deviated from a straight line. A general solution of the problem for any possible distribution of dielectric constant with the height at any point along the radio path is virtually impossible because of a large number of variables involved, so some simplifying assumptions are needed in order to obtain an engineering solution which will permit the calculation of radio field strengths under known meterological conditions. The complexity of this problem, together with the facts that detailed meteorological data which would permit calculation are no more readily available than radio data and that meteorological conditions are not readily predictable over long periods of time, has led to the statistical treatment of radio data, for the purpose of predicting long-distance effects and for the calculation of television service and interference, as in Statistical Evaluation of Propagation.

Stratification and Ducts

In the earlier work in this field the assumption was made that the air was horizontally stratified.[22,23] A simple engineering solution for average conditions can be obtained by making the additional assumption that the dielectric constant is a linear function of the height. On this basis, the effect of atmospheric refraction can be included in the expression of diffraction around the smooth earth, without discarding the useful concept of straight-line propagation, by multiplying the actual earth's radius by k, to obtain an effective earth's radius, where

$$k = \frac{1}{1 + a/2(\Delta\epsilon/\Delta h)} \tag{1-11}$$

where a is the radius of the earth and $\Delta\epsilon$ is the change in dielectric constant in going from height h to $h + \Delta h$.[9]

Meteorological measurements indicate that the actual curve of dielectric constant vs. the height above the ground is frequently complex with one or more sharp bends, rather than a straight line as required in using the concept of an effective earth's radius. Theoretical considerations indicate that this curve can be approximated with reasonable accuracy by a series of straight lines as long as each individual line corresponds to a change in height of not more than 20 to 50 wavelengths. At 30 Mc height intervals of 600 to 1,500 ft can be assumed. Since most of the radio energy transmitted between two ground stations travels in the first of these height intervals, the concept of effective earth radius is a useful one and is sufficiently accurate at 30 Mc. However, as the frequency increases, the straight-line approximation is valid over smaller and smaller height intervals. At 3,000 Mc, for example, this interval is only 6 to 15 ft, and the concept of effective earth radius becomes inadequate for analytical use. The rate of decrease of time-median measurements with distance is relatively consistent with theoretical propagation over an equivalent knife edge rather than with values calculated from assumed earth-radius factors.[16]

The dielectric constant normally decreases with increasing height, k is greater than unity, and the radio waves are bent toward the earth. Since the earth's radius is about 2.1×10^7 ft, a decrease in dielectric constant of only 2.4×10^{-8} per foot of height results in a value of $k = \frac{4}{3}$, which is commonly assumed to be a good average value. When the dielectric constant decreases about four times as rapidly (or by about 10^{-7} per foot of height), the value of k becomes infinite. This means that, as far as radio propagation is concerned, the earth can be considered flat, since any ray that starts parallel to the earth will remain parallel.

When the dielectric constant decreases more rapidly than 10^{-7} per foot of height, radio waves that are radiated parallel to or at an angle above the earth's surface may be bent downward sufficiently to be reflected from the earth, after which the ray is again bent toward the earth, and so on.[8,9,24] The radio energy is thus trapped in a duct or wavegnide between the earth and the maximum height of the radio path. For low-layer heights, this phenomenon is variously known as trapping, duct transmission, anomalous propagation, or guided propagation. Elevated layers of this type at heights up to several thousand feet are believed to be responsible for the occurrence of high field strengths at distances somewhat beyond the horizon from the transmitter. Theoretical studies indicate that attainable values of dielectric variation could produce the field strengths which are usually observed at such distances for small percentages of the time.[23] Confirmation has also been obtained through simultaneous observations of radio field strengths and of meteorological conditions.[22] In addition to the simple form of a duct where the earth is the lower boundary, trapping may also occur in an elevated duct. For example, in the lower segment of the duct the dielectric constant may decrease very slowly or may even increase, so that the waves travel upward into an upper segment in which the dielectric constant decreases more rapidly than 10^{-7} per foot and in which the waves are again refracted in a downward direction to encounter the lower segment again, after which the process is repeated. In the case of either of the two foregoing forms of ducts, if there were no losses of energy involved, the field strengths at any given distance would exceed the free-space fields, since the spread of energy is restrained in the vertical dimension. However, experience indicates that over land paths the losses are such that the received field strengths are seldom greater than the plane-earth values.[9]

Tropospheric Scatter

More recently a theory has been developed by Booker and Gordon[25,26] attributing the distant tropospheric fields to the scattering of the radio waves by atmospheric turbulence rather than by reflection from horizontal stratification. There is considerable activity, both theoretical and experimental, to determine whether elevated stratified layers, turbulence, residual effects from the normal gradients of dielectric constant, or contributions from all three, are responsible for the high field strengths beyond the line of sight, which are of concern in estimating the interference between television broadcast stations. In addition to these higher field strengths, which occur for small percentages of the time, there are rather consistent fields of about 80 db below free space, which are largely independent of frequency. The rate of decrease for the median values of these fields is consistent with the theory of scatter from random turbulence.[22,28]

Atmospheric Fading

Variations in the received field strengths around the median value are caused by changes in atmospheric conditions. Field strengths tend to be higher in summer than in winter and higher at night than during the day for paths over land beyond the line of sight. As a first approximation, the distribution of long-term variations in field strength in decibels follows a normal probability law, as shown by graph N of Fig. 1–23.

Measurements indicate that the fading range reaches a maximum somewhat beyond the horizon and then decreases slowly with distance out to several hundred miles. Also the fading range at the distance of maximum fading increases with frequency, while at the greater distances where the fading range decreases, the range is also less dependent on frequency. Thus the slope of the graph N must be adjusted for both distance and frequency. This behavior does not lend itself to treatment as a function of the earth's radius factor k, since calculations based on the same range of k produce families of curves in which the fading range increases systematically with increasing distance and with increasing frequency. Methods for the statistical treatment of fading are described in Statistical Evaluation of Propagation.

Effects of the Upper Atmosphere, or Ionosphere

At the present time four principal layers or regions in the ionosphere are recognized. These are the E layer, the $F1$ layer, and the $F2$ layer, centered at heights of about 100, 200, and 300 km, respectively, and the D region, which is less clearly defined but lies below the E layer. These "regular" layers are produced by radiation from the sun, so that the ion density, and hence the frequency of the radio waves which can be reflected thereby, is higher in the day than at night. The characteristics of the layers are different for different geographic locations, and the geographic effects are not the same for all layers. The characteristics also differ with the seasons and with the intensity of the sun's radiation, as evidenced by the sunspot numbers, and the differences are generally more pronounced upon the $F2$ than upon the $F1$ and E layers. There are also certain random effects which are not fully explained. Some of these are associated with solar and magnetic disturbances. Other effects which occur at or just below the E layer have been established as being caused by meteors.[30]

Briefly the presently recognized ionospheric effects can be grouped into seven major categories as follows: (1) D region, (2) regular E layer, (3) regular $F1$ layer, (4) regular $F2$ layer, (5) sporadic E layer, (6) meteoric, and (7) anomalous and irregular ionization. The effects of the first three categories are either negligible or nonexistent at frequencies above 30 Mc and will not be referred to in detail. Categories (4), (5), and (6) will be discussed briefly as to their probable impact upon television service. The impact of (7) on television service is expected to be negligible.

F2 Layer

Data taken mainly during the years 1946 to 1948, when solar activity was high, indicate that during certain seasons of the year long-distance propagation by way of the regular *F*2-layer ionization can occur in temperate latitudes on frequencies up to about 50 Mc. The percentage of the total time during which it is possible is small, being, for example, of the order of 4.5 per cent on 50 Mc over the London–New York circuit, during the most favorable month of the year at sunspot maximum. In the tropics, however, such propagation can occur up to 60 Mc, with almost regular propagation on waves of 30 to 40 Mc. The field strengths observed are very variable, ranging from values exceeding the free-space value to those near or below the receiver noise level, over very short periods of time. However, since the radio noise fields are also very low, reception is often continuous for long periods of time and serious interference may result to services which are designed to provide communication at relatively low field strengths.

For several years around the solar maximum, on a widely occupied channel, intolerable long-range interference may be expected on frequencies below about 50 Mc during daylight hours in the equinox and winter seasons. The lowest frequency at which such interference becomes so infrequent as to be inappreciable is about 50 Mc for stations in temperate latitudes and about 60 Mc for stations in the tropics.[31, 32]

Worldwide predictions of *F*2-layer maximum usable frequencies (MUF) are given in monthly charts published by the Central Radio Propagation Laboratory of the National Bureau of Standards (CRPL).[33] Because of the variability of the *F*2 layer, precise predictions cannot be given for individual days, but statistically in one case out of ten the critical frequency at a given location will vary from the running average by more than 15 per cent. In other words, for the estimation of interference from this cause between television stations, it may be assumed that the daily MUF will exceed the monthly median MUF by more than 15 per cent on an average of 1 to 2 days per month. The occurrence in percentage of the time and in numbers of hours during the 1933-to-1944 sunspot cycle, as a function of the frequency and of the skip distance, is shown in Fig. 1-16, as estimated from the vertical incidence measurements made by the CRPL.[34]

Sporadic E

About five different forms of E_s are presently recognized and their occurrence varies in different latitudes. The form most prevalent in the United States and of interest to television can occur at any time of day but has a broad peak around midday and a subsidiary peak around sunset. It exhibits a marked seasonal variation and is especially prevalent during the months of May to September inclusive and of relatively small importance during the remaining months. Transmission by way of it is ordinarily confined to a single hop, at distances between about 400 and 1,400 miles. No definite correlation with the sunspot cycle has as yet been established.

The nature and causes of E_s are not well understood, but the most widely accepted explanation is that the typical E_s of the temperate latitudes consists of turbulent and rapidly moving clouds of ionization. When the clouds are large, steady and intense fields may be received for periods ranging from a few minutes to several hours. When the clouds are small and numerous, interference between the several reflected wavefronts produces very rapid fading. Superposed on the rapid fading are changes in the average field strength over longer periods of time, resulting from changes in the sizes, shapes, and positions of the clouds. These characteristics make difficult the estimation of time of occurrence and the probable interference therefrom. Figure 1-17 shows the number of hours and the percentage of the total time of occurrence of E_s from September, 1943, through August, 1944, as a function of frequency and of skip distance, estimated from vertical incidence measurements made by the CRPL. In Fig. 1-18, the curve $N = 1$ represents estimated field strengths exceeded for the times indicated in Fig. 1-17. Curves $N = 0.25$, $N = 0.5$, $N = 2$, and $N = 4$ represent the estimated field strengths to be expected for the corresponding multiples of the percentages of time shown in Fig. 1-17. For example, from Fig. 1-17, at a frequency of 40 Mc and at 1,000 miles, E_s field strengths occur for 1 per cent of the time. Referring to Fig. 1-18, at 1,000 miles, a field strength

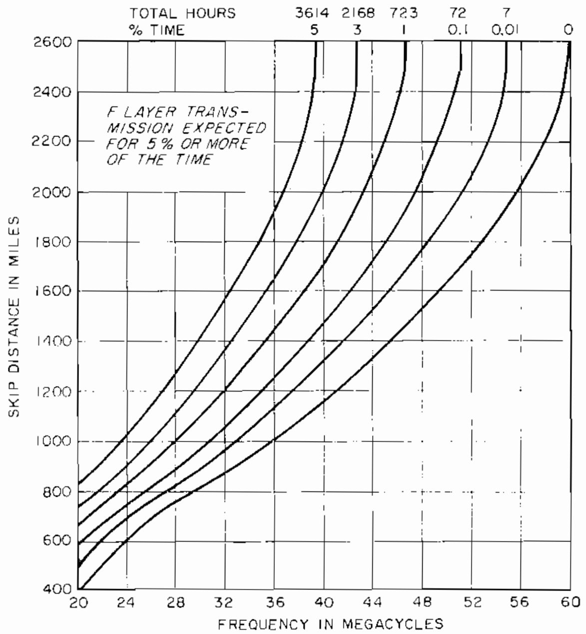


FIG. 1-16. Occurrence of $F2$-layer propagation.

of 27 db below free space was exceeded for 1 per cent of the time (curve $N = 1$), or 21.5 db for 0.25 per cent of the time (curve $N = 0.25$). At 81 Mc these fields would be exceeded for 0.01 and 0.0025 per cent of the time respectively. The rate of increase in the expected times of interference due to additional transmitters is not known. It is probably a function of the frequency, since the apparent size of the E_s clouds will decrease with increasing frequency. Thus for frequencies above 54 Mc, the lowest of the television channels, there is likely to be little correlation between the times of interference received from transmitters separated by a few hundred miles.[34, 35]

The above information is based on a relatively small amount of data taken over a 1-year period. It is known that there are significant variations in E_s from year to year. Predictions of E_s for 3 months in advance are given in CRPL Series *D* and measured data in Series *F*, publications of the National Bureau of Standards.[33] The values given are monthly median values, and for short periods of time fluctuations about the median may result in the propagation of frequencies well above the values shown. Until more is known of the nature and causes of E_s, more detailed predictions cannot be given. For the same reasons, the above information is to be considered more as a guide as to the order of magnitude of these effects than as the basis for reliable estimates of interference from E_s.

Meteoric Ionization

Radio waves are reflected from the ionized trails produced by meteors at the height of the E layer and somewhat below. Because of the transitory nature of such ionization, the waves are usually received in short bursts of signal lasting for a fraction of a second. However, long bursts of from several seconds' to several minutes' duration will be received at infrequent intervals. Measurements made at a frequency of 44 Mc and over distances of 300 to 700 miles indicate that during the diurnal maximum, which occurs in early morning hours, about 100 bursts exceeding a field strength of 70 db below free space may occur per hour. The peak amplitudes for distances between 300 and 1,100 miles lie between 40 and 50 db below free space.[36]

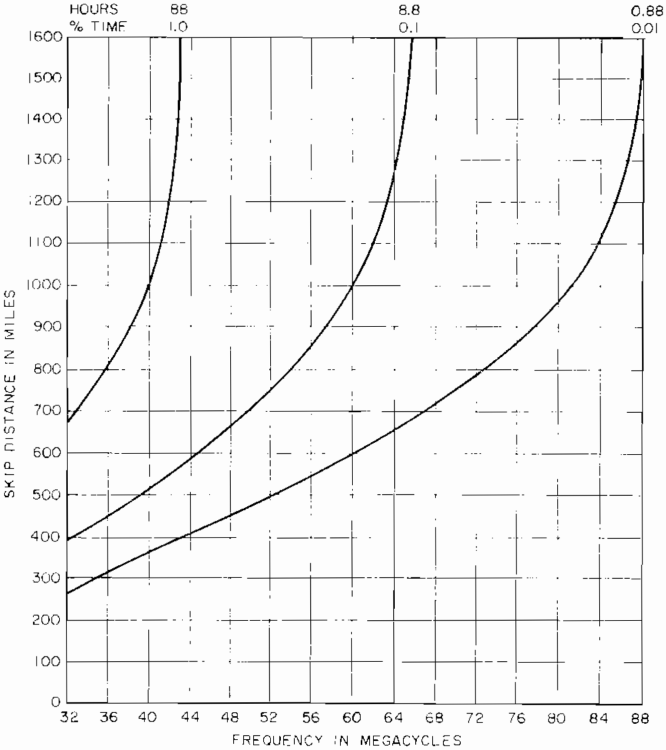


FIG. 1-17. Occurrence of E_s-layer propagation.

STATISTICAL EVALUATION OF PROPAGATION

In previous sections a partial statistical description has been given of the separate effects of terrain and of the variation of field strengths with time. Methods have been given for the prediction of the median field strengths to be expected for areas of size comparable to the gross features of the terrain, to which correction factors may be applied for the presence of buildings and vegetation and within which the fields may be described in terms of the strengths which are expected to be exceeded at a given percentage of locations. Alternatively, the distribution of field strengths as a function of the percentage of locations may be regarded as the probability, in per cent, that a given field strength will be exceeded at a particular location within the area in question.

For the purpose of formulating a national plan for the assignment of television channels, it was felt to be impractical to consider in detail even the gross features of terrain, so that a statistical approach has been adopted to prepare families of propagation curves reflecting the median values found from all available data. Figures 1-19 and 1-20 show the field strengths in decibels relative to 1 μv/m for 1 kw of effective radiated power to be expected at the best 50 per cent of receiving locations for at least 50 per cent of the time, for antenna heights from 100 to 10,000 ft. These field strengths are referred to as $F(50,50)$. The field strengths are based on an effective power of 1 kw radiated from a half-wave dipole in free space, which produces an unattenuated field strength at 1 mile of about 103 db above 1 μv/m (103 dbμ). The antenna height to be used with these charts in any particular case is the height of the center of the radiating element above the average height of the profile between 2 and 10 miles from the transmitter along the desired radial. Figures 1-21 and 1-22 show the corresponding field strengths

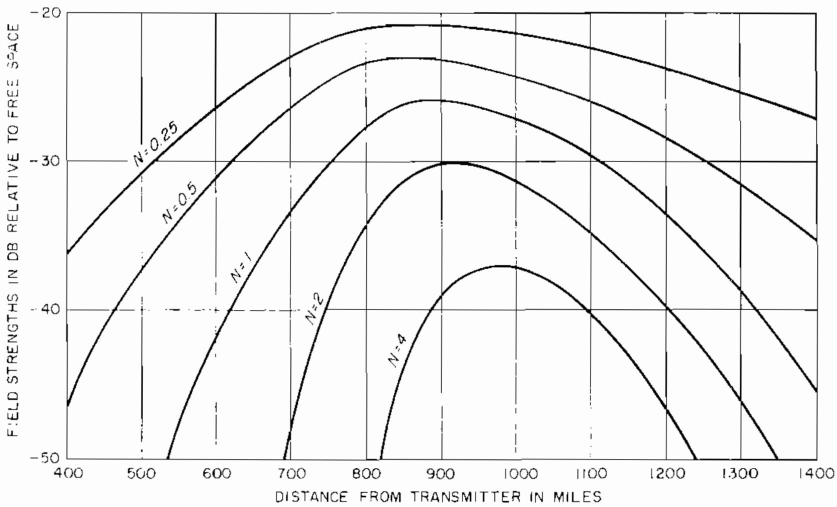


FIG. 1-18. E_s field strengths.

for 50 per cent of the locations and 10 per cent of the time $F(50,10)$. These families of curves, in conjunction with curve N of Fig. 1-23, may be used to estimate the service provided by television stations, in accordance with the following procedures.

Prediction of Field Strengths for Television Service [19]

The field strengths required to provide television service are derived in the following manner: Test receivers of known characteristics as to sensitivity, selectivity, etc., are set up under typical home lighting and viewing conditions. Viewers then rate the relative acceptability of pictures at varying levels of input signals as obtained from a calibrated source, such as a television signal generator. The ratings are then analyzed statistically in terms of the percentages of viewers who rate the pictures as of a given quality, such as satisfactory, at each level of signal input. These results follow the normal probability law of curve N. It is impractical to satisfy 100 per cent of viewers and values satisfying 50 to 70 per cent are usually adopted for broadcast purposes. From the signal level thus selected and the known bandwidth and noise characteristics of the receiver, a required signal-to-noise ratio is determined. The required instantaneous fields F' to provide service of this quality are then derived by applying the proper values for the receiver-noise figure and the antenna and transmission line characteristics of the typical receiver installation. Similar procedures are used for deriving the desired to undesired ratio for various types of interfering signals. For this purpose the undesired signal is also fed into the receiver input in various ratios and at various frequencies in relation to the desired signal.[39]

The service at a particular location is said to be satisfactory if the minimum required field F', as above determined, is exceeded for some agreed percentage of the time T, such as 90 per cent. This may be expressed as a T per cent field strength $F'(T)$. The required time median field $F'(T = 50)$ to provide the minimum field for the desired percentage of time $F'(T)$ is given by the equation

$$F'(T) = F'(T = 50) + N'(T) \qquad (1\text{-}12)$$

$N'(T)$ is the time distribution factor in decibels for T per cent of the time. This factor is assumed to be independent of location so that Eq. (1-12) can also be written

$$F'(L,T) = F(L,50) + N'(T) \qquad (1\text{-}12a)$$

and

$$F'(50,10) = F(50,50) + N'(T = 10) \qquad (1\text{-}12b)$$

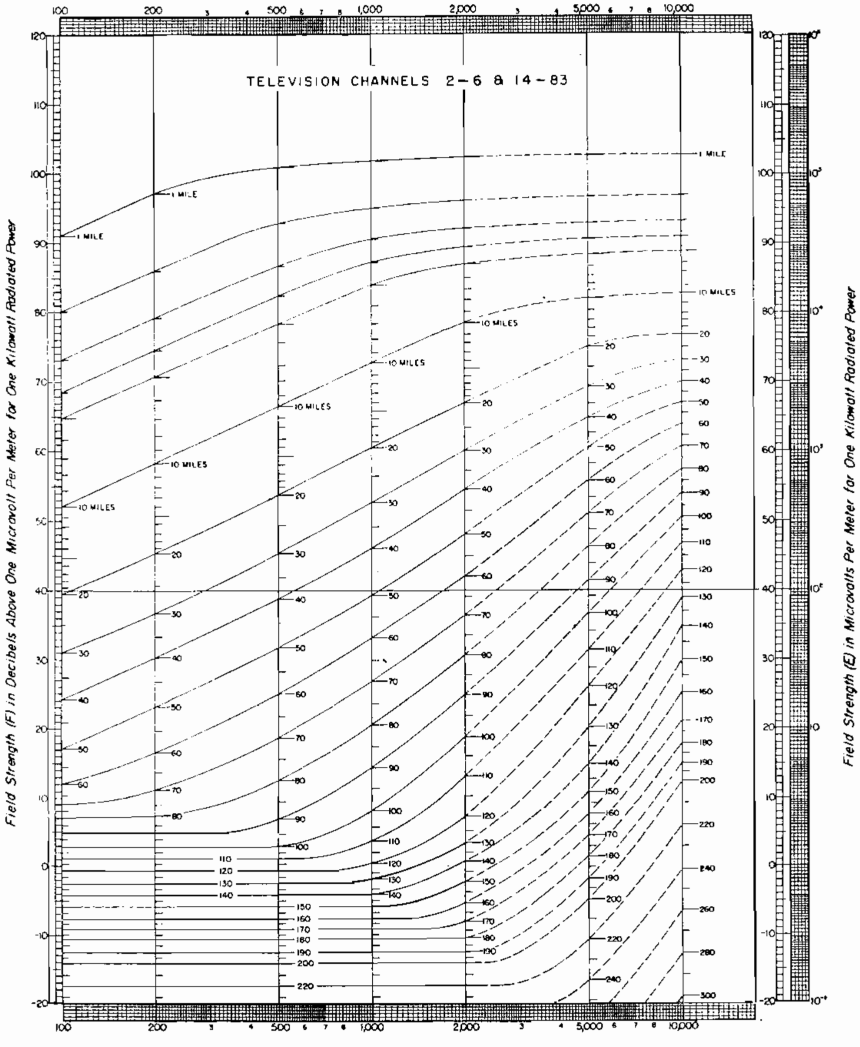


FIG. 1-19. $F(50,50)$ for television channels 2 to 6, 14 to 83.

Thus $N'(T = 10)$ can be determined for various frequencies, distances, and antenna heights, using the appropriate values of $F(50,10)$ shown in Figs. 1-21 and 1-22 and of $F(50,50)$ shown in Figs. 1-19 and 1-20. The distributions of field strengths for waves propagated via the troposphere are highly variable. For short periods of time during which the characteristics of the troposphere do not vary materially and the variation is due mainly to wave interference, the distribution may approach the Rayleigh distribution shown in curve R of Fig. 1-23. For longer periods of time the distributions of instantaneous values and of hourly median values assume complex forms of which the curve T of Fig. 1-23 is characteristic. Since the field strengths from which the curve was constructed have contributions from various modes of propagation and since the shape of the curve varies with such parameters as frequency, distance, transmitting

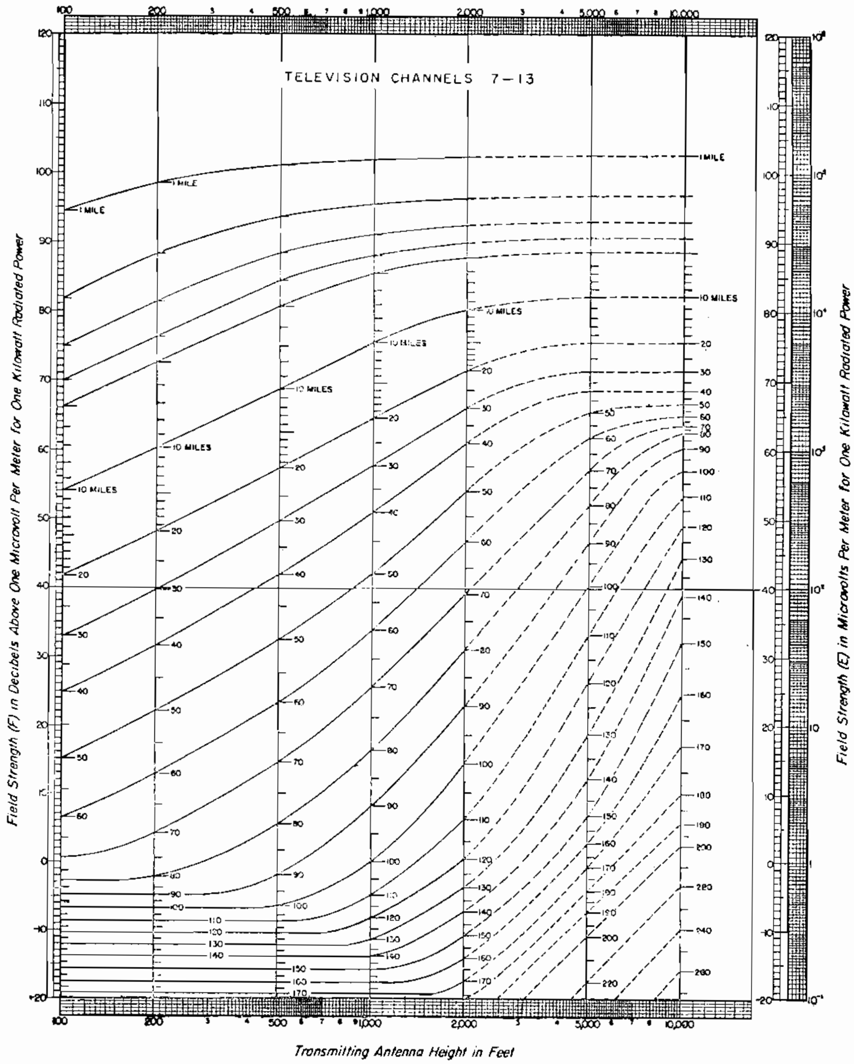


FIG. 1-20. $F(50,50)$ for television channels 7 to 13.

antenna height, receiver location, etc., an exact expression is not possible. However, the curve is sufficiently close to the log normal curve N, so that with attention to the proper slope as determined by the appropriate value of $N'(T = 10)$, a log normal distribution can be used for the purposes of estimating service and interference. Thus $N'(T)$ for values of T other than 10 per cent can be approximated by the formula

$$N'(T) = N'(T = 10)\frac{N(T)}{N(T = 10)} \tag{1-13}$$

The percentage of locations L or the percentage probability L that the received fields $F'(L,T)$ will exceed the required T per cent fields $F'(T)$ at a particular location within the area may be determined by the formula

$$N'(L) = F'(L,T) - P' - F(50,50) - N'(T) \qquad (1\text{-}14)$$

where $N'(L)$ is the location distribution factor in decibels for L per cent of locations or L per cent probability at a particular location. For VHF television Channels 2 to 13, $N'(L)$ is equal to 0.53 times the values given by the normal probability curve N of Fig. 1-23, or $N'(L) = 0.53\ N(L)$. For UHF Channels 14 to 83

$$N'(L) = 0.75\ N(L)$$

$F'(L,T)$ is the minimum field strength, in dbμ, to be expected at the best L per cent of locations for at least T per cent of the time. P' is the effective radiated power in

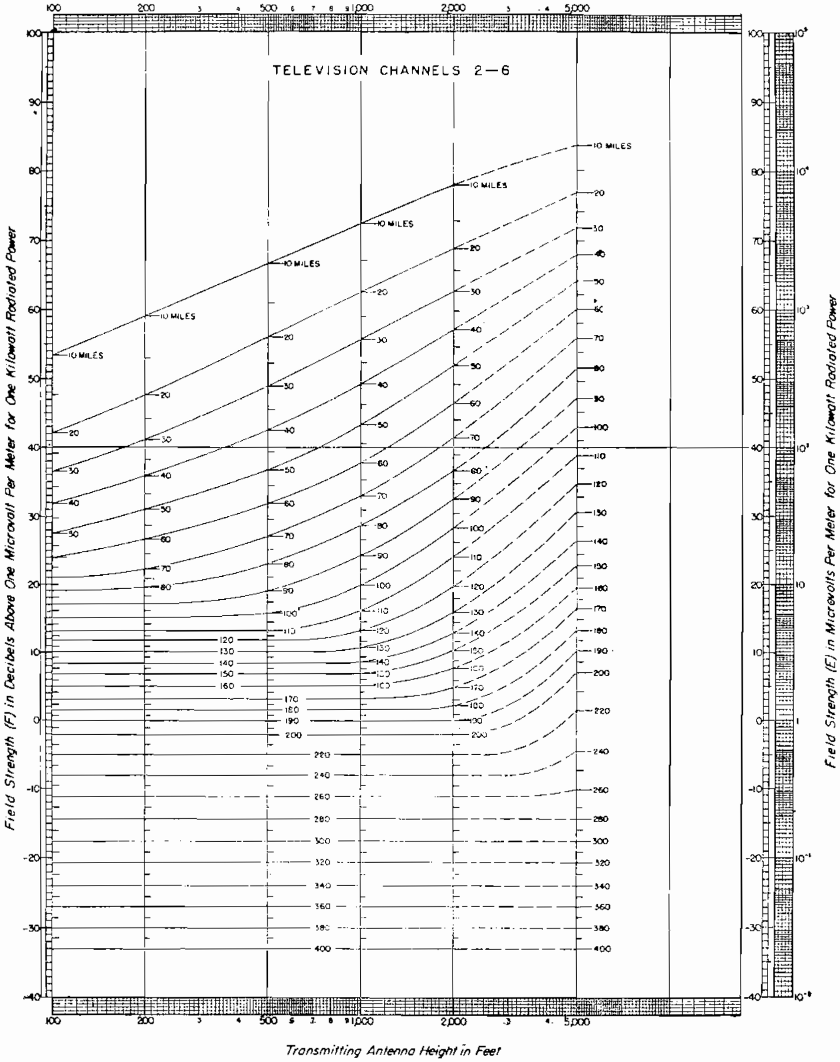


FIG. 1-21. $F(50,10)$ for television channels 2 to 6.

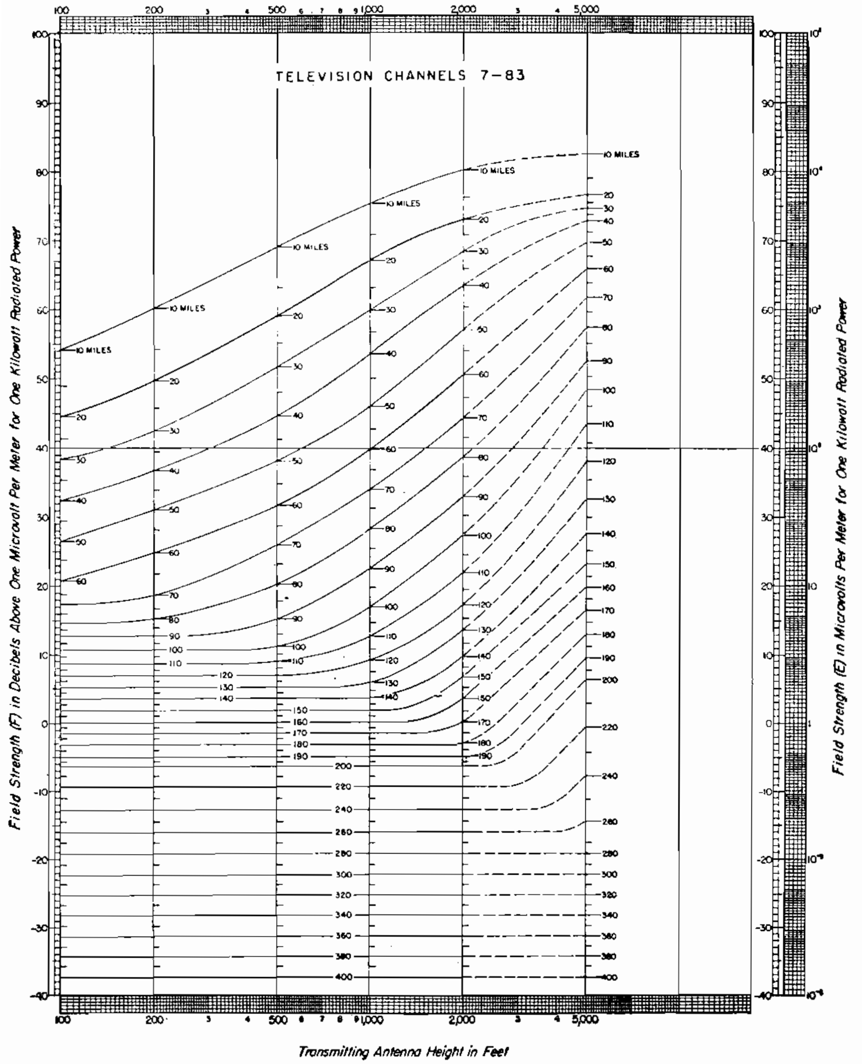


FIG. 1-22. $F(50,10)$ for television channels 7 to 83.

decibels relative to 1 kw (dbk) radiated from a half-wave dipole. $F(50,50)$ is the median value of field strength in dbμ for an effective radiated power of 0 dbk for the area in question, as taken from Fig. 1-19 or 1-20, for the appropriate frequency, distance, and transmitting antenna height.

Example: For a television station operating on Channel 2, with an effective radiated power of 100 kw (20 dbk) and an average transmitting antenna height of 500 ft for 2 to 10 miles along the radial, what percentage of locations in an area 20 miles from the transmitter may be expected to have field strengths exceeding 74 dbμ for at least 90 per cent of the time?

$$F'(L,90) = 74 \text{ db}\mu$$
$$P' = 20 \text{ dbk}$$
$$F(50,50) = 54 \text{ db}\mu \text{ (from Fig. 1-19)}$$
$$F(50,10) = 56 \text{ db}\mu \text{ (from Fig. 1-21)}$$
$$N'(T = 10) = 56 - 54 = 2 \text{ db [from Eq. (1-12}b\text{)]}$$
$$N'(T = 90) = \frac{2(-20)}{20} = -2 \text{ db [from Fig. 1-23 and Eq. (1-13)]}$$

Substituting in Eq. (1-14)

$$N'(L) = 74 - 20 - 54 - (-2) = +2$$
$$N(L) = \frac{N'(L)}{0.53} = 3.8$$
$$L = 41 \text{ per cent (from Fig. 1-23)}$$

Several points at various distances along each radial can be calculated in the above manner and the distance at which desired percentages of locations, or desired probabilities, such as 50, 70, 90 per cent, etc., occur may be determined by interpolation. Iso-service contours may be drawn by connecting the points having the same probability on each of the several radials.

Some analyses have been made of this problem using different characteristic slopes for values of T above and below 50 per cent. Since values of T between 10 and 90 per cent are usually of principal interest for broadcast purposes, a closer fit to the curve T can be made by this method within the range of interest.

Prediction of Service in the Presence of Interference from One Undesired Station [19]

The percentage of receiving locations, or the probability in per cent L, at any given distance from a desired station and one undesired station (for which an acceptable ratio

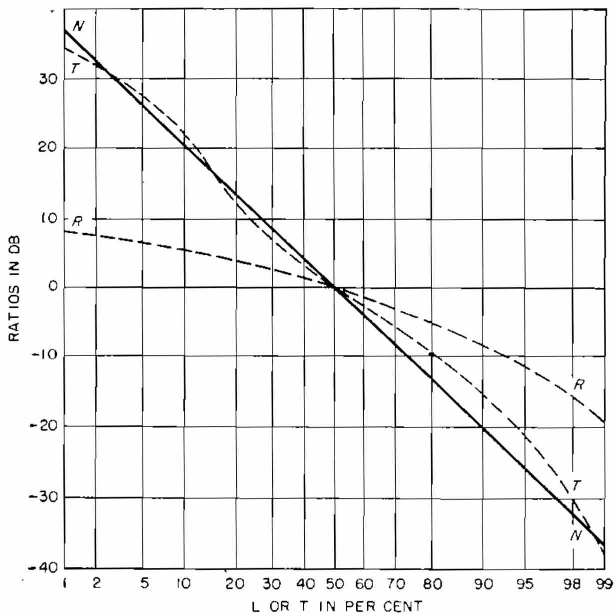


FIG. 1-23. Time and location distributions.

A, in decibels, of desired-to-undesired signals is exceeded for at least T per cent of the time at the receiver input) can be determined from the following equation

$$n'(L) = A + P_u' - P_d' + g_{ru} - g_{rd} + F_u(50,50) - F_d(50,50) + \sqrt{N_d'(T)^2 + N_u'(T)^2} \quad (1\text{-}15)$$

The subscript d denotes values applicable to the desired signal, and the subscript u denotes values applicable to the undesired signal. As above, the effective radiated powers of the desired and undesired station in P_d' and P_u' are expressed in decibels above 1 kw radiated from a half-wave dipole. g_{ru} and g_{rd} are, respectively, the gains of the receiving antenna in the directions of the undesired and the desired transmitters. $F_u(50,50)$ and $F_d(50,50)$ are the indicated field strengths from the undesired and desired transmitters taken from the appropriate curves of Fig. 1-19 or 1-20. $N_d'(T)$ and $N_u'(T)$ are the time-distribution factors for the desired and the undesired field strengths, respectively. The factors for 90 per cent of the time can be determined by subtracting the (50,10) field strength from the (50,50) field strength for each station at the proper distances on the appropriate curves of Figs. 1-19 to 1-22, in accordance with Eq. (1-12*b*). The factors for any other desired percentage of time may be found by the use of Eq. (1-13) and curve N of Fig. 1-23.

The answer for the factor $n'(L)$ is obtained in decibels. For Channels 2 through 13, $n'(L) = 0.75\,N(L)$ and the percentage of locations at which the ratio A is exceeded may be read from the probability distribution, $N(L)$, as a function of L in Fig. 1-23. For Channels 14 through 83, $n'(L) = 1.05N(L)$.

It will be seen from Eq. (1-15) that the time-distribution factor applicable to two fading signals combines as the square roots of the individual factors. When the fading of the undesired signal is three or more times the fading of the desired, the latter fading may be neglected with negligible error. Thus, the charts for the desired signal $F(50,50)$ and the tropospheric charts $F(50,10)$ for the undesired, with appropriate corrections for the effective radiated powers of the two stations and the directional patterns of the receiving antennas, can be used to determine directly the isoservice contours for 90 per cent of the time and 50 per cent of the locations.

The approximate method, in which the fading of the desired signal is neglected, can be expressed in the following formula:

$$n'(L) = A + P_u' - P_d' + g_{ru} - g_{rd} + F_u(50,10) - F_d(50,50) \quad (1\text{-}16)$$

This formula permits the approximate method to be applied to the case where it is desired to locate the contour at which an acceptable ratio is exceeded for a percentage of the locations other than 50 per cent.

Prediction of Service in the Presence of Interference from Several Sources

This problem was studied by the Ad Hoc Committee and four methods of calculating the combined effects of several interfering signals were reported in vol. 2 of the report of the Committee.[11] The methods involve somewhat different assumptions as to the subjective effects of interference and as to the time and space correlations of the various signals. Reference should be made to that report for details as to the assumptions made and the limitations involved in each method. The application of three of these methods is somewhat tedious, and since the results obtained by all four methods are reasonably consistent, just one relatively simple method will be described in detail.

This method involves the conclusion that the probability of a receiving location receiving satisfactory service for a particular percentage of time in the presence of a plurality of interfering signals is equal to the product of the probabilities that satisfactory service will be received for the same percentage of time in the presence of each of the interfering signals alone. Thus the values of $n'(L)$ for the desired signal and each of the interfering signals are computed individually from Eq. (1-15) or (1-16), and the resulting probability found by multiplying the individual values together. Take as an example the case of two interfering signals, the first of which yields a location probability of 0.90 (90 per cent of locations), and the second of which yields a location probability of 0.70, at a given point. The probability of receiving satisfactory service of the same time availability at the same point is $0.90 \times 0.70 = 0.63$, or 63 per cent.

Distribution and Summation of Service

The method of describing service areas by isoservice contours, while relatively simple and useful for some purposes, is in fact a rather incomplete method which may lead to erroneous conclusions unless applied with understanding. Contours are frequently used to describe the outer limits of recognized grades of service for administrative purposes. The treatment of an isoservice contour as a limit of service, rather than as a contour of equal service availability, leads to errors in estimating service availability as well as the number of people who are expected to receive service. The foregoing analysis shows that in any small area only a percentage of the residents is expected to have service of a given quality available, so that this percentage of the population, rather than the total population of the area, should be included in a population count. Also, the percentage varies from area to area within the contour, increasing generally with decreasing distance from the desired transmitter, so that to obtain a fairly reliable count, variable percentages should be used for different areas.

As the distance from the desired transmitter increases, the quality of service does not change abruptly as might be inferred from the drawing of service contours but shades gradually from service of generally high quality to service of low quality. Thus it is proper to represent the expected quality of service as a continuous function of distance. Figure 1-24 shows the percentages of locations at various radii from a television station, at 63 Mc, with 100 kw ($P' = 20$ dbk) radiated from a 500-ft antenna, which would be expected to receive service for at least 90 per cent of the time in the presence of receiver and cosmic noise only. In Fig. 1-25 the percentages of locations in each annular ring at the radius r from the transmitter have been multiplied by the area of the ring, to produce service distributions in terms of integrated service area Y, as a function of distance from the transmitter. The thickness of each ring has been taken as $1/2\pi$ so that the ring area is equal to the radius in each case. The curve labeled $P' = 20$ dbk corresponds to the conditions of Fig. 1-24. Curves for powers of $P' = 0$ dbk, $P' = 10$ dbk, and $P' = 30$ dbk are also shown to illustrate how the service varies with changes in the effective radiated power. In order to estimate the equivalent service area provided by the station, the area under the curve is integrated by the use of a planimeter or in accordance with the formula

$$\text{Service area} = 2\pi \int_0^\infty Yr\,dr$$

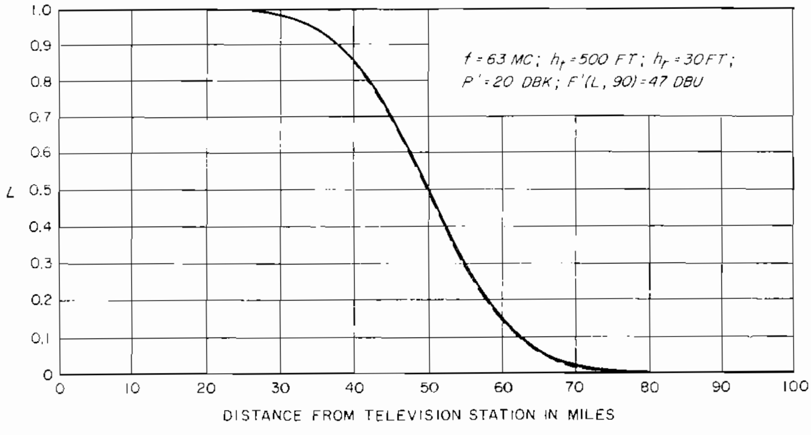


Fig. 1-24. Distribution of noise-limited-service probability.

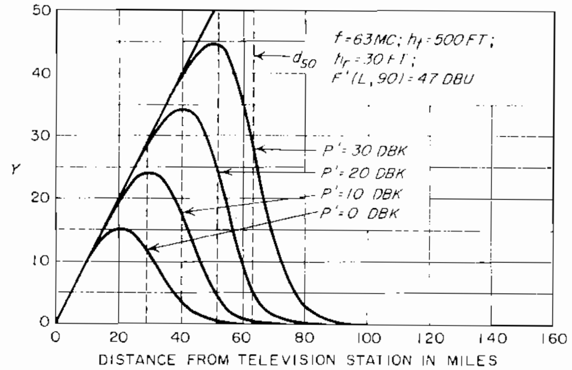


FIG. 1-25. Distribution of noise-limited service.

As an additional step, the integrated service area may be represented graphically by a circle of equivalent radius. These radii are indicated for each power on Fig. 1-25 by the dashed lines labeled d_{50}.

A similar approach can be used for cases in which it is desired to estimate the resulting service areas in the presence of interference from other television stations and other sources. Needless to say, the procedure becomes exceedingly complex in particular cases where there is a lack of symmetry between the sources of interference and the various radials along which service is to be estimated. In addition, as stated above, the available propagation data are subject to large probable errors when used to estimate service for any particular station. For these reasons, application of the procedures has so far been limited to broad studies of channel utilization, which are useful in developing station assignment plans and rules.

As illustrative of the methods of estimating service in the presence of several sources of interference, assume a case in which co-channel and adjacent-channel stations are assigned in a saturated triangular lattice, as shown in the inset of Fig. 1-26. The proba-

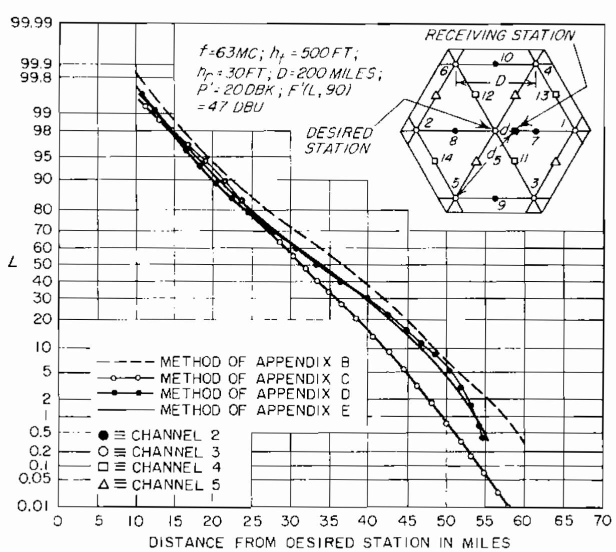


FIG. 1-26. Distribution of service probability limited by interference.

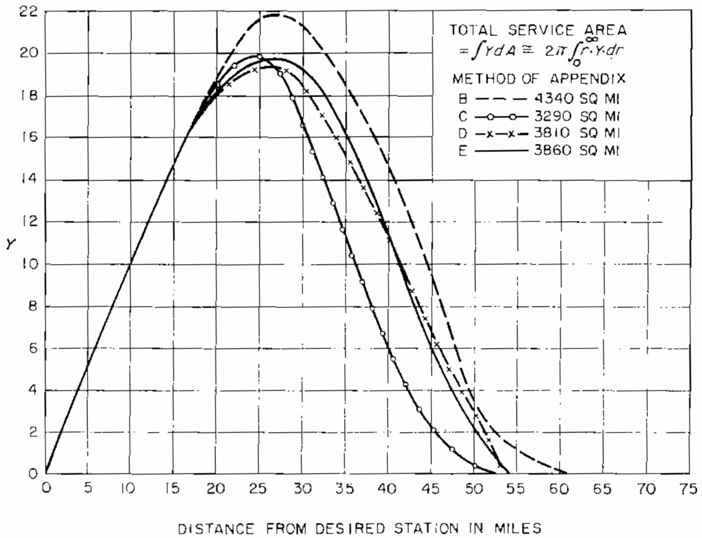


FIG. 1-27. Distribution of service limited by interference.

bility of receiving service of a given quality for a specified percentage of time from the desired station in the presence of the several sources of interference can be calculated for particular receiving locations along a radial in accordance with the four methods. The resulting distributions are shown in Fig. 1-26. Figure 1-27 shows the corresponding area probability and total areas for the four methods. It can be seen that the simple method described in Appendix C of vol. 2 of the Ad Hoc Report, and described previously herein, yields smaller estimates of service than do the other three methods.

Using this concept of total area it is possible to estimate the probable efficiency of utilization of the available television channels for various combinations of station power, antenna heights, and station spacings. While it is known that as a practical matter the station assignment pattern will follow the pattern of cities rather than the idealized and somewhat more efficient lattice, from the standpoint of area coverage, useful conclusions as to station-spacing requirements have been drawn from such studies.[19]

SELECTION OF STATION SITES

The sites for the antennas of permanent relay stations and for television broadcast stations should be selected carefully, as the success of the operation depends to a great extent upon the care and foresight used in selecting the sites. In previous sections, quantitative information has been given which will assist in estimating the transmission loss incurred over television relay links under specified conditions and in estimating the probable service obtained from a television broadcast station. The purpose of this section is to give a few guides which engineers have found to be of assistance in selecting sites which will yield optimum results for the area in question.

Selection of Sites for Radio Relay Stations

A large amount of preliminary work is necessary in laying out a radio relay system. For microwave systems it is usual that adjacent sites have a clear line-of-sight path between their antennas. To determine station locations, the best available topographical maps should be used. These, however, usually will not be adequate for final station location, particularly since for some areas no maps are available and for others existing maps may be found to be inaccurate. In some cases, aerial surveys have been used. Before finally selecting a site, radio transmission tests should be made with the adjacent sites. For these tests, portable towers with parabolic antennas and transmitters mounted on carriages which can be moved up and down the towers are used.

If the intervening terrain is rough and the intermediate clearances satisfactory, no large change in received signal will be found as the antennas are raised and lowered on the towers, until the antennas are lowered so far that clearance of the first Fresnel zone no longer exists.

In some cases, however, substantial earth reflection may be encountered, and this will be evidenced by substantial variations in received signal strength as the antennas travel up and down. It is desirable that transmission be largely confined to a single ray arriving from the distant station. If one or more additional rays are present, owing to reflection from the earth at some intervening point or points, the resultant signal will be that due to the combination of rays and will depend on their relative phase relations. Sites showing such earth reflection are not desirable, as substantial amounts of fading may be expected at times when changes in the atmosphere cause the amount of bending of the waves to change with consequent changes in phase relation of the arriving rays. If such variations are observed in these path tests, the intervening terrain should be inspected with a view to determining whether by moving one or both sites a short distance the reflecting earth surface can be avoided.

It is usually difficult to recognize the areas which are responsible for earth reflection, but a few guides can be given to assist in inspection at the site. If the suspected area is fairly flat, areas of a size equivalent to an ellipse capable of reflecting the wavefront over the first Fresnel zone should be inspected. Smaller areas are capable of supporting a reflection, but in general the strength of the reflected component will be decreased. When the intervening area is rolling or irregular, the determination of the location and size of the responsible area is still more difficult. It will also be necessary to decide whether the surface roughness is too great to support reflection at the frequency of interest. For this purpose, Rayleigh's criterion of roughness is used. The surface is considered to be smooth if $h \sin \theta < \lambda/8$, where h is the average height of the features of roughness, θ is the angle of incidence of the wave to the reflecting surface, and λ is the wavelength expressed in the same units as h.

In one case where transmission was to take place over extensive salt flats which are smooth and of high conductivity, it was not possible to avoid earth reflection by any reasonable change in the station locations. The fading due to such reflection was minimized in this case by employing very low antennas at one end of the section and high mountain-top antennas at the adjacent station. With this arrangement, the earth-reflection point was close to one of the stations thereby minimizing the change in phase relations between the direct and reflected rays during periods of varying transmission conditions.[17]

Selection of Sites for Television Broadcast Stations

Sites for the antennas of television broadcast stations should be so chosen that at least first Fresnel-zone clearance is obtained over all near obstructions in the directions of the areas to be served. Thus hills with gentle slopes or with foothills which prevent such clearance should be avoided. Not only will the field strengths be reduced in the shadows of foothills and along the slope of the hill, owing to the low height of the antenna above the effective plane of reflection, but also nonuniform fields and ghosts may occur in distant areas which are within the line of sight of the transmitting antenna. Similarly, sites in the midst of tall buildings should be avoided unless the antenna can be placed well above them.

If relief maps of the proposed site are available or can be made, small grain-of-wheat lamps placed at the antenna location will assist in locating shadowed areas. Both theory and experience indicate that the radio shadows are of lesser length than the optical shadows.[37]

Profiles, taken from topographic maps, should be drawn for at least eight radials from the antenna site, and for any additional radials which from inspection appear to present particular problems, in the manner shown in Fig. 1-11. Estimates of the areas of service should be made, both by the methods provided by the Rules of the FCC.[40]

In doubtful areas, actual measurements should be made over these radials, either from existing transmitters at or near the chosen site which have frequencies near the chosen frequency or from test transmitters installed for the purpose. If test transmitters are pulsed and mobile measurements are to be made, the pulse repetition rate should be sufficiently rapid so that the peak detector of the field-strength meter can distinguish between the pulse peaks and the peaks caused by standing-wave patterns through which the meter will pass. Otherwise the meter will indicate the peaks of such standing-wave patterns rather than the desired average value which is indicative of the strength of the incident fields.

There is as yet no unanimity among engineers as to the preferred method of making field-strength surveys for television broadcast stations. Because of the relative ease and dispatch with which the area may be covered, some prefer the taking of mobile measurements with a simple nondirectional antenna mounted on the vehicle at about 10 ft above ground. Because of the difficulty of estimating height gain and antenna gain of the typical receiving antenna in a typical location as compared with the simple mobile measuring antenna under the nonideal conditions to be found in all service areas, many engineers prefer to obtain relatively fewer measurements under conditions which they consider to be more nearly typical for broadcast receiving installations. For this purpose a collapsible mast carrying a typical antenna is mounted on a vehicle and measurements are made at various accessible locations along each of the radials. Several techniques have been employed with this type of measuring equipment: (1) maintaining the antenna at a fixed height during a short run,[37] (2) clusters of spot-sampling measurements with the antenna at a fixed height,[38] or (3) moving the antenna vertically at a fixed location.[20] All three techniques have specific advantages and disadvantages. Spot sampling, which is most nearly analogous to the typical receiver situation, also presents the most difficulty in obtaining a significant sampling of the existing fields. All measurements should be made in accordance with the standards of the Institute of Radio Engineers.[41]

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Part 2

DESIGN, ERECTION, AND MAINTENANCE OF ANTENNA STRUCTURES

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INTRODUCTION

This is not intended to be a treatise on tower design. The object of this discussion is to give the average broadcaster, owner, manager, or engineer a practical understanding of tower structures. General problems concerning tall structures are discussed in order to aid the broadcast people who are responsible for buying and maintaining towers. Electrical problems will not be discussed.

TOWER COST

The approximate cost of a tower installation is of prime importance for planning purposes. The accompanying curves show approximate costs of typical installations. These curves are intended to show the scale or range of dollars involved. The cheapest tower structure is the simplest one, such as an AM tower. This tower merely holds itself up, with a set of lights. Obviously, anything you add to the tower such as coaxial lines, signs, and so on, will increase the wind load, which in turn increases the weight and cost. It is impossible to show all the different conditions which arise. For example, only a few of the items which will increase cost are:

Winter erection
Inaccessible sites
Foundations in swamps, rock, sand, tide water, or any water
Heavier wind-design load
Top hats
Special insulators
Electric signs
Large high-gain antennas
Large amount of coaxial
Elevators
Multiple antennas

Towers over 1,000 ft usually involve special engineering for the particular conditions required. Hence, the cost of towers over 1,000 ft is very approximate. People often inquire about the tallest tower which can be built. At the present time, there is no particular engineering reason why towers can not be built up to 3,000 or 4,000 ft with present-day materials and equipment.

Self-supporting Towers vs. Guyed Towers

The obvious advantage of a self-supporting tower is that it requires less ground area at the base of the tower. This often is necessitated because of crowded conditions, such as putting up a tower in the center of a city block, on a roof top, or on a small mountain top. The area required for a typical self-supporting tower will be roughly a square or a triangle somewhere between 7½ and 20 per cent of the over-all height of the structure, depending on the designer. AM towers tend to be a little more slender than the TV towers. The disadvantage of a self-supporting tower is that, as a general rule, it is more expensive. An additional disadvantage of a self-supporting tower is that the designer does not usually investigate whip or inertia forces. These whip forces tend to be larger in a tall, slender self-supporting tower with a heavy weight on top (such as an antenna) than in a guyed tower.

The obvious advantage of a guyed tower is its cheaper (installed) cost. Most guyed towers today are built with a uniform cross section and, in many instances, a constant weight in cross section. This makes for cheaper fabricating and easier and cheaper stacking during erection. A guyed tower is lighter than a self-supporting tower. The guys, in effect, form a very large base. A guyed tower having less steel

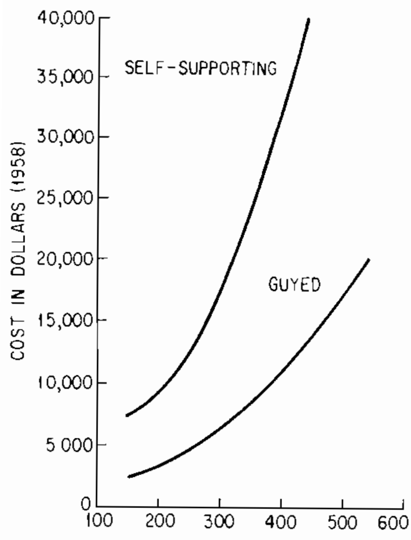


Fig. 2-1. Approximate installed cost of 30-lb insulated AM towers. Cost includes tower, foundations, FAA lights, and erection.

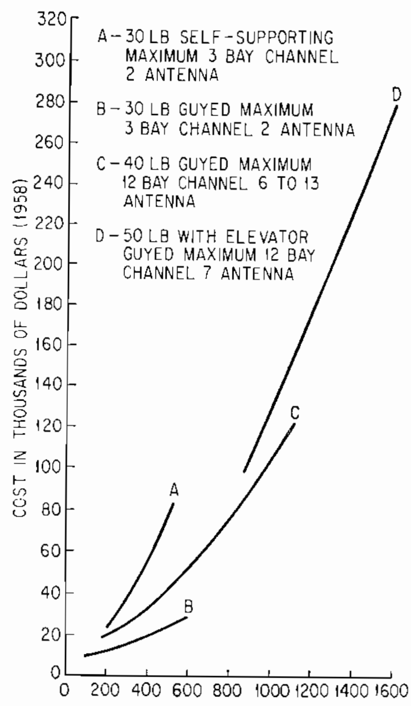


Fig. 2-2. Approximate installed cost of TV towers. Cost includes tower, foundation, erection, FAA lights, erection of coaxial and antenna.

is usually cheaper to paint and to maintain, since it has fewer members and the members are easier to reach on the way up and down the tower.

The area required for a guyed tower varies with the designer. Current practice is to place the guy anchors out from the base pier a distance equal to 50 to 100 per cent of tower height. The tower designer knows that as he pulls in his guy anchor distance, he increases the down load on the tower and so runs up the size of guys and the size of vertical members. This tends to run up the cost of the tower.

It is not always necessary to buy all the land enclosed by the outline connecting the anchors. Many towers have guys crossing a public road. There are many tower installations where it was necessary to buy or long-lease a small plot at each guy anchor and at the base of the tower.

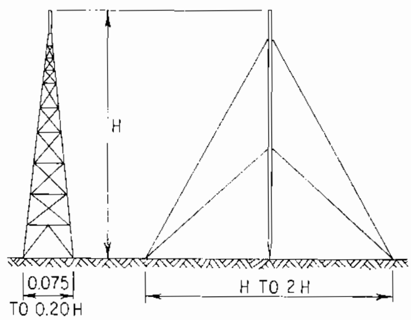


FIG. 2-3. Relative space requirements for self-supporting and guyed towers.

Tower Material

Most towers today are built from steel for the simple reason that steel is more economical than any other material available at the present time. It is possible to build towers from wood, any number of aluminum alloys, and a number of other materials. Wood is usually uneconomical over 80 or 90 ft, and the broadcast range begins at 150 ft. Aluminum alloys tend to give a lighter but a more expensive tower. The broadcaster usually is more interested in the cost than the weight of the tower. There may be a day when the basic cost of some of these aluminum alloys will come down and steel will go up, so that it may be economical to use these aluminum alloys.

Probably the most commonly used steel is structural carbon steel which comes under ASTM A-7 specifications. The yield of this material is 33,000 psi. It has good elongation and very good working and welding properties. Its base price is relatively cheap.

Pipe is used by some manufacturers. Pipe comes under ASTM A-120. This pipe has a yield of 25,000 to 35,000 psi, depending upon the grade. Pipe is fairly easy to work as a rule and is suitable for welding. Its popularity is due to the fact that it has a low base price. The disadvantage is it comes only in certain specific sizes.

Mechanical steel tubing, both welded and seamless is used in various grades and alloys to meet specific requirements. Exacting properties such as tensile strength, ductility, and weldability can be produced. A big advantage of tubing is that both the outside dimensions and the wall thickness can be varied at will by the buyer. The disadvantage of tubing is its relatively high base price.

Some designers of the taller towers like to use one of the so-called low alloys. There are a number of these alloys on the market in a number of forms. The most popular form is the solid round bar, although tubes are available as well. The advantage of these low alloys is an approximate 50,000-psi minimum yield strength. These alloys have good working and welding properties, and they seem to have a somewhat higher corrosion resistance than mild steel. The advantage of these materials is that they save wind load and weight of structure. One of these new alloys is T-1, a 90,000-psi-yield steel. The virtue of this material is its high yield and its low carbon content, making it weldable in the shop with no heat treating after welding being required by the fabricator. The base price of this material is several times that of structural steel, and it has proved economical to date only on tall towers. T-1 does not lend itself to galvanizing.

There have been some towers using high carbon strip rolled into Vs. Towers using this material very seldom have welding connections because of the previously mentioned difficulty encountered in welding.

High yields up to 110,000 psi are obtainable from stainless steel in the 17-7 or 18-8 varieties which have good working and welding properties. Although an excellent material, its high cost prohibits its use in commercial tower construction at the present time. It has been used by the U.S. Navy for masts on seagoing ships.

Commercial machine parts usually get high strength by heat-treating higher carbon steel. The higher carbon steel is more difficult to weld. Also, heat treating large, bulky tower columns is uneconomical. For this reason, high-carbon heat-treated steel is very rarely used in tower work.

SHAPE OF MATERIAL

There is no particular magic in any one structural shape. All shapes have their advantages and their disadvantages. The different tower designers have different shape preferences. Different tower manufacturers have different shape-fabricating facilities. It might be interesting to review some of the more commonly used steel shapes.

Steel Angle

The most easily available shape and the one used in great amounts is the structural steel angle. The advantages of a steel angle are its universal availability, low initial cost, ease in fabricating, ease in shipping, ease of galvanizing, and ease of assembly. Because these structural angles make 90° angles, most towers which use angles are four sided. Three-sided towers using angles are possible. The largest single disadvantage of a structural angle shape is that the angle runs up the wind load and, consequently, the weight of the tower, particularly as the height of the tower increases. Almost all towers were made of angles, at one time, when the heights were low. Today most tall towers make use of cylindrical shapes.

A much-used shape is a steel strip which is rolled into a V or some shape approximating a V. The main advantage of a rolled strip is that it is possible to form an approximate 60° angle. This makes it relatively simple to fabricate a triangular cross-sectional tower. The advantages and disadvantages of formed strips are about the same as those of structural angles.

Cylindrical

A solid round steel bar has become popular, particularly in the taller towers. The advantage of a solid bar is that it has low wind resistance for a given cross-sectional area. Its base price is also relatively inexpensive. The solid bar tower tends to run the tower weight up if the designer is not careful.

The advantage of a tube to a tower designer is that it has a circular shape which keeps the wind load down and it gives the tower designer the most efficient material distribution to carry a column load. Tubular towers are usually more efficient and lighter, have fewer parts, and are cleaner looking than those of other shapes. The greatest disadvantage of a tube is its relatively high initial base price for the material.

To sum up shapes, it must be borne in mind there is no particular magic in any of the shapes used. It always amazes people to see different companies using different designs, different types of facilities, and different shapes and coming out with approximately the same tower cost.

TOWER ASSEMBLY

The three principal methods of putting a tower together in the field are bolting, riveting, and welding. The latter two methods are seldom used. Since bolts are used almost universally in tower erection, a discussion of the various types of bolts and bolting practices is in order.

We may also note at this time the advantage of the prefabricated tower section where most of the assembly work is done in the shop. The expensive erection bolting is then kept to a minimum with a resultant saving in time and cost.

Bolts

The most commonly used bolt is the square-head machine bolt and nut. Hex-head bolts and nuts are available at slight extra cost.

High-strength bolts are becoming more popular with the tower designer. They allow the designer to use a smaller and hence a lighter bolt with the same strength for the same load. The high-strength bolt incurs additional advantages by allowing the designer to cut down the size of the connecting parts. A high-strength bolt, properly tightened, is self-locking and requires no additional locking nut or device. The properly tightened high-strength bolt exerts a high clamping force, thereby creating a stiffer connection. It is desirable that the high-strength bolts be tightened to at least the minimum tension specified by the manufacturer. The following are the most commonly used methods for torquing high-strength bolts.

1. Torque wrench. An indicator which registers torque is a component part of this wrench.
2. Pneumatic impact wrench. Air pressure is controlled so that the wrench stalls at desired torque.
3. Pneumatic impact wrench with internal automatic cutoff which shuts off air supply when proper torque is reached.
4. The nut is turned to an initial tightness. Then the nut is given prescribed amount of visual turn with the wrench.

Ribbed or Dardelet bolts are sometimes used. These bolts have ribs along the body of the bolt. These ribs dig into the bolted material, providing the holes are undersize. If properly used, they make a rigid connection. They are not popular with erectors because of the extra work involved in driving the bolts into undersized holes. Their effectiveness is lost if holes are not undersized. These bolts require locking devices.

It is mandatory that all bolts and nuts be drawn tight. All nuts (except on high-strength bolts) should be locked in some manner to prevent them from working loose. This can be accomplished in many ways. A simple way is to stake the nuts by upsetting the thread on the bolt after bolt is on. A great variety of patented lock nuts, washers, and devices are available. They all seem to be fairly effective providing they are put on and put on tightly.

Number of Faces on a Tower

The number of faces a tower has is usually dictated by the economy of fabrication and erection. The simplest tower is one which has a circular cross section, which, in effect, has no face at all. Wooden poles would make such a tower, and tall radio towers have been designed out of large-diameter steel or aluminum tubes. An extreme case of the number of faces on a tower would be a tower made up of eight, ten, or even twelve faces. There is no reason why good towers with that number of faces could not be built, and they sometimes are. It should be pointed out that a poorly designed tower is a poorly designed tower and a well-designed tower is a well-designed tower irrespective of the number of faces the tower has. At the present time, most towers are built using either a triangular or a rectangular cross section.

Preassembly by Welding

Some towers are preassembled by welding in the shop. These prefabricated sections may be anywhere from 5 to 30 ft in length. The length of the section preassembled in the shop is dictated usually by handling, shipping, and erection facilities. The advantage of prefabrication is that it takes some work from the erector in the field and puts it into a better equipped and organized shop. These preassembled sections may be made from material of any shape. The welding gives a stiffer, lighter, and cleaner subassembly as a general rule.

Erectors like prefabricated sections because they save money by merely stacking sections, having fewer bolts to contend with, and fewer joints to check. The biggest disadvantage of the prefabricated tower is its bulk and resultant increased freight cost. For this reason, prefabricated sections are used in shorter towers. For example, shipping a 1,000-ft tower in sections 1,000 miles would incur a total freight bill far in exeess of the savings in erection. It is not correct to state that a prefabricated or preassembled tower is better than a knocked-down one, or vice versa. Total cost is the measure.

TOWER CONFIGURATION

The Uniform-cross-section Radiator

Most people are under the erroneous impression that the uniform cross section in radio towers was dictated by the radiation properties of an AM tower. It is true that the radiator of uniform cross section from top to bottom has radiating properties which an electrical engineer says are easier to predict. But note that self-supporting towers are tapered, although it is possible to build them with a uniform cross section. The electrical engineer simply has to contend with the radiating properties of a tapered structure.

Tapered guyed towers and nontapered self-supporting towers are built but not as a general rule. Most guyed towers are built with constant cross section and most self-supporting towers are tapered because of one simple reason—it is cheaper to build them that way.

Straight Base vs. Pivot on a Guyed Tower

A guyed tower may be designed to come straight down at the base pier or to a pivot. Either method is satisfactory providing the conditions encountered are properly engineered. The advantage of a pivot base is that the pivot relieves a large bending moment at the pivot. In Fig. 2-4 this is graphically illustrated by comparing the moment curves of the two types of towers. The pivot saves steel and takes bending off the base insulator, if there is an insulator. The load on a pier is pure down load and the pier is a bit easier to design. The advantage of a straight fixed base is ease in fabrication. The erector can start erecting without using temporary guys. However, the bending moment tends to increase weight, the size of insulators (if any), and the size of the base pier. Also, the pier top must be perfectly level to distribute the load evenly from each tower leg.

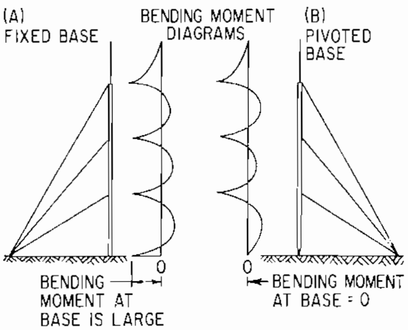


FIG. 2-4. Effect of a fixed base on a guyed tower.

Tower Weight

The weight of a tower is quite important. The weight comes into the calculations of the strength of the tower in a very simple manner. The heavier the tower, the greater is the total down load; consequently, more steel is needed and the sizes of the base insulator and base pier go up. In the 200-ft AM guyed tower range, the weight is relatively a small percentage of the total design load, usually somewhere between 10 and 20 per cent. This percentage increases with the height of the tower. In the 1,000-ft tower range, the weight becomes an appreciable item. Skillful designers of steel towers recognize this fact and make some effort to keep down the dead weight. It is possible to have two towers equally strong and yet with entirely different weights. For example, as a general rule a four-sided tower made up of structural angles will weigh more than a triangular tower using round members and yet the design strength will be about the same in either case. The statement that tower *A* is stronger than tower *B* because it is

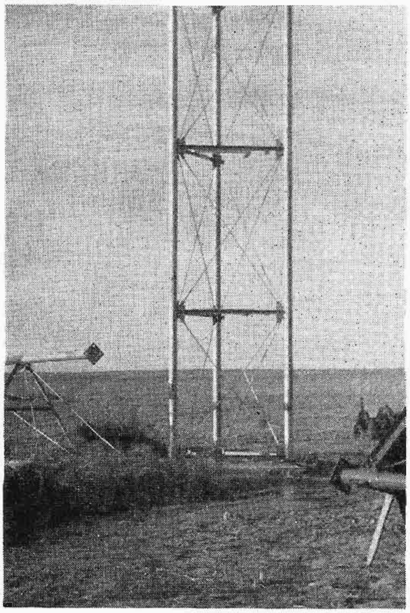


FIG. 2-5. Photograph showing fixed-base tower.

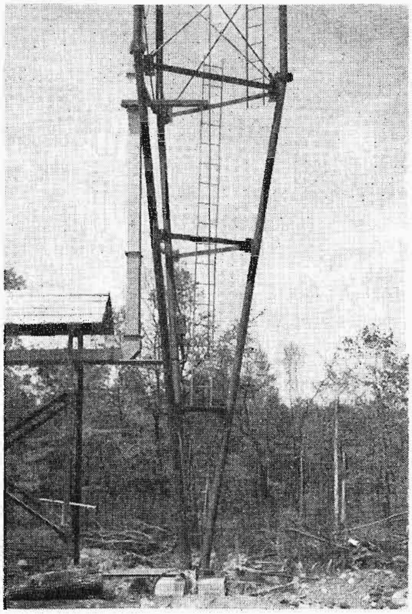


FIG. 2-6. Photograph showing tapered-base-type tower.

heavier or vice versa is simply not true if both towers are designed to the same specifications.

A heavier tower will generally tend to have larger inertia or whip forces than a lighter tower. Usually these forces are not serious, but they may well be. For example, in a tall, self-supporting tower with a slender ratio and with a heavy antenna on top, whip forces are appreciable.

There is one practical minimum limit to the weight of a tower. The size of the members should not be so small that they are susceptible to damage in transit, during erection, or during maintenance climbing operations later on. Tower members should be rugged enough so that they can be handled as structures and not as fragile china. The average erector with heavy boots should be able to climb the tower without rolling over edges, bending thin members, or kinking small rods. Most towers used in the broadcast range today have members which are sturdy enough for ordinary usage.

Rigid-frame Trusses

Towers are designed as trusses, either the conventional type X or diagonal bracing or the rigid-frame type. The joints of a rigid-frame type of truss are moment-resisting and are usually welded. Conventional-type trusses are usually bolted at joints, and the joints are considered to be hinged. In rigid-frame trusses, the members have bending stresses as well as axial stresses. Standard methods of analysis can be used for determining the stresses. Rigid-frame trusses tend to be very clean aerodynamically and offer a minimum re-

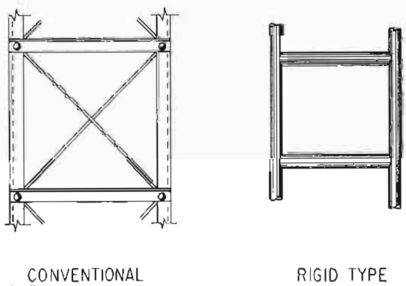


FIG. 2-7. Conventional X-type and rigid-frame bracing.

sistance to wind. They have also proved themselves quite economical for towers, particularly in the short heights.

TOWER ATTACHMENTS

Antenna

The prime purpose of a TV tower is to support the TV antenna and its feed system. The attachment of the antenna to the tower is a problem, especially when the antenna is large.

Antennas have been mounted on towers in three different methods. One method is to side-mount the antenna onto the tower. In general, when this method is used, the radiating elements are clamped onto the vertical tower members. This method of mounting the antenna has the advantage that the loads caused by the antenna are kept to a minimum and also the antenna loads can be distributed over the tower easily.

A second method of mounting an antenna on a tower is with the telescoping-pole type of mount. The pole telescopes down the center of the tower, the distance depending upon the size of the antenna. At the top of the tower, the pole has some sort of adjustable guide so that it can be plumbed. The bottom of the pole fits into the pole socket. Usually the pole socket is a fixed position and is not adjustable.

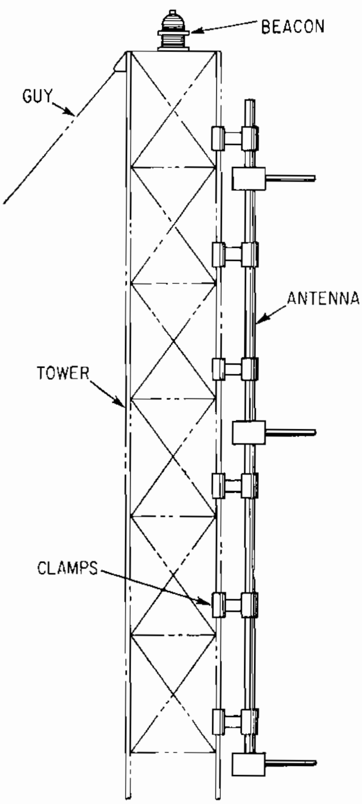


FIG. 2-8. Side antenna attachment.

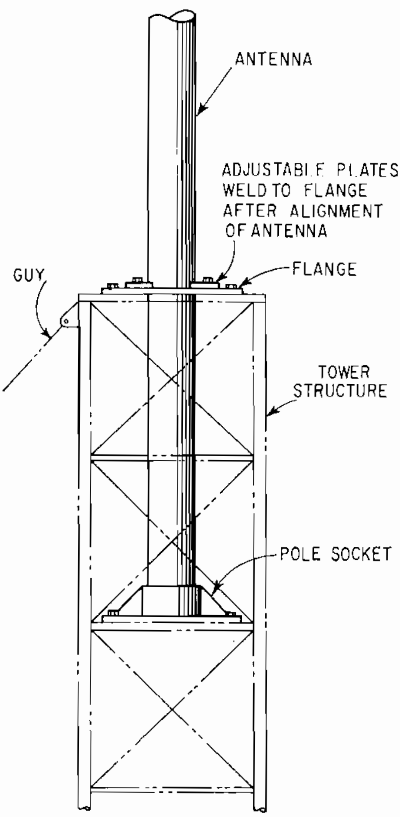


FIG. 2-9. Telescopic antenna mast attachment.

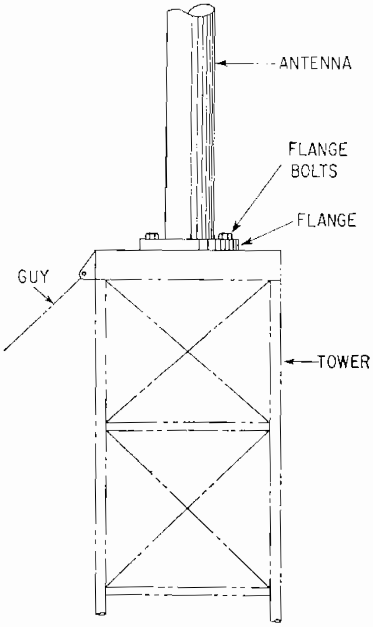


FIG. 2-10. Flange antenna attachment.

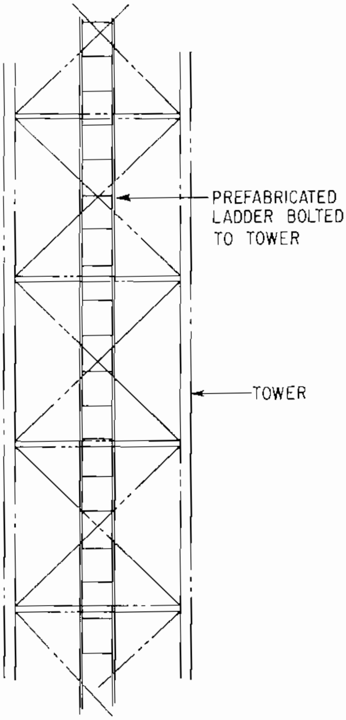


FIG. 2-11. Ladder mounted on tower face.

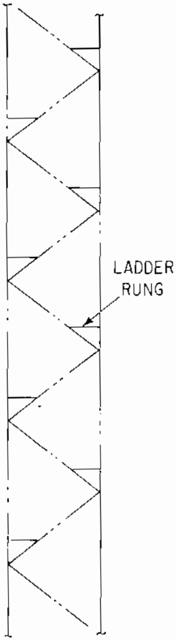


FIG. 2-12. Ladder steps welded to tower structure.

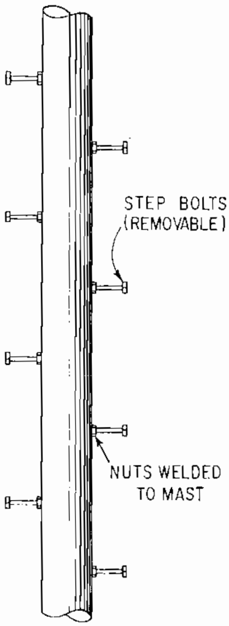


FIG. 2-13. Step bolts on cylindrical mount.

The third common type of antenna mount is the flange mount. A flange-type antenna mount suddenly dumps a large overturning moment into the tower. If the moment is large relative to the capacity of the tower as with some TV antennas, the problem can become quite nasty structurally.

Usually it is necessary to install the antenna in a vertical position. The top of the tower or the leveling plates as furnished by some manufacturers should be checked to make sure they are level before actual installation of the antenna.

Climbing Facilities

A tower must have some climbing facilities in order to maintain it and its equipment. Sometimes short towers have the tower members themselves arranged in such a manner that they act as step bars. Various climbing facilities are illustrated in Figs. 2-11, 2-12, and 2-13. When towers are short, step bolts similar to the ones seen on telephone poles are occasionally used. As the tower height increases, these step bolts do not give a feeling of security to the person climbing. As a general rule, ladders are provided on tall towers. Erectors themselves usually prefer a ladder on the face of the tower, since the erector likes to climb on the outside of the tower where he has fewer encumbrances. Most engineers and station people, however, who climb the tower occasionally to check antennas or lights feel safer if the ladder is within the confines of the tower cross section so that the outside of the tower forms, in effect, a natural safety cage. A safety cage is sometimes provided so that it is practically impossible to fall out. Usually, safety cages are not called for, since they add wind load to the tower and, consequently, increase the cost.

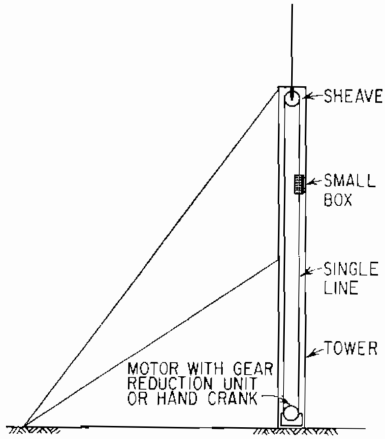


FIG. 2-14. Dumb-waiter type of lift.

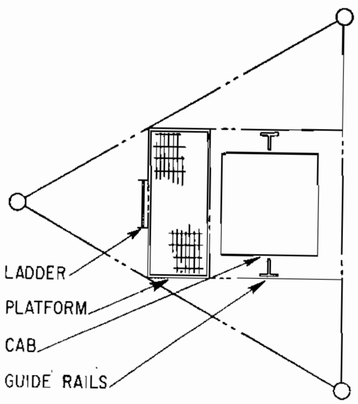


FIG. 2-15. Typical section through elevator.

On taller towers, some form of hoist or elevator is occasionally used. The simplest arrangement, shown in Fig. 2-14 is, in effect, a form of dumb waiter.

Tower Elevators

It may take a man ¾ hr to climb the full length of a 1,000-ft tower. If there is any equipment to be lugged up, this adds quite a burden to the climber. For this reason, it is often desirable to install an elevator in towers over 1,000 ft.

The elevator adds to the wind and dead loads, and so, the tower has to be designed originally to carry the elevator. A well-designed elevator embodies the elements noted in Fig. 2-16. There are many variations of the details required.

An elevator suitable for use in a tower consists of a driving mechanism, car, guide rails, hoisting cables, counterweights, integral and auxiliary cab controls, and two-way communication system. The guide rails should be machined to provide a smooth, steady ride. The T shape is commonly used, but rounds are used to cut wind loads. The driving mechanism should be a traction type with a high starting torque and low starting current. Rope guards are necessary to prevent entanglement of the hoisting rope in the tower structure during severe wind storms.

Different people prefer cages of different sizes. The tower designer leans toward a small cage; the owner would rather have a large cage. Elevators have a relatively slow rate of climb, simply because it keeps the power requirements and the cost down. The commonly used rate of ascent for elevators today is 100 fpm. Elevators are available with electronic controls and two-way communication systems in cab and tower base so that the operator is able to stop the cage at any height.

Considerable attention is given to safety devices in the design of a tower elevator. For example, in case of hoisting-cable failure, spring-loaded cams automatically are brought into play to freeze the car against the guide rails. Limit switches stop the car motion past either the upper or lower landing platforms should the operator fail to do so. The brakes on the driving mechanism are spring applied, electrically released, and designed to be automatically applied in the event of interruption of power from any cause. A tension device is supplied, limited by moistureproof switches which will cut off power in the event of cable stretch or excessive cable motion. Finally an access ladder is supplied for the full height of the tower to be used as an emergency descent.

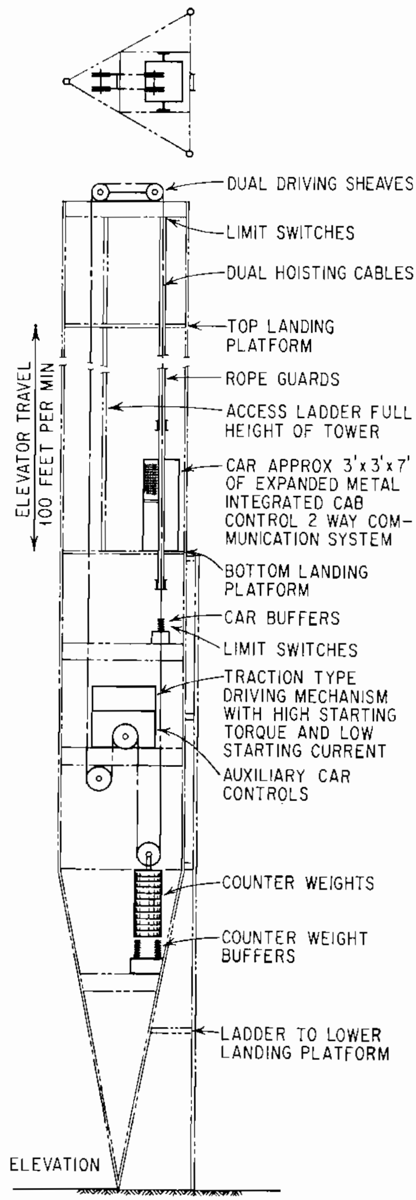


FIG. 2-16. Typical elevator installation.

TOWER PROTECTION

Galvanizing

Galvanizing is the process of coating metals, usually steel and iron, with zinc. One of the peculiarities of the zinc trade is that this coat is expressed in ounces of zinc for a square foot of surface. Most galvanizing is done via the "hot-dip" method. That is, steel is dunked into a zinc bath and then pulled out. The excess zinc drips off, and a certain thickness of zinc stays on the steel. If a thick coat is desired, the steel is dunked a second or even a third time. This is termed a double or triple hot dip. How does this zinc help? Zinc is higher than steel in the electrochemical series. It means that the zinc tends to be eaten away over an area before the steel does, even if the zinc surface is scratched to expose bare steel. Corrosion of steel is delayed until the adjacent blob of zinc is depleted.

Obviously, the life of the coat depends on the thickness or weight of the zinc coating and the atmosphere. For years, the American Society of Testing Materials has been testing miscellaneous weights of zinc on steel structures in different parts of the country. There are available estimated life curves of zinc coats in various atmospheres, expressed in years vs. the coat thickness, in such locations as Pittsburgh, Pa.; Sandy Hook, N.J.; and Ames, Iowa.

Almost all guy strand and wire rope are zinc-coated for the simple reason that the individual wires making up the guy are small and usually run in diameter from 1⁄16 to 3⁄16 in., so that corrosion is a critical factor.

Since the zinc coat will impose an additional cost, should one galvanize? This will depend upon conditions. First of all, it is impossible for steel to corrode if the paint is properly kept up. However, there may be installations in certain highly corrosive atmospheres where maintaining the paint will present quite a problem. Those installations are not too frequent. If the broadcaster properly maintains his paint, then this should be adequate. On small, unattended towers where inspection may not be too regular, there is some merit in galvanizing. It is also possible in large, unusual towers where a special dispensation has been obtained to paint only a portion of the tower that it may be worth galvanizing only those portions of the tower which are never painted.

Tubular members, if galvanized, should be galvanized both inside and outside or else the drain holes should be plugged up. Care should be taken to seal the ends of tubes on tubular structures if they are not galvanized. Moisture or oxygen cannot get inside a properly sealed tubular member, and therefore there is no possibility of corrosion on the inside surface.

Painting

FCC Requirements

The Federal Communications Commission has prescribed a set of standards to provide an effective means of indicating the presence of obstructions to air commerce. Radio and TV towers, because of their height, are considered as possible obstructions to air navigation by the Federal Communications Commission and, therefore, must be marked and lighted accordingly.[1]

To comply with these regulations, the towers are painted in contrasting colors of white and international orange in alternate bands for maximum visibility during daylight hours. The exact spacing of these bands is spelled out on the face of the construction permit. The FCC also requires that towers be painted as often as necessary to maintain good visibility. Obviously the painting becomes quite a maintenance problem, and if it were not for this paint regulation, probably the cheapest finish would be a coat of zinc.

Surface Treatment

Paint will not stick to brand-new galvanized surfaces. The erector should treat the surfaces of the galvanized parts. Some fabricators give galvanized parts a special treatment prior to shipment so that the surface is prepared for painting. Any number of solutions have been made to etch this smooth zinc coat. The simplest and most commonly used treatment is plain vinegar or a weak acetic acid solution which is applied to the surfaces in the field prior to painting. A better solution is as follows:

2 oz copper chloride
2 oz copper nitrate
2 oz sal ammoniac

[1] Federal Communications Commissions Rules and Regulations, Part 17.

2 oz muriatic acid
1 gal water

Apply with rag or brush to the tower, and allow to dry for 10 hours before applying paint. Galvanizing will fist turn black and then a dull gray. Such a treated galvanized surface requires no primer. Another way to treat galvanized sections is to let them weather a period of three months to a year depending on whether the tower is located in a dry or a salty and moist atmosphere.

Application

Paint usually consists of two coats. The outside coat is a hard enamel, either orange or white and sometimes black. The enamel has wearing qualities and is relatively tough. However, enamel does not stick very well to plain steel. For this reason, towers usually have a primer coat. The purpose of the primer coat is to effect a bond between the steel and enamel.

Primer will not stick to a surface which has scaled rust, mud, dirt, oil, or grease. For that reason, the surface has to be fairly clean. If the rust is scaly, it should be wire-brushed off. If the surface is dirty or oily, it should be wiped with a thinner, alcohol, gasoline, or any number of cleaners or detergents. There are many good primers—red lead, iron oxide, zinc cromate, and combinations thereof. The primer should be on the thin side, since a thick primer has a tendency to peel. The primer has no staying qualities; that is, it will not weather very long.

Tests show that international orange and white enamels from most reliable companies are good. The life of the orange and white paint depends upon the location. In the dry desert parts of the United States towers do not require repainting for 10-year stretches. Towers along the seacoast, which are constantly subjected to salt spray and sunshine, require a new coat of paint approximately once a year. There is no fixed rule in the length of the life of the outside coat.

Broadcasters should be cautioned about getting unusually cheap prices for painting or repainting a tower from unknown erectors who happen to be passing through town. These "fast prices" sometimes leave one with a tower where only the bottom 100 ft are painted beautifully and the rest of the tower is painted on the bottom surfaces only.

On paint maintenance contracts, broadcasters should make sure that the painter has public liability and property damage insurance coverage, since it is very difficult to keep the paint from flying, even in a very small wind. This is a very definite hazard, since neighboring buildings and cars are constantly being covered by flying paint.

TOWER GUYS

Steel Guy Material

Rope and Strand

Tower guys are usually made out of steel rope or steel strand. Both rope and strand are made up of high-strength steel wires. A number of wires spun as a single group is called a strand. A number of strands spun to form a group is called a rope.

The advantage of steel rope is that it is flexible. That is, it is capable of being run over sheaves or pulleys continuously. The disadvantage of rope is that it has a low modulus of elasticity (it is more stretchable than strand) and, as a general rule, it is more expensive than strand. Strand as a rule is preferred in towers because it has a high modulus of elasticity, does not stretch so much as wire rope, and is cheaper per foot for a given strength.

Catalogue value for strand modulus of elasticity is 24 million. This 24 million is a minimum figure. The 24-million figure is fairly consistent and constant. Coiling and uncoiling strand decrease this figure less than 1 per cent, but it comes back to the 24 million.

It is the considered opinion of most engineers that there is no such thing as a yield point for strand. The curve falls off gently to a breaking strength. The catalogue values of the ultimate strength or breaking strength of strands are always minimum. The range of breaking strength is usually 2 to 10 per cent above catalogue values.

Strand is made from high-carbon cold-worked wire. It is very rugged and very insensitive to notch defect. It will take quite a beating. A good approximation of estimating the percentage of reduction in strength of strand is to note how much wire is cut. For example, if you have 19 wires in a strand and one wire is nicked halfway through, then that strand is subject to a reduction in breaking strength of approximately 1/38 of the catalogue value.

As a rough rule of thumb, it takes 2 per cent of the breaking strength of a 19-wire strand to stretch that strand or cable out to its true length. A 1 by 7 strand will require approximately 5 per cent of breaking strength.

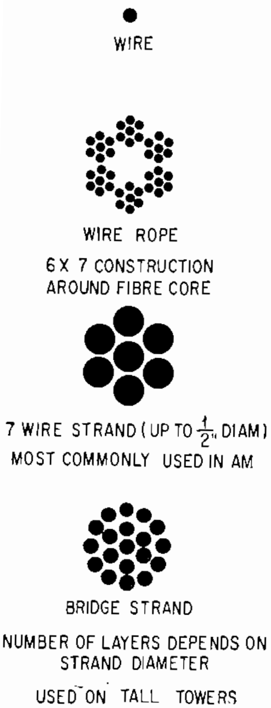


Fig. 2-17. Composition of typical guy material.

Prestressing

When a prestressed cable is wound up on a reel and then unwound in the field, there is a negligible amount of length lost. This has been proved many times by checking on long cables for 1,000-ft towers and on suspension-bridge cables.

Prestressing the guys at a strand manufacturer's plant takes out some of the structural stretch. Most wire manufacturers will pull the guy to 50 per cent of ultimate and hold for approximately ½ hr. Prestressing will stretch the strand somewhere from 1/10 to ¼ of 1 per cent of the length.

Bird Caging

Bird caging can occur in both manufacturing and in handling in the field. Bird caging prior to shipping is rare. Bird caging in the field is caused by a kink in the strand, unreeling improperly, allowing a large reel to get away, getting a loop in the strand, dropping a guy, or anything that puts wires in compression. Since most strands (19 wires and over) have lays going both ways, there is no method of really fixing a true bird cage. There is no tendency for wires to unravel and bird-cage by themselves. That is, all strands are basically very stable.

Fatigue

We have never heard of a fatigue failure of wire where it enters a socket on a guyed tower. However, such failures have occurred in sockets which come out on highly loaded shovels where there is continuous large vibration on strands which are constantly highly loaded in tension.

This question arises every now and then when the tower guy has been stretched in a wind storm and you take up the slack: Is the guy breaking strength reduced? The answer is No. For example, strand in preloaded concrete slabs have initial tensions up to 70 per cent of the breaking strength, and the working tension of the strand is 50 per cent of the breaking strength. Notice that you can take strand and load it to 70, 80, or 90 per cent of the breaking strength; unload the strand; and still get 100 per cent breaking strength.

Zinc Coat

The usefulness of a zinc coat on a guy comes from the fact that the zinc coat wastes away instead of the load-carrying steel. The zinc does not protect the strand wire indefinitely. The fact that zinc wastes away rather than steel is good. It should be pointed out that the smaller the wire diameter, the thinner is the zinc coat. Using a galvanized socket instead of a black one on the end of a guy will not appreciably increase the life of the guy. It is also for this reason that when you have a corroded clip, the best thing to do is to leave it alone. Corrosion usually starts at the threads where the zinc is stripped, and there is usually enough "meat" in the rest of the clip and in the guys to take care of itself.

AM Guys

Guys on AM towers have to be made nonradiating. The currently accepted method is to break the guys up with insulators into lengths approximately one-seventh of the wavelength on the radiator. Obviously, this breaking up of the guys is a necessary nuisance. People constantly are looking for guy materials which would be nonradiating. To date, such materials as nylon and dacron have too much stretch to be of any practical value. However, in the foreseeable future, it is possible that some such material may be usable. A new polyester film material Mylar bears watching. At the moment it is expensive, but it does not have the great stretch which nylon has.

Guying Arrangement

A three-way guying arrangement where the guys are laid out 120° apart in plan form shown on accompanying sketch *A* of Fig. 2-18 gives the simplest possible guying arrangement which will support a tower in a wind from any direction. This gives the smallest number of guys and usually tends to give you cheaper foundations and a smaller number of insulators.

A much-used guying arrangement is shown on sketch *B* of Fig. 2-18. A four-sided tower has four sets of guys spaced 90° apart in platform.

A guying arrangement such as shown in plan form *C* (Fig. 2-18) has been used in tall towers. The disadvantage is the need for more anchors. The advantage is that it tends to save in the column load on the tower and some weight.

A guying arrangement as shown on plan form *D* (Fig. 2-18) shows double guys coming off each face. The advantage of this system is that it gives the tower some torsional resistance until the tower has twisted. The disadvantage of plan form *D* is extra handling by the erector. Most erectors prefer single rather than double guys.

Guy Connections

Clips

The most commonly used guy connections at the insulators are steel clips. These clips are relatively cheap, and they are easily available. They are used by the millions. The efficiency of the clip depends upon drawing the clip up tight. In Fig. 2-22 showing a properly drawn up clip, you will notice that the yoke must make a definite dent on the surface of the strand. It is also a known fact that after you put load on a guy, you can pull the clip up a little more. Since this is very difficult to do in a guy with many insulators in it (which are made in the field), clip efficiency should not be rated over 80 per cent. It is possible to get clip efficiencies in a laboratory over 95 per cent. The greatest danger in a clip is that the erector may forget to draw up all clips securely. The best visual inspection that we know of is to check whether the yoke of U part of the clip puts a definite dent in the guy. These clips come in many shapes and forms such as shown. All clips rust sooner or later. When a clip is drawn up, some of the zinc strips off the threads and you have

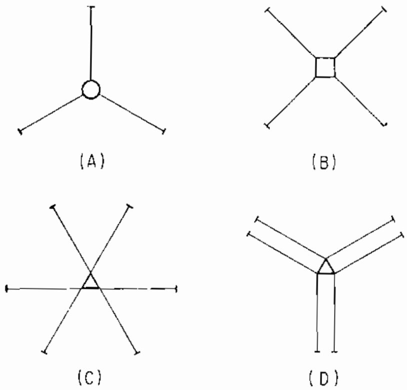


Fig. 2-18. Commonly used guying arrangements.

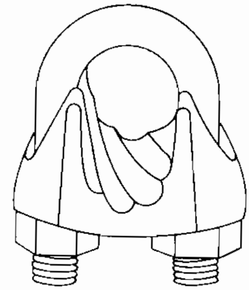


Fig. 2-19. Wire-rope clip.

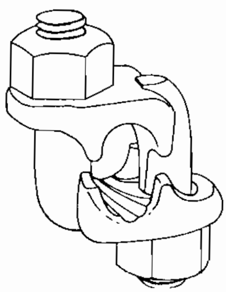


Fig. 2-20. Laughlin safety clip.

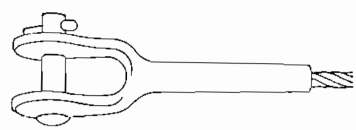
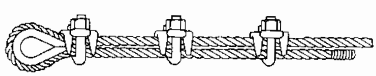


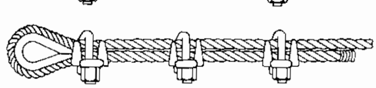
Fig. 2-21. Swage fitting.

THE RIGHT WAY TO CLIP WIRE ROPE



NOTE THAT THE BASE OF THE CLIP BEARS AGAINST THE LIVE END OF THE WIRE ROPE, WHILE THE "U" OF THE BOLT PRESSES AGAINST THE DEAD END.

THE WRONG WAY TO CLIP WIRE ROPE



THE "U" OF THE CLIPS SHOULD NOT BEAR AGAINST THE LIVE END OF THE WIRE ROPE, BECAUSE OF THE POSSIBILITY OF THE ROPE BEING CUT OR KINKED.

FIVE OF THE SIX CLIPS SHOWN ON THE TWO ILLUSTRATIONS ABOVE ARE INCORRECTLY INSTALLED. DO NOT USE EITHER OF THE METHODS SHOWN.

Fig. 2-22. Proper method of applying rope clips.

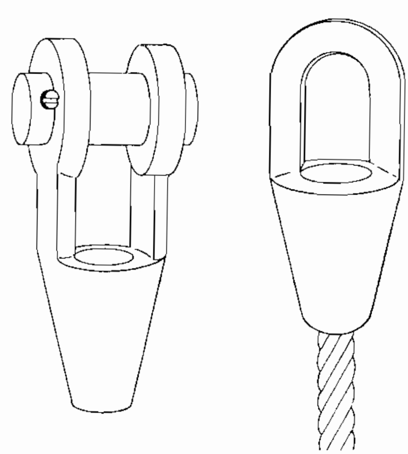


Fig. 2-23. Wire-rope sockets.

a focal point of corrosion. Most clips are sturdy and have enough "meat" in them to last for many years. This corrosion depends on the atmosphere in which the tower is sitting. Some erectors have lately been spraying their clips with clear plastic lacquers which come in pressurized cans.

Serving

A neat and clean-looking connection which is very simple to apply has been developed by the power companies in their work. It is the so-called "serving." The several wires are unraveled, then each individual wire is rolled back on the strand. The efficiency of this method is usually in the high 90 per cents. It makes a clean connection. It is a safer connection than a clip connection, since you do not run the risk of forgetting to run up the clips tightly. It also does away with the problem of corrosion of the clips.

Sleeves and Sockets

There are several makes of sleeves which are press fittings. This again was developed by power companies. They are good-looking and neat on smaller sized guys.

Large guys usually make use of zinc sockets. On most towers today, the sockets are supplied on the strand by the guy fabricator, since their application takes a certain amount of skill and technique. These sockets are usually made of cast or forged steel.

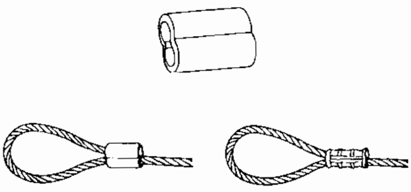


FIG. 2-24. Nicopress sleeve-type fitting.

Guy Tension

The proper initial tension in guys is an integral part of tower design and should be determined by the tower manufacturer. Proper guy tension is necessary in order to control the deflection of the tower so that certain specified limits are not exceeded and in order that deflection of the tower does not weaken it.

Common values of initial tension in guys vary between 5 and 25 per cent of the breaking strength of the guy, depending on the design and requirements. In general, a low initial tension tends to give a more flexible and lighter tower. A high initial tension tends to give a stiffer and heavier tower. Initial guy tension in a properly designed tower seems to have little effect on the ultimate strength of the tower.

During erection and in maintenance, there is danger of putting too much tension in guys. This overloads the tower as a column and literally pulls the tower down to failure.

Initial tension is seldom specified on small AM and communication towers up to heights of 200 or 300 ft. In these cases where the exact initial tension in guys is not critical from the deflection point of view but is critical in that overload can cause tower failure, tower manufacturers should specify an initial tension and the erector or the maintenance men should check the guy tension by some convenient method such as with a dynamometer.

It is common practice on taller towers with a pivot base that guy tensions are adjusted either so that the tower deflects as a straight line from its base to its top when loaded with the design load or so that the differential deflection at guy points is taken into account in calculating the stresses in the tower members. On these large towers, the erection drawings always specify guy tension and some method of checking it. A number of methods commonly used to measure initial tension in the field are described.

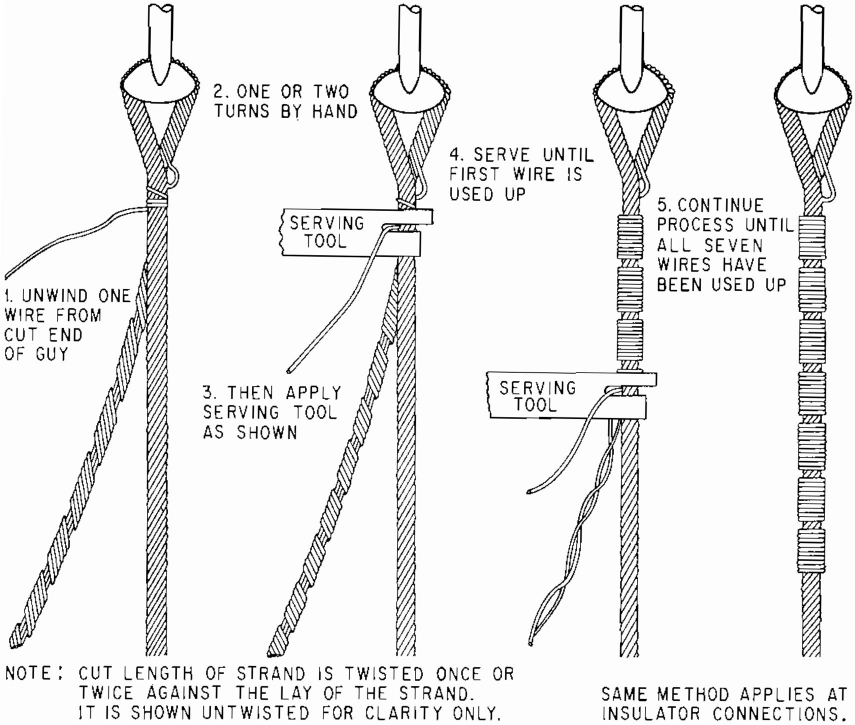


FIG. 2-25. Serving guy connections.

Methods for Determining Guy Tension

Calibrated-rule Method. In the calibrated-rule method, two buttons are attached approximately 8 ft apart to the lower end of the guys. During fabrication of the guys, the required initial tension is applied to the guy. While this load is on the guy, a rule is marked exactly the same as the buttons. In erection, the guy is tightened up until the marks on the buttons line up with the marks on the rule.

Although various stable metals are used to fabricate the rule, this system is subject to errors from several sources. The most likely source of error is the fact that the gauge length (approximately 8 ft) is relatively small and therefore the change in length of the guy in the 8-ft length will be very small. The eye cannot see much closer than 0.01 in., and an error of this magnitude would result in a 10 to 20 per cent error in the initial guy tension. It is doubtful that the erector in the field would take the trouble to read these calibrations with any great precision.

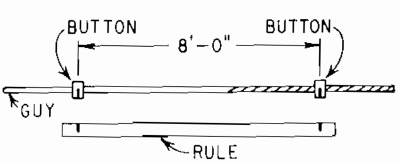


FIG. 2-26. Calibrated-rule method.

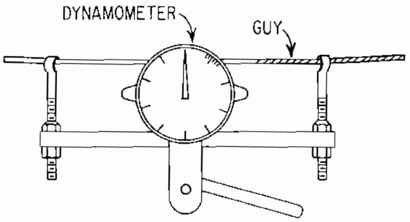


FIG. 2-27. Shunt-type dynamometer.

Temperature is another factor that must be compensated for, particularly when the linear coefficient of expansion of the guy differs from the rule.

Shunt-type Dynamometer. This type of dynamometer or tensiometer is used in determining and maintaining the proper sag or tension in guys. It can be used without breaking-in on the guy to be tested and can be left on the guy until the dial shows the desired reading.

The principle of the shunt dynamometer is based on the relation of the tension in the strand to the force necessary to displace it in a direction perpendicular to the axis of tension.

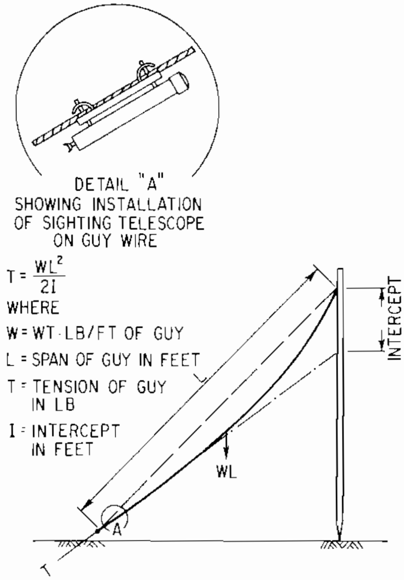


FIG. 2-28. Use of "sight bar" for determining guy tensions.

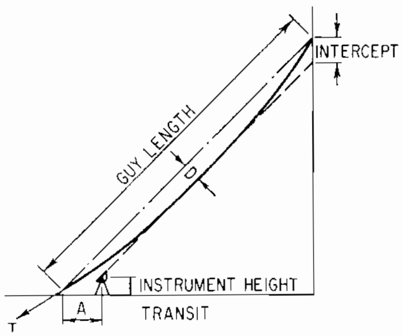


FIG. 2-29. Transit-intercept method for tensioning guys.

The dial is graduated from 0 to 100 units and does not read directly in pounds. Tension is determined from graphs specially prepared for each size and type of wire or cable on which the dial reading is plotted against tension in pounds. The manufacturer guarantees the accuracy to within plus or minus 2 per cent of the dial reading.

On relatively short towers with small guys, use of a mechanical tensiometer is probably the most practical method to measure guy tensions. On tall towers with large guys, the sag of the guys becomes appreciable and can be used as a measure of guy tension. The guy-sag method is a relatively simple and very practical way to check the guy tension.

Guy sag can be checked with a transit or with a sight bar. We shall briefly describe the sight-bar method. A straight bar made of steel or wood with two hooks is used to make the line of sight parallel to the guy. If the unaided eye cannot see clearly to set the intercept, a telescope can be used as shown in Fig. 2-28. It is important in making up this sight bar that the line of sight of the bar be parallel to the guy at its point of attachment. This method is quite accurate in setting initial tension when the guys and intercepts are large. For example, a 100-ft intercept read with 2 ft has an approximate error of 2 per cent. Tension is given by the following formula:

$$T = \frac{WL^2}{2I}$$

The values of the weight of the guy per foot, the span of the guy, and the recommended tension of the guy should be readily available from the tower manufacturer.

Example: 1,000-ft tower with 1-in. guy strand

$$L = 1{,}220 \text{ ft}$$
$$W = 2.14 \text{ lb/ft}$$
$$I = 160 \text{ ft}$$
$$T = \frac{(2.14)(1{,}220)^2}{(2)(160)} = 9{,}950 \text{ lb}$$

Transit-intercept Method for Tensioning Guys. With guy length and desired tension T known, the sag D is calculated from standard formulas. Again with known instrument height a sight line is established tangent to the guy and ground distance A and tower intercept determined. At erection a transit is set up using these intercepts to establish the line of sight. The guy is then tightened until it becomes tangent to the line of sight.

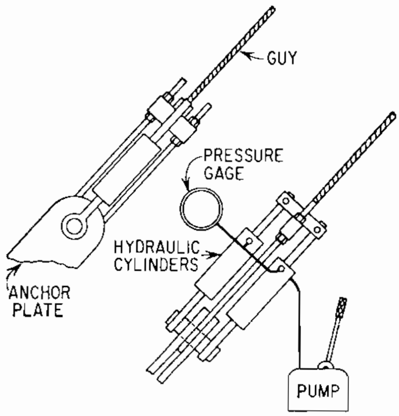


Fig. 2-30. Hydraulic-cylinder method for measuring guy tensions.

Hydraulic-cylinder Method for Measuring Guy Tensions. The guy is put under the required tension with two push-pull hydraulic cylinders which are usually pumped up by hand. The required tension is read on the pressure gauge. The nuts are pulled up on the U bolt or turnbuckles to hold this tension in the guys. Hydraulic units are then removed. It is recommended that the hydraulic cylinders and gauge be checked accurately prior to use, since there is a tendency for errors to creep into the gauge.

Spring Method of Tensioning Guys. A spring with known deflection characteristics is selected and installed in the guy anchor connection. The guy is tightened until the spring has deflected the desired amount, thereby obtaining the required tension in the guy. A combination tubular spring cover and spacer of predetermined length is normally used to obtain the correct deflection. Caution: Do not continue to tighten the guy after the spacer has bottomed; otherwise, excessive tension will be applied to the guy.

Vibration Method of Measuring Guy Tensions. The guy is set properly vibrating by pulling the guy back and forth sideways with the hands. Vibrations are timed with a stop watch. This reading is then substituted in the following formula and the initial tension is calculated.

$$\text{Cycles/min} = \frac{170T}{L \times (\text{wt/ft of guy})}$$

where L = length of guy, ft
T = guy tension, lb

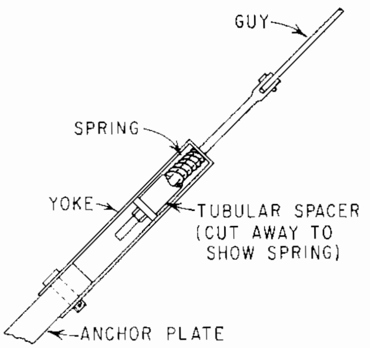


FIG. 2-31. Spring method of tensioning guys.

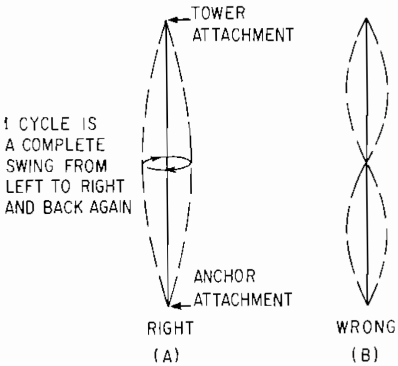


FIG. 2-32. Vibration method of measuring guy tensions.

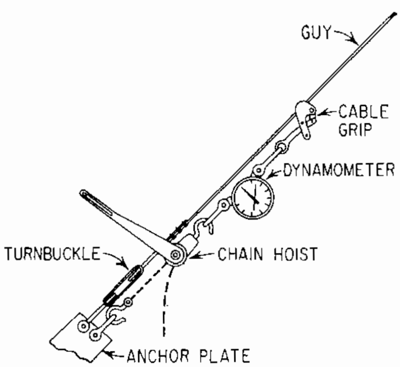


FIG. 2-33. Dynamometer method.

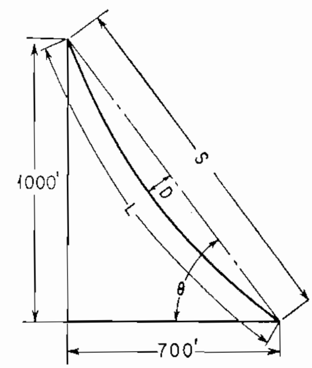


FIG. 2-34. Method of calculating guy lengths.

The vibration method applies to guys of uniform weight and is not applicable to guys with insulators or other concentrated weights. It must be pointed out that this system is only as accurate as the measurement of the frequency of the guys.

Dynamometer Method. As shown in Fig. 2-33, a tension-type dynamometer is mounted between a cable grip and usually a chain hoist. A load is applied to the dynamometer, and when the desired reading is reached, the guy turnbuckle is tightened accordingly. The dynamometer equipment is then removed.

$$S = \sqrt{1{,}000^2 + 700^2} = 1{,}220.6555 \text{ ft}$$

Given: $W = 2.073$ lb/ft—1-in.-diam guy
$T = 10{,}000$ lb—initial tension

Sag in guy wire with 10,000-lb tension

$$D = \frac{WS^2 \cos\theta}{8T}$$
$$= \frac{2.073 \times (1{,}220.6555)^2 \times 0.57346}{80{,}000}$$
$$= 22.1411 \text{ ft}$$

Assume that the guy takes the shape of a parabola

$$L = S + \frac{8D^2}{3S}$$

$$= 1{,}220.6555 + \frac{8(490.2283)}{3{,}661.9665} = 1{,}221.7265 \text{ ft}$$

Length of guy at 10,000-lb tension

Guy Vibration

Although guy vibration is not, as a rule, a serious problem, it may be well to note its effect. Tower guys have been known to vibrate in a few isolated instances. The natural frequency of any tower guy is a function of:

1. The length of the guy
2. The tension in the guy
3. The weight distribution of the guy

A change in any of these constants will change the frequency of the guy. The natural frequency of a guy without ice is different from that with ice simply because the weight of the ice changes the weight distribution of the guy and automatically increases the tension in the guy. Obviously, if a guy begins to vibrate, changing any of these constants, namely, knocking ice off the guy, adding weights to it, shortening its effective length by a bridle, increasing or decreasing its tension, should kick the guy out of the vibrating frequency. If long guys are provided with weights which are attached to the guys at irregular intervals, the probability of vibration is theoretically reduced. Insulated towers have these weights already on them in the form of guy insulators. Some towers come with some form of cast-iron weights which are clamped around guys to form the guy dampener. Most tower designers feel that a guy dampener is easy enough to install should you get vibration where no dampeners were specified.

WINDS, WEATHER, AND HAZARDS

Wind Velocity

The Weather Bureau aims to get true wind velocities at a height of approximately 10 m (33 ft) in open exposure and ten times as far from any obstruction as it is high. The Bureau tries to approach this ideal, but it should be obvious that sometimes it is virtually impossible to find such an exposure for all wind directions in a well-built-up city and even in some airports. The Weather Bureau's figure for true wind is measured over a 1-min time interval. Some countries use up to 10 min. The Weather Bureau also gives the fastest mile as maximum gust velocity or the peak indication of a pressure tube anemometer. A cup anemometer tends to overregister in a gusty wind. However, this overregistration is very small and never more than a few per cent.

Indicated vs. True

There is misunderstanding about indicated and true wind velocity. Any figure obtained from a Weather Bureau today or in the last quarter century is a true wind velocity. This true wind velocity is also the indicated velocity. This is because anemometers have been calibrated and the indicated and the true are practically the same. However, in about 1898, the Weather Bureau discovered that the anemometers were registering approximately 25 per cent too high. In order to avoid throwing away at least a quarter century of Weather Bureau records already obtained, the Bureau decided to keep on with the figures which were 25 per cent high. This continued until about 1924. This means that records prior to 1924 may show an indicated and a true wind velocity differing by approximately 25 per cent. Any wind velocities given by a Weather Bureau since that time are true wind velocities.

Since air is a viscous fluid, the ground has a certain amount of "slowing-up" effect on the wind velocity. Another way of putting it, wind velocity tends to increase as height above the ground is increased. Obviously this velocity gradient is not a constant, nor is it easy to express. The Weather Bureau gives the formula shown in Fig. 2-35 for velocity ratios as expressed in terms of height. The constant N is somewhere between 2 and 7. Although we do not know how much faster it is actually blowing

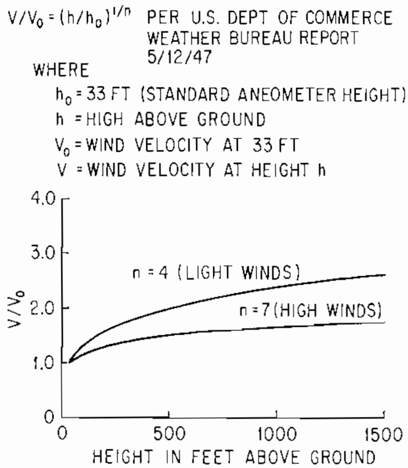


FIG. 2-35. Variation of wind velocity with height.

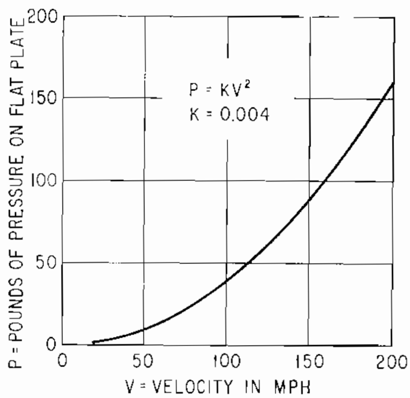


FIG. 2-36. Wind pressure vs. velocity curve.

at 1,000 ft as compared with ground, we are sure that it is blowing faster. For that reason, taller towers should be designed to a slightly higher wind load.

In addition to this wind gradient, there is what the Weather Bureau calls a velocity gradient. This means that in addition to the average maximum wind velocity, there may be superimposed gust velocities for short durations. Much work has been done studying these gusts, and there are some empirical estimates. There is no sure prediction of gusts. It is reasonable to assume that gusts are possible which exceed the maximum wind velocity by a factor between 10 and 30 per cent.

Hurricanes

Hurricanes are large-diameter tropical storms. These hurricanes usually start out in the Gulf of Mexico or the Caribbean Sea or in the Atlantic Ocean east of the Caribbean. The plotted tracks of past hurricanes cover practically every part of the Gulf of Mexico and the Caribbean Sea and much of the North Atlantic Ocean. They are apt to strike most of the Gulf ports and most of Florida. A good many veer off the southeastern coast of the United States and swing out to sea. However, many of them cruise up through Georgia, the Carolinas, and New England. Hurricanes have a counterclockwise wind system. The strongest winds are somewhere between 75 and 100 mph. Occasionally, they may get up to 150 mph. The eye, or the dead portion of the storm, usually runs about 10 miles in diameter. The outside dimensions of a hurricane which covers the width of the destructive winds could be anywhere from 25 to 400 miles. In the United States, hurricanes reach a peak frequency in August, September, and October. It is possible to design hurricaneproof towers at slight additional cost. The EIA Tower Standard RS-222 shows recommended tower strengths for different heights and locations.

Some hurricanes are accompanied by a strong tide which in some cases can be 10 or 12 ft high when it reaches the seacoast. In certain bays where there is a narrow channel, this rise may be as high as 50 ft. These waves are certainly unusual, and although towers have been known to be washed away, no attempt has been made to design towers to withstand such tides.

Tornadoes

Tornadoes, or twisters, occur in most parts of the United States. The highest probability of their occurrence seems to be the Mississippi Valley, but one can expect them in the Southwest, Middle West, or Southeast parts of the country. The highest frequency occurs during the months of April, May, and June. A typical tornado starts in the late afternoon, usually moves from the southwest to the northeast, and cuts a path of destruction somewhere between several hundred yards and a mile wide. The winds inside this twister are very high and are believed to exceed 500 mph at times. No attempt is made to design towers to withstand these high wind velocities, but because of the narrow path involved, the probability of a tornado hitting a tower is not too high.

Wind Pressure

The commonly accepted formula for wind pressure is $P = KV^2$. P is wind pressure in pounds per square foot of projected area; K is the wind conversion factor depending on the shape; V is the actual wind velocity in miles per hour. The nominal value for K pressure on flat surfaces is 0.004. Notice that the pressure is proportional to the square of the velocity. If we plot this, we get the curve in Fig. 2-36. The commonly accepted practice is to use 0.004 for flats and angles and shapes and two-thirds of this value for cylindrical shapes.

Specifications

The EIA specifications for towers were drawn up by representatives of various tower manufacturers. These specifications cover very broadly, but very adequately, all important points in designing steel towers. It is best if broadcasters keep this in mind. There are other specifications probably as good, but they tend only to confuse things. For example, the American Institute of Steel Construction has a set of specifications which were drawn up primarily for large buildings and bridges. It is possible to misuse specifications. For example, AISC reads, "members subject to stresses produced by wind forces may be proportioned for unit stresses 33⅓ per cent greater than those specified for dead and live streses." The intent of that paragraph was secondary wind bracing for structures with heavy live loads. A tower is not such a structure. This paragraph should not be used in radio-tower design, for if it is carried out to its literal conclusion, it is possible for broadcasters to specify a 30-lb wind-load AISC tower and obtain approximately a 20-lb EIA tower.

EIA specifications take a practical look at the method of analysis. EIA recommends that wind loads be expressed in terms of pounds per square foot projected area. Consequently you hear the expression "the tower is a 30-, a 40-, or a 50-lb tower."

Wind vs. Tower Failure

The question often arises, at what wind velocity will a tower fall down? It is very difficult to give an honest answer to that question. Let us take an example: Assume a 40-lb tower. This means that the tower was designed for 40-lb wind pressure on flats, safety factor 1.8, so that the yield of the structure would be approximately at a wind pressure of 40 times 1.8, or 72 lb. Looking at the pressure–wind-velocity curve, 72 lb equals about 134-mph wind velocity. Theoretically, a wind of 134 mph distributed uniformly over the structure produces yield in a structure, and this usually means failure. But how do we know how fast the wind was blowing on the tower? How do we know that the wind was distributed uniformly over the structure? Probably the best record available is the Department of Commerce

Weather Bureau, miles away at a different elevation. For example, assume the anemometer 750 ft below your tower. Wind velocity at your tower could be 134 mph, but the wind velocity vs. height curve in Fig. 2-35 shows that there is approximately a 1.5 times increase in velocity, or at the anemometer, 750 ft below, the wind is blowing about 90 mph. If you throw in a 10 per cent gust factor, it is possible that the anemometer 750 ft below your tower registered 80 mph when it was 134 mph at the top of your tower. For this reason, it is very difficult to correlate wind velocities as given by the Weather Bureau miles away from the tower site with the actual wind velocity blowing through the top of the tower. We do know that from past experience, in certain locations, towers designed to certain wind pressures seem to stay up and are adequate. The best indication for any given location is past experience.

Wind Loading

It is interesting to note the effects of installing different items on a tower. By far the greatest single contributor to the load on a tower is the area exposed to the wind. This means that the less area there is exposed to the wind, the less tower is needed

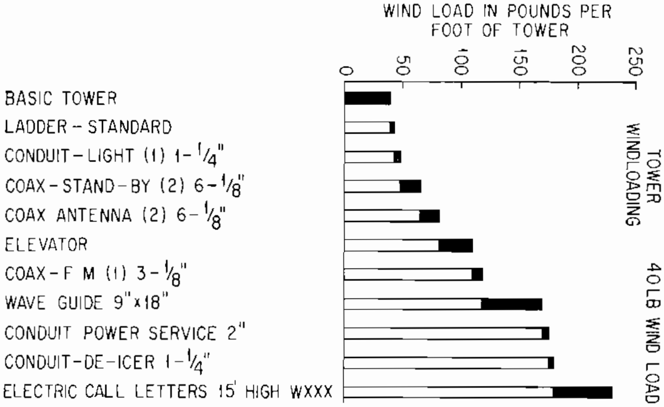


FIG. 2-37. Wind load in pounds per foot of tower.

to support itself. The simplest tower is a small AM radiator whose function is to support itself, with possibly one small lighting line. The other extreme is where signs, elevators, spare coaxial lines, antennas, and other equipment are installed on the tower. The accompanying graph (Fig. 2-37) is made in an attempt to show vividly the effect of various items "hanging" on a tower. The tower is a typical clean tower in the 500- to 600-ft height range with various items being added on, one at a time. Obviously, it is not very difficult to double or even triple the side load on a tower by adding these items. The addition of any single item or article to the tower increases the wind load on it. This, in turn, means that the tower has to be stronger, heavier, and possibly a little bigger in cross section. This additional cross section increases the wind load, which increases the weight and the cost of the tower. Obviously, you cannot hang all these components on the tower without increasing the weight and cost.

Icing

Ice tends to form on all structures exposed to the elements under certain conditions of humidity and temperature. The temperature is usually a little below freezing, and the air is superladen with moisture. Icing is spotty both in location and in frequency. You usually do not get much ice in dry climates, in very cold weather, or in very warm weather. There has been ice as far south as Atlanta, Ga. To find out how icing conditions are in your locality, ask the engineers at your local power company. Utilities constantly have trouble with ice. Tall towers, around 1,000 ft, tend to get layers of ice farther up the tower. You usually find more ice on mountain tops.

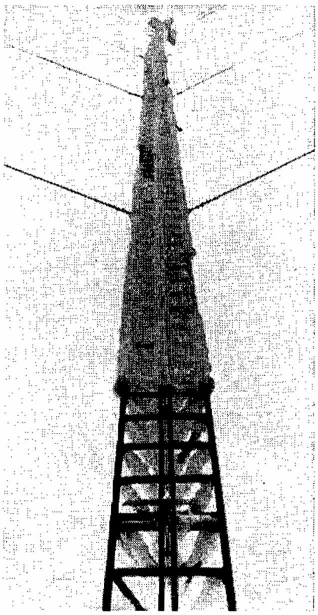


FIG. 2-38. Ice formation on a tower.

It is the feeling of the people who drew up the EIA specifications for towers that, since ice and wind do not occur simultaneously as a rule, the tower should be designed for wind pressure alone. If you are in a location where icing exists, specify a tower somewhat stronger, say a 40- instead of a 30-lb tower.

Prevention of Icing

A number of ideas on preventing ice formation on towers and guys have been advanced. Heating elements have never been tried to deice the tower as far as we know. Heating elements are used on the antennas, not to prevent damage to the antenna, but rather to prevent damage to the radiating properties. The most practical solution seems to be to make the tower strong enough to carry the ice.

Falling Ice

Ice falling off the structure presents a hazard. A chunk of ice 4 or 5 in. thick falling several hundred feet carries quite a "wollup." Automobiles parked at the base of the tower or even some distance from the base of the tower can be damaged. Ice has been known to break beacons, lights, and microwave gear on the way down. It is certainly a hazard to horizontal runs of coaxial lines. A simple corrugated-iron or wooden shield to deflect the flying ice is adequate. Icing over 1 in. in thickness, except in isolated cases, is rare. Pictures of ice 1 and 2 ft thick taken on Mount Washington should not be used as a guide in designing a tower.

Earthquake Loading

Towers on the West Coast are usually required to meet the Pacific Coast Uniform Building Code for earthquake loadings. This code says as follows:

In determining the horizontal force to be resisted, the following formula shall be used:

$$F = CW$$

where F = horizontal force, lb
W = total load tributary to the point under consideration
C = 0.05 for towers which are connected to a building
= 0.025 for radio towers which are not supported by a building

This horizontal force F is added directly to the wind load. In a short, light tower, say 200 ft, this does not add an appreciable amount of load to the tower. In a tall, heavy tower, this factor may be considerable.

Atomic Blasts

One of the atomic blasts out in the Nevada flats was made to test a number of civilian defense items. The bomb was set off on a 500-ft steel tower. Two small cities were built, the first approximately a mile from the blast, the second approximately 2 miles from the blast. Depending on the size of the bomb, all steel within a certain radius is immediately atomized and, for all practical purposes, simply vanishes. So it is impossible to build an atomic bombproof tower. One practical observation was that in the test city, alongside brick and wooden homes which were badly mangled, a guyed 150-ft AM tower designed as a 30-lb EIA tower at 250 ft survived undamaged, although there was evidence of the tower having moved a great deal during the blast. A 100-ft self-supporting tower, noninsulated, loaded with two-way radio antennas, designed to approximately 20-lb EIA load, failed at the same site. A very rough conclusion may be that a short guyed 40-ft EIA tower is approximately a little better than average small buildings. Since the blast gave the tower a violent "jerking about," as it were, the whip or inertia forces must have been high. Consequently, the above conclusion may not be the same for towers which have larger inertia or whip forces. Inertia forces are greater in the case of self-supporting towers and guyed towers with heavy top loads from antenna.

INSULATORS

Base Insulators

Current practice for AM radiators is to have the base of the tower insulated, although there still are some shunt-fed installations.

Most insulators today are made of porcelain. There is no reason why other materials could not be used, such as wood, glass, or fiberglass and other new plastics.

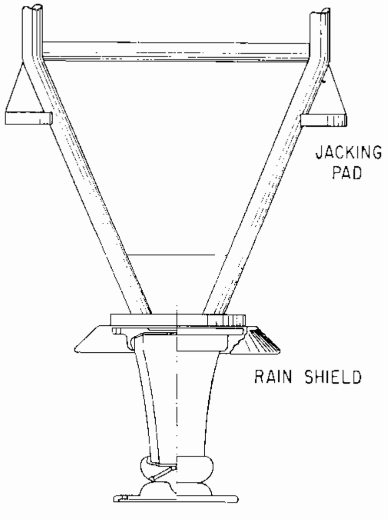


FIG. 2-39. Typical base insulator for guyed towers.

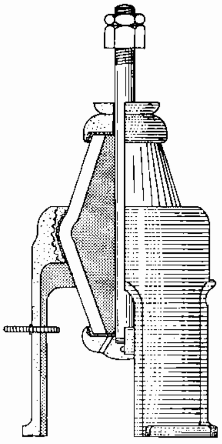


FIG. 2-40. Push-pull type of insulator for self-supporting towers.

Since current practice is to use porcelain, this discussion will concern porcelain insulators. A designer of porcelain insulators always keeps in mind that porcelain is strong in compression but weak in tension. Therefore, the insulators are always designed so that the load pushes on either a mass of solid porcelain or a cone of porcelain. The designer tries to make sure that there is no bending or tension induced into the porcelain portion of the insulator. Most guyed towers come down to a single-point pivot, and the insulator will have a rounded surface so that the tower can pivot. This is to prevent any bending being induced back into the porcelain, and most of the load is pure compression. Figure 2-39 shows a typical installation. Sometimes a rain shield is put over the top of the insulator in an attempt to keep the insulator dry, since the flashover value of dry porcelain is better than that of wet porcelain. However, most rain shields are very ineffective in a driving rain unless they form a complete shroud down and around the porcelain. Since porcelain is fragile and subject to cracking, some care should be exercised in handling it. There have been instances where water has got into the cone, the drain hole has plugged up with dirt, and the water froze and shattered the insulator. This is quite unusual. The cost of base insulators with leakage paths greater than 10 ft increases rapidly.

The self-supporting tower presents a unique problem in that the base insulator has to transmit either compression or tension from the leg member. The accompanying cross section of a typical push-pull insulator in Fig. 2-40 shows how this is accomplished. This insulator works in such a way that the upper cone works when the load is down (compression on the pier) and the bottom cone works in compression when the load is an upload on the leg member. These insulators are usually very bulky and expensive, and except for the smaller sizes, delivery and availability are not too good.

It is perfectly possible to have a three-legged or four-legged guyed tower which is shaped so that it sits on all three or four legs on the pier, in which case, three or four insulators will be required at the base of the tower. Some designers prefer this form, and there is nothing wrong with it providing the insulators are capable of transmitting a certain amount of tension and the foundation pier is absolutely level.

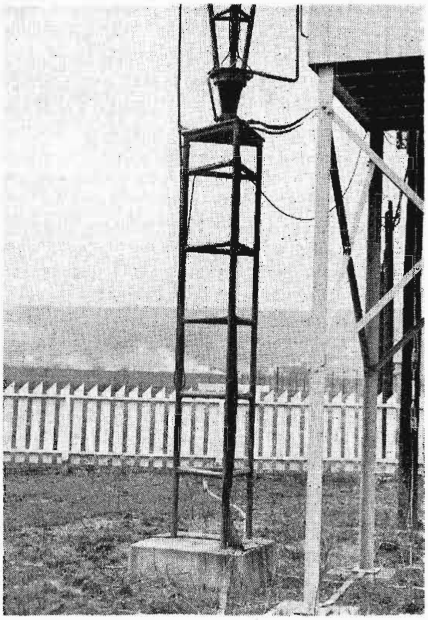


FIG. 2-41. Example of raising base insulator for flood-water conditions.

Large special insulators are sometimes used, but they are not typical.

Once in a great while, the porcelain on a base insulator will crack. The crack may be due to an old flaw, an external blow, a lightning hit, or water getting inside the porcelain and freezing. In order to change the base insulator, the tower must be raised slightly. This is not a particularly difficult operation, but it is very critical. Sometimes, on tall towers, jack pads are incorporated into corner legs to facilitate raising the tower.

Raising Base Insulator above Ground

The base insulator of an AM tower is located so that unusual weather will not ground the insulator. Sometimes, 1 or 2 ft above the ground is adequate. The insulator is usually placed in a concrete pier 3 to 5 ft tall. Occasionally, insulating may be as much as 25 ft above the ground as is shown in the accompanying photograph, Fig. 2-41. Sometimes, in an array of four towers on a sloping piece of ground, it may be desirable to locate all insulators in the same horizontal line. Each tower sits on a pier of a different height. Concrete is generally used up to about 5 to 10 ft. Over that height, some sort of steel pier is probably the most economical.

Guy Insulators

Typical guy insulators and guy-insulator assemblies are shown.

The most commonly used guy insulator for AM work is the so-called strain insulator. Since most AM towers are under 300 ft, most towers use these insulators. The insulators were developed by the power companies and are made in large quantities so that they are easily available and the cost per unit is very low. They come with multifins to increase leakage path and are used with strand up to ½ in. Another advantage of a strain insulator is that if an insulator cracks, the tower fails safe; that is, the interlocking loops of strand keep the guy intact.

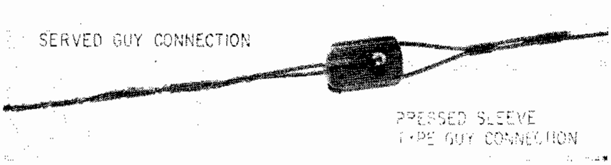


FIG. 2-42. Typical strain insulator.

Where it is desired to have the insulators capable of being inserted after erection, the open-type insulator is sometimes used. A strand over ½ in. is very stiff, and it is very difficult to pull around the insulator. Great care must be taken to make sure that the strand hugs the loop all around its periphery. In other words, the strand must be forced around the grooves on the insulator. If this is not a snug fit at both sides of this insulator, the insulator will tend to cock, the insulators will be loaded at a point rather than over a surface, and the desired mechanical strength will not be obtained.

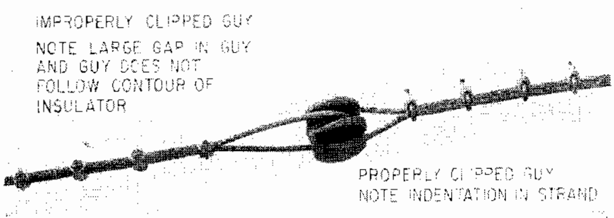


FIG. 2-43. Improperly and properly clipped guy.

On large guys and when the leakage path is greater than that obtained by strain insulators, the so-called cone insulators are used. This cone insulator is nothing more than a base insulator with a basket around it. You will notice that the load is transmitted through a cone of porcelain in compression. It is interesting to trace the load transmitted through one of these insulators. The load comes down the guy, through the top socket, then around the insulator, through a steel yoke and to the bottom of the cone. All this load so far is tension. The load is transmitted through the porcelain to the top of the cone in compression. The top of the cone has a pivot with a gonglike piece hanging down to pick up the bottom socket. These insulators are large, clumsy, expensive, and not easily available. Also, they do not fail safe.

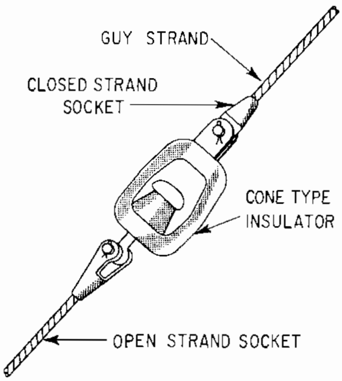


FIG. 2-44. Cone-type guy insulator.

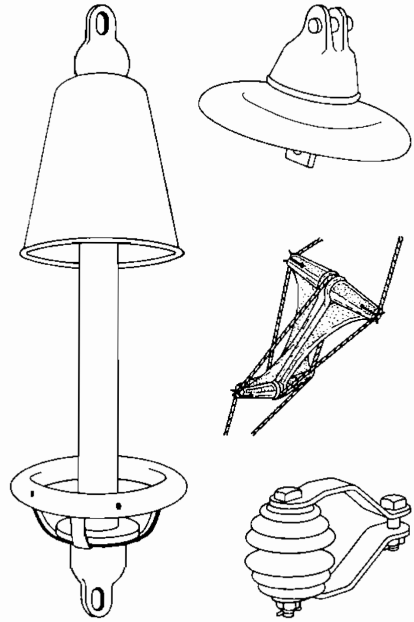


FIG. 2-45. Miscellaneous guy insulators.

Several other types of guy insulators which have been used are shown. Porcelain insulators have a very good life. Replacement of cracked strain insulators is not common. For replacement, the guy is dropped or an erector slides down the guy to the point in question.

Sectional Tower Insulators

There are some installations where by sectionalizing a tower it can be used for more than one function. A sectionalized tower can be used to control the AM radiating characteristics of a tall tower. This allows a tall TV tower to be used as an AM tower. This is possible by insulating portions of the tower from one another. As shown in the illustration (Fig. 2-46), either the pivot type or the push-pull type of insulator can be used to sectionalize a tower. It is desirable to taper the tower for the pivot-type insulator. The push-pull type of insulator is used at each leg member as is used in a self-supporting design. In either case it is necessary to check the shear transfer across the insulator.

With a sectionalized tower, periodic inspections of the insulators are mandatory. A failure in a sectionalizing insulator very likely will cause the tower to fail.

BONDING

An AM tower is a radiator. Hence, it is important that the steel tower acts as one continuous electrical unit. Faying surfaces on a galvanized tower are not painted and as a rule are considered sufficiently bonded through the zinc contact. Two methods of bonding steel towers are shown below.

The weld type of bond is positive, but extreme care must be taken when welding near guys. It is possible to damage guy strand with the molten weld slag. The copper-jumper type of bonding is a bit more troublesome. The holes must be abso-

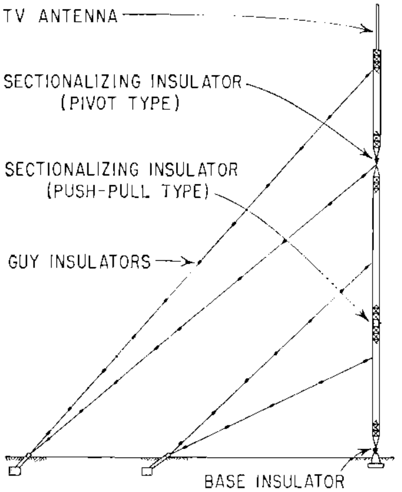


FIG. 2-46. Example of a sectionalized tower shown with two types of sectionalizing insulators.

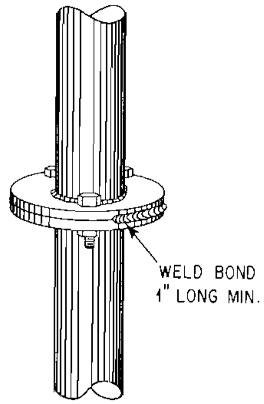


FIG. 2-47. Weld-type bonding.

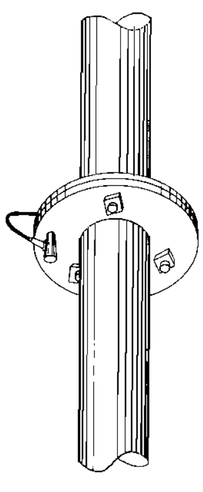


FIG. 2-48. Jumper-type bonding.

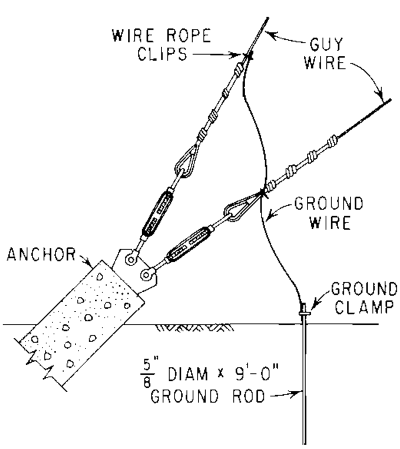


FIG. 2-49. Grounding at guy anchor.

lutely clean and free from rust and paint. The wedges should be driven in tightly to make good contact and exclude any moisture to preclude any electrolytic action.

LIGHTNING

Since the steel tower is usually the tallest object in its vicinity, it is always the first to be hit by lightning. As a matter of fact, the tower itself forms an electrical umbrella, as it were, for adjacent structures. Since steel is a very good conductor, lightning does not damage the tower or its guys. Although there have been many rumors about lightning shattering concrete foundations, we have never been able to find a record of such an incident. An AM tower, with its screen and radials, automatically makes a very good ground for dissipation of lightning. TV and other towers

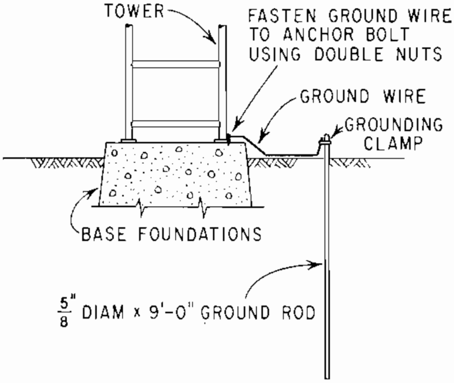


FIG. 2-50. Grounding at tower.

should be adequately grounded simply as a precaution to keep the lightning path away from the transmitter house. A typical guy cable grounding system is shown in Fig. 2-49 (see page 2-71). Lightning, however, can and has done damage to any and all kinds of electrical equipment on the tower. It seems almost impossible to build a tower where the manufacturer can guarantee that lightning will not knock out pieces of electrical wiring, lamps, junction boxes, etc.

SOILS, ANCHORS, AND FOUNDATIONS

Soil Exploration

On small towers such as a 200-ft guyed AM tower, the magnitude of loads is not large enough as a rule to warrant soil exploration, unless, of course, the soil is very sandy or swampy. If the condition of the ground is in doubt and on tall TV installations where the magnitude of load is appreciable, a thorough soil exploration is certainly advisable. In most parts of the country, there are soil engineers who are familiar with the type of soil in a particular location. Test bores are usually made at the tower base and at the anchor foundation locations. At the base of the tower, test bores should be approximately 25 or 35 ft deep, whereas at the guy anchors, test bores should be a little deeper than the anchor depth.

The purpose of the test bore is to help determine the allowable unit bearing pressure for design. Sometimes, local building codes set their own values for local conditions. There are any number of methods used to study the subsurface conditions. A simple test which permits classification of the soil may or may not be adequate to tell the bearing capacity. For that reason, a test boring log should be turned over to competent soil engineers, who will then convert the data to allowable bearing capacities of the soil. Soil engineers are usually more familiar with local conditions, codes, and geology than others far removed. For purposes of approximation, the allowable bearing values of foundation soils are given in Table 2-1.

Table 2-1. Approximate Allowable Bearing Value of Foundation Soils

	Bearing Capacity, Tons per Sq Ft	
Soils	*Approximate Depth 3 Ft*	*Approximate Depth 6 to 10 Ft*
Soft silt and mud	0.1–0.2	0.2–0.5
Silt (wet but confined)	1–2	1.5–2
Soft clay	1–1.5	1–1.5
Dense firm clay	2–2.5	2.5–3
Clay and sand mixed firm	2–3	2.5–3.5
Fine sand (wet but confined)	2	2–3
Coarse sand	3	3–4
Gravel and coarse sand	4–5	5–6
Cemented gravel and coarse sand	5–6	6–8
Poor rock	7–10	7–10
Sound bedrock	20–40	20–40

A typical log of a boring is shown in Fig. 2-51. This log is in turn analyzed by a competent soil engineer who will recommend allowable unit bearing pressure for design.

Anchors and Piers

Tower base foundations are usually made of reinforced concrete and are designed to carry the total column load of a tower. The area of the footing should be of sufficient size to prevent detrimental settling of the tower structure.

Anchor foundations, on the other hand, exert little down loads. The vertical component from a guy is resisted by the weight of the concrete and earth overburden. The horizontal component is resisted by friction on the anchor base and by the lateral resistance of soil on the face of the anchor.

At some installations the allowable bearing pressure of the soil is very low or an underlying stratum is exceptionally poor. Serious settling of the foundation may occur under these conditions, and it is advisable to drive piles under the footing.

Figures 2-52 to 2-62 show the many types of base pier and anchor designs for radio and TV towers. Many metal-type anchors for small tower installations are available for different soil conditions, and the illustrations are self-explanatory. The screw-type swamp anchor has a pipe for its shank. The length of the shank is increased by coupling additional pieces of pipe until the screw has been driven into hard soil. Various types of guy anchors are shown.

The photograph in Fig. 2-63 shows an anchor installation at KOA-TV, Denver. Usually, the small flats on top of hills make a self-supporting tower a must. However, it is possible to install tall guyed towers in rough, mountainous terrain. Naturally, this usually brings about installation problems. Probably the costliest item is making the tower base and each anchor point physically accessible to trucks and erection equipment. Tower designers like to choose sites so that each anchor falls off approximately the same. However, this is not always possible or absolutely necessary.

Concrete Foundations

Reinforcing

Most foundations are made of reinforced concrete (see Fig. 2-52). Since the concrete is in a wet plastic state when it is poured, it must be confined until it hardens. Usually, these forms are made of wood. Sometimes in small towers, forms are dispensed with at the anchors simply by digging a hole of rectangular shape and allowing the sides of the earth to give the concrete its shape. On a large tower, the wooden forms run into a considerable amount of money.

Except for tiny foundations, concrete piers and anchors are always reinforced with reinforcing bars of the deformed type of steel. The purpose of these bars is to help

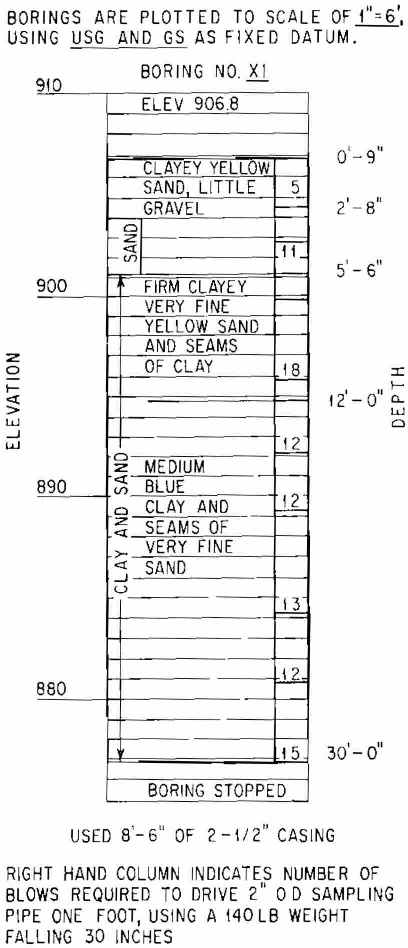


FIG. 2-51. Typical boring log.

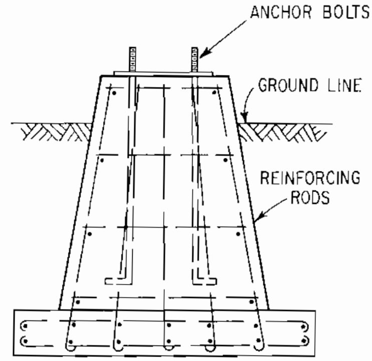


FIG. 2-52. Typical reinforced-concrete base pier.

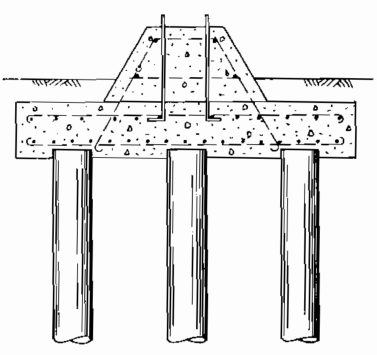


FIG. 2-53. Base pier of reinforced concrete on piles for use in poor soils.

carry any tensile stresses in the concrete block, since concrete is essentially a compressive load-carrying material. Deformed steel is used, since the deformed surfaces give a better mechanical bond to the concrete. Since reinforcing bars are universally obtainable, the steel is usually procured locally. The reinforcing bars should be carefully wired and placed together as called for on the foundation drawing prior to pouring the concrete. Sometimes these bars are welded together into a subassembly.

Mix

The concrete is usually obtainable from a local ready-mix plant. The foundation designer always specifies the proportions of the mix and the water-cement ratio or strength of concrete. These items should be relayed to the supplier of the concrete. A typical mix is 1-2-4, where the numbers 1-2-4 represent the proportions of cement, sand, and gravel. The water-cement ratio is often expressed by specifying approximate compression strength of the concrete after 28 days. A typical strength is 2,500 psi.

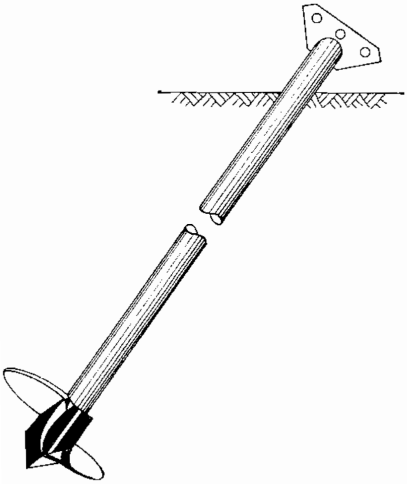


FIG. 2-54. Screw-type swamp anchor.

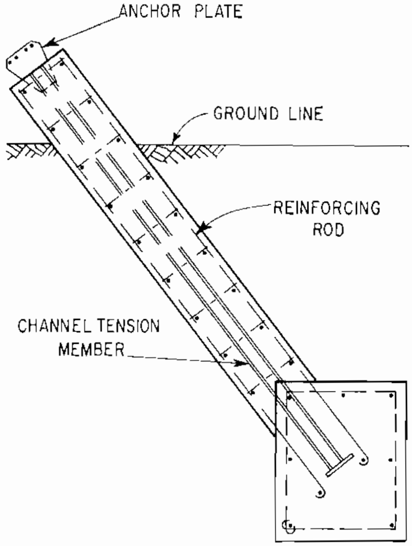


FIG. 2-55. Typical reinforced-concrete guy anchor.

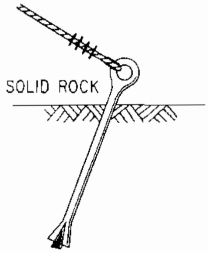


FIG. 2-56. Wedge-type rock anchor.

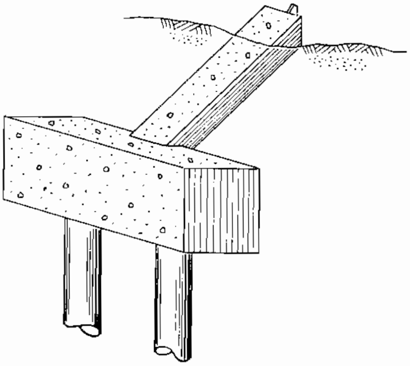


FIG. 2-57. Reinforced-concrete guy anchor on piles for use in poor soils.

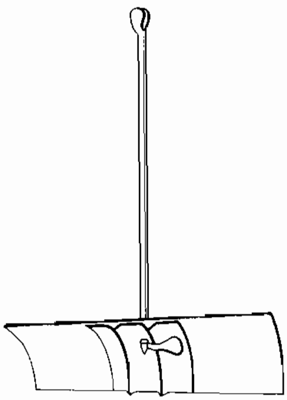


Fig. 2-58. Two-piece metal anchor for clay or loam.

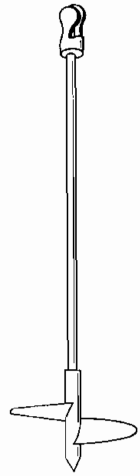


Fig. 2-59. Screw-type earth anchor.

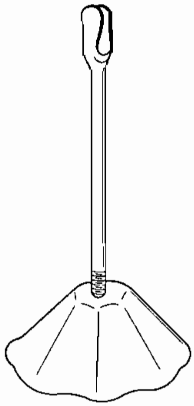


Fig. 2-60. Cone-type anchor for rocky soils.

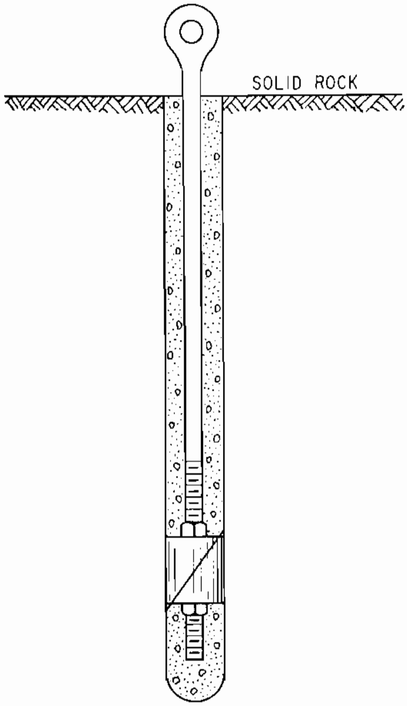


Fig. 2-61. Expanding rock anchor.

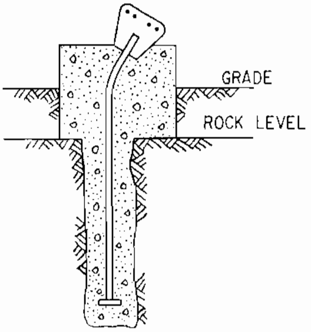


Fig. 2-62. Concrete-type rock anchor.

Pouring

As the concrete is being poured, precautions should be taken to see that the forms are filled completely. The usual method is simply to poke or churn the concrete with a pole or shovel, especially along the edges of the forms. Care should be taken to see that the steel arms which protrude from the forms are not moved or disturbed by the pouring of the concrete.

On towers where the guys are supplied with fixed lengths, it is most important to know the exact dimensions from the working points at each guy anchor. These are

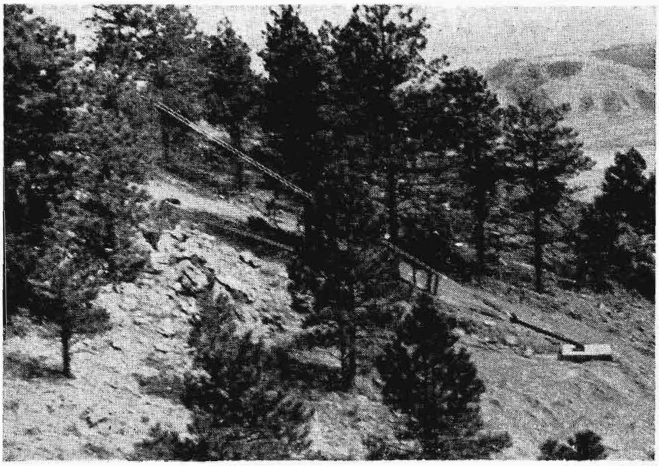


FIG. 2-63. Guy anchor installation at KOA-TV, Denver, Colo.

surveyed and determined prior to pouring the concrete. Since the concrete may disturb the steel anchor arms, it is advisable to survey the installed anchors and get a new set of readings locating these work points.

When concrete is poured under water, proper forms and a comparatively dry mix will aid procedure. Where the simple method of depositing the concrete under water directly is not possible, a cofferdam can be built. A cofferdam is a temporary wall structure out of which water is pumped so that work can be carried on in a comparatively dry area.

Freezing

Frozen concrete may not suffer any visible deterioration, but its strength is greatly decreased. Some precautions must be taken during freezing weather. Fresh concrete, when frozen, is easily recognized by its white color, whereas ordinary concrete will remain a slate color. One precaution is to heat the ingredients and water prior to mixing and then cover the poured concrete with layers of hay or straw. Sometimes heat is introduced from a portable heater. Another precaution is adding calcium chloride to the mixture. This generates heat during the setting period.

Strength

There are occasions where high strength in concrete foundations at an early age is desired so that the erection of steel can begin at the earliest possible moment or to make possible early reuse of forms. In cold-weather construction, high early strength reduces the time of protection required. High strength at early ages can be achieved by using a type III portland cement usually designated as high-early-strength portland cement or by using richer mixtures of other types of portland cement. The type III cements cost more than the normal portland cement.

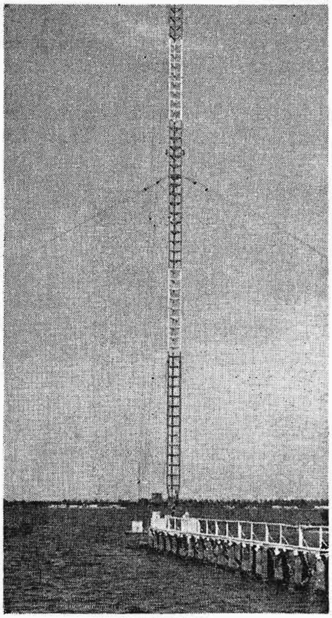


FIG. 2-64. Photograph of a water installation. The erection costs rise very rapidly. Cofferdams are built prior to pouring the foundations, and the erector must invent ingenious devices to get his material to the base of the tower in the water. The photograph is Station WMMB, Melbourne, Fla.

Since the important factors which govern the strength of portland cement concrete are the relative proportions of cement and mixing water and conditions during curing, great latitude in obtaining desired strengths at a given period can be obtained by adjusting these factors. Sometimes, calcium chloride is used as an accelerating admixture to increase the rate at which concrete develops its early strength. The calcium chloride is particularly effective in increasing strengths at 1 to 3 days. On the other hand, for a given water content, high-early-strength cements give higher strengths than normal portland cement either with or without the accelerator at the later ages up to about one year.

TOWER ACCEPTANCE

Inspection

Most towers are very simple structures physically. Assuming that the tower was designed by a competent engineer to EIA standards and that the number and size of members called for by the manufacturer are adequate, the job of checking should not be too complicated. The following is a suggested checkoff list:

Tower Inspection Checkoff List

1. Has the site been cleaned of all debris, paint cans, reels, and miscellaneous erection junk?
2. Is the tower plumb?
3. Is the tower painted properly—international orange and white—per construction permit?
4. Are the bolts pulled up tight?
5. Are all the nuts secured and locked as called for by the manufacturer?
6. Are the turnbuckles safety-wired to prevent back turning?
7. Is the service entrance cable or conduit attached securely?
8. Check anchor distances against tower drawing.
9. Were holes for the foundations dug deep enough as per drawing?
10. Are the anchor holes backfilled? If not, the first rain will make a sizable depression over the anchor.
11. Is the coaxial system tight?
12. Does the lighting system work?
13. Are all the junction boxes secured with watertight gaskets in them?
14. Look at the face of the tower. Is there any appreciable twist in one face?

15. On large towers, check the guy tensions by the method given to you by the manufacturer.

16. Look at all the members from the ground. Are any of them visibly damaged or bent during the course of construction?

17. Did the erector leave any unpaid bills around town that you know of?

Three chronic complaints about erectors are:

1. Shorting in the lighting system
2. Sloppy paint job
3. Leaks and dents in the coaxial system

General Erection Notes

There is a tendency for the broadcaster to take a long time to decide what tower to buy and then expect an erector on the site before the material has arrived. These boys do not get paid for days they do not work. If they are held up because of lack of material, they resent it! Very often, the broadcaster, with no ill intent, tells the erector that most of the material is on the site and the balance is in transit. This may be true, but unless the last bolt and every piece of coaxial, anchor, and tower is on the site, one can never be sure when it will get there! Less-than-carload shipments are very slow. The erector will cry for extras, and bad feeling begins. You can't blame the erector. Bear in mind that the average erector many times works under adverse conditions and is away from home.

Tower-erection business is very competitive. Most bids are based on the erector's being able to get to the site. He does not necessarily need a four-lane highway, but he should be able to drive the truck to the base of the tower and drive to each anchor. The fact that you can walk on the site does not necessarily mean that it will hold up a truck. He also needs a cleared piece of land to assemble his material.

It is not the erector's responsibility to get a building permit. It is customary for the tower buyer to get all permits simply because they are usually obtained under local conditions which change from town to town all over the country. Sometimes it is a matter of a two-dollar license. In other cases, political intervention or an expensive engineering analysis and approval are required.

Erectors bid on the understanding that they will work regular hours. Overtime is expensive, and one should expect some resentment from the erector when he is asked to work overtime at no extra cost.

It would be wise to allow a somewhat longer time for erection than promised by the erector. He usually thinks in terms of elapsed working days and does not count Sundays, Saturdays, holidays, opening day for fishing, opening days for hunting season, or days or rain, sleet, and high winds. Often winds are 10 mph on the ground but 30 mph aloft at 700 ft (see Fig. 2-35).

Erection work is usually risky work simply because it is off the ground. The more you push the workmen, the more prone to accidents they become. The erector is not going to get paid until he finishes the job, so he, too, is anxious to complete it.

The erector expects electrical power at the base of the tower prior to starting the job. Otherwise, he has trouble getting temporary lights and he will complain.

Erection work is usually thankless and dangerous. Working conditions, because of cold, rain, mud, swamps, rocks, snow, wind, and weather, in general are never so good as those in an air-conditioned factory. The men have to be of a tougher breed. Understanding their problems helps everyone.

Insurance

If a station decides to hire its own erector to install the tower, it is recommended that the following evidence of insurance from the erector (in the form of certificates) be obtained. The following different insurance certificates are customary today:

1. Workmen's compensation and occupation diseases, including employer's liability insurance. *Limits:* This insurance should be checked with the statutory requirements

as applicable in the state in which the work is being performed. Employer's liability should be at least $25,000.

2. Contractor's public liability insurance which covers damage and injury to objects and people not under the care and custody of the contractor. *Limits:* Bodily injury, $15,000/100,000; property damage, $15,000/100,000.

3. Contractor's protective liability insurance protects the contractor with his subcontractors. For example, the contractor may sublet the foundations or sublet the electrical work or paint because of union problems. *Limits:* bodily injnry, $15,000/100,000; property damage, $15,000/100,000.

4. Automobile liability insurance. This covers all motor vehicles owned or leased, including nonownership liability covering contractors' employees' personal cars and trucks. *Limits:* Bodily injury, $100,000; property damage, $100,000.

5. Direct damage insurance. This insurance provides for protection against all risk of the tower, antenna, lines, and the equipment which the erector is working on or material which is in his (erector's) custody until completion of the job. *Limits:* Should be set to cover the value of the tower, lights, coaxial lines, antenna, and any other equipment he is installing, plus erection labor involved.

The owner should have an insurance policy covering any loss to the tower once the tower erection is completed and the customer has accepted the tower. Values are set for replacement values, namely, the price which he has paid for the tower and equipment on the tower plus the cost of erection.

TOWER LIGHTING

Since a tower is a hazard to air navigation, the government prescribes certain warning lights to be installed on the broadcast towers. In general the lighting requirements are spelled out in a pamphlet put out by the FAA called "Standards for Marking and Lighting Obstructions to Air Navigations, November 1, 1953." However, the exact lighting requirements are given very specifically in detail in the construction permit from the FCC for every station. These specific instructions may differ from the general specifications. Since the maintenance of the tower lights is a never-ending problem, it behooves the station management to see what can be done to keep the lighting requirements down. For example, any tower in the shadow of a taller obstruction, such as a taller building, a taller tower, or a taller hill, can usually be installed without any lighting.

The electrical system is essentially very simple. It consists of a number of lamps which are fed by one or more circuits either 110 or 220 60 cycles alternating current. On AM towers, the RF must be isolated from the 60-cycle current. Circuits are made and broken intermittently by a flasher. A photocell is used to turn the lights on and off automatically at certain light levels.

Maintenance of lighting systems as a rule is fairly simple. Lamps burn out and must be replaced. It is possible to double the lamp-replacement period by installing two lamps at every light requirement and connecting these two lamps with a small relay which turns on lamp 2 upon failure of lamp 1.

The most chronic tower-lighting complaint is water getting into the system and causing shorts. Here again, it is a matter of making sure that all connectors and covers are installed neatly and made watertight. It seems that about as many leaks occur in the conduit system as in the system which uses flexible cable.

Some stations with tall towers have experienced broken glass on beacons due to falling ice and have installed small ice shields over the beacons. Most flashers today use a mercury switch to make and break the circuit. These mercury switches are relatively trouble-free. Flashers which use contactors for making and breaking a circuit tend to give trouble because contact points burn and pit.

Tall towers requiring several beacons and side lamps are usually fed with several circuits of color-coded TW wire in rigid conduit. Most short AM towers make use of service entrance cable or any number of flexible cables, since this system is cheaper.

Since the beacon is the uppermost point on a tower, it is usually protected with a lightning rod, which reaches a couple of feet above the beacon. Most TV antennas have a lightning rod built into the antenna. As a conservative precaution, it is wise to ground physically in the junction boxes the neutral or ground wire in the lighting system at several levels on the tower.

SIMPLIFIED TOWER DESIGN

Calculating Wind Load

The method of calculating wind load on a tower is given in Sec. 2 of EIA Standard RS-222. On triangular tower structures, wind pressure is applied to 1.5 of the projected area of all members in one face. Pressure is applied to the projected area of lighting lines. Calculations below are for 30 psf on flat members and 20 psf on round members.

1. Tower:

Member	External Diameter, in.	Length, in.	Number of pieces	Projected area, ft²
Cross member ¾ in. I.P.S.	1.05	16.34	8	0.95
Diagonals ¾ in. I.P.S.	1.05	39	7	1.99
Verticals 1¼ in. I.P.S.	1.66	240	2	5.53
Total projected area				8.47

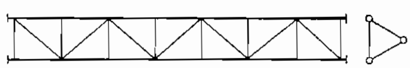


Fig. 2-65. Typical triangular tower section.

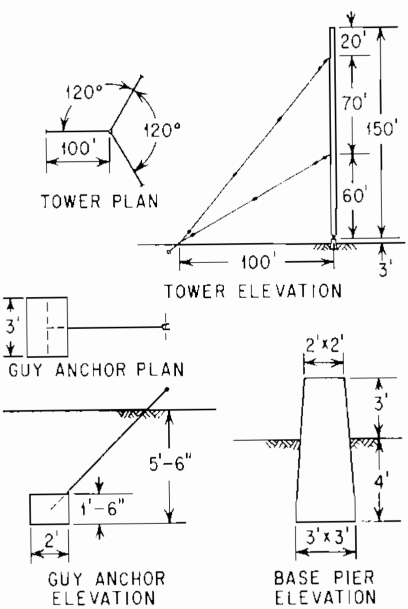


Fig. 2-66. Tower sample analysis.

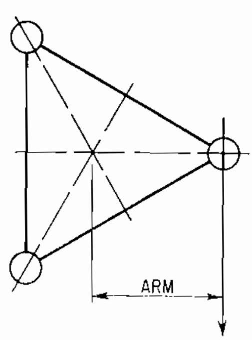


Fig. 2-67. Shear and moment analysis.

Wind load:

$$\frac{\text{Projected area} \times 1.5 \times \text{wind pressure}}{20 \text{ ft}} = \frac{8.47 \times 1.5 \times 20}{20} = 12.71 \text{ psf}$$

2. Lights:

$$\text{Total projected area} = \frac{1 \times 20}{12} = 1.67 \text{ sq ft}$$

$$\text{Wind load} = \frac{\text{projected area} \times \text{wind pressure}}{20 \text{ ft}} = \frac{1.67 \times 20}{20} = 1.67 \text{ psf}$$

3. Total wind load = 12.71 lb/ft + 1.67 lb/ft = 14.38 lb/ft

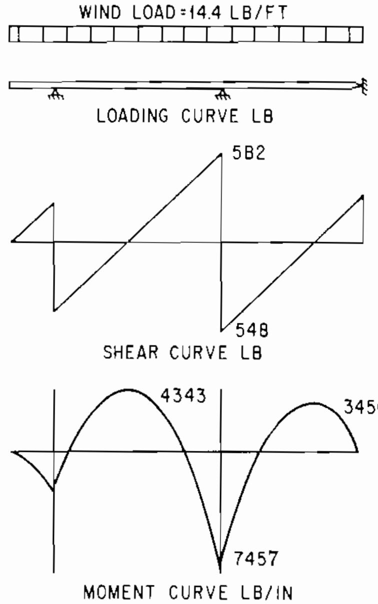


FIG. 2-68. Loading, shear, and moment curves.

Shear, Moment, and Loading

Obtain shears and moments, considering the tower as a continuous beam. Assume that the points of support deflect as a straight line. Use the moment-distribution or similar method. Allow for eccentric application of the load by the guy. The eccentric moment is the vertical component of the load in the guy multiplied by its distance from the center of the tower.

Diagonal Struts

Diagonal struts resist tower shear. Assume that two-thirds of the shear is carried by one face of the tower.

Maximum shear = 582 lb

$$\text{Load} = \tfrac{2}{3} \times 582 \times \frac{34.1}{18} = 735 \text{ lb}$$

Check the strength of the member for compression and for tension using allowable stresses (see RS-222 Par. 3.1.1).

Horizontal Struts

The load in horizontal members is equal to the horizontal component of the load in diagonal members.

$$\text{Load} = 735 \times \frac{18}{34.1} = 388 \text{ lb}$$

Check the strength as for diagonal strut.

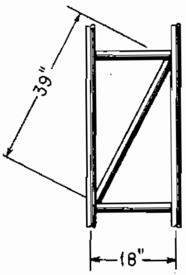


FIG. 2-69. Diagonal and horizontal struts.

Column Load on Tower

The wind direction shown is critical for the column load on the tower. Two guys are on the windward side of the tower and apply a vertical load. Assume that the tension in the leeward guy is negligible, then the load in each guy is

$$\text{Tension} = \text{reaction} \times \frac{\text{length}}{\text{guy radius}}$$

The column load is the sum of the weight plus the vertical components of the guys.

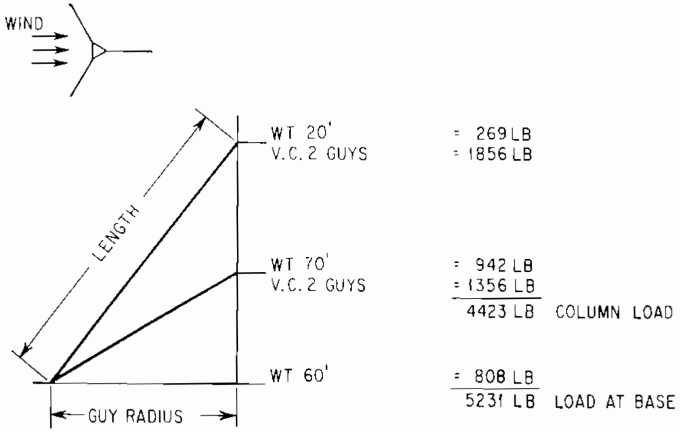


FIG. 2-70. Column-load analysis.

Load in Vertical Member

The vertical members of the tower must be designed for combined compression and bending. The load in a vertical member is equal to the column load divided by 3 plus the chord load due to bending M/d where d is depth. The tower must be checked for tension in the vertical members and for compression. At the point of maximum moment in the first bay, the member is checked as follows:

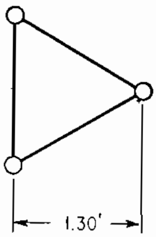


Fig. 2-71. Vertical-member load.

$$\text{Column load} = 4{,}423 \text{ lb}$$
$$\text{Moment} = 3{,}450 \text{ ft-lb}$$
$$\text{Load} = \frac{4{,}423}{3} \pm \frac{3{,}450}{1.30}$$
$$= 1{,}474 \pm 2{,}650$$
$$= 4{,}124 \text{ lb compression}$$
$$= 1{,}176 \text{ lb tension}$$

Check the strength of the member for compression and for tension, using allowable stresses in RS-222 (Par. 3.1.1).

The tower acting as a column between guys may be critical if the slenderness ratio becomes large. In general, if the ratio of the span between guys divided by the face width of the tower is 40 or less for triangular towers and 50 or less for square towers, column action of the tower is not critical.

Guy Load

The load in guys depends on the guying arrangement and on the direction of the wind. For any number of equally spaced guys, there is a critical wind direction, and this direction must be used to obtain the maximum guy load. Critical loads for three-way guying are shown in Fig. 2-72.

By statics

$$\text{Horizontal component (guy } A) = \frac{\text{tower reaction}}{\cos 30°}$$

$$\text{Horizontal component} = \frac{R}{0.866} = 1.154R$$

and

$$\text{guy tension} = T = 1.154R \times \frac{L}{d}$$

In practice, especially on tall towers, an allowance is made for wind loads on guys and for erection tension or initial tension in guys. EIA Standard RS-222 (Par. 8.2)

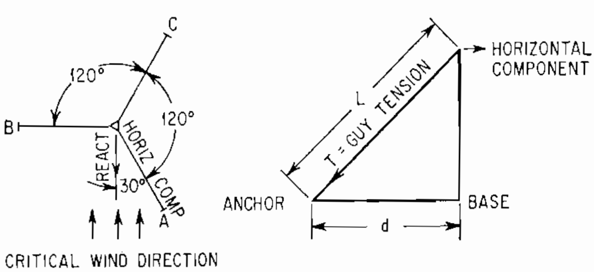


Fig. 2-72. Critical loads for three-way guying.

requires a factor of safety of 2.5, based on the ultimate strength of the guy strand.

For a sample tower, guy loads are as follows:

Guy No.	R, lb	L, ft	d, ft	Crit. guy load, lb	Guy size, in.	Ultimate strength, lb	Factor of safety
1	1,130	117	100	1,526	1 × 7 × ¼ E.H.S.*	6,650	4.36
2	714	164	100	1,350	1 × 7 × ¼ E.H.S.*	6,650	4.93

* Extruded Hardened Steel.

Foundation Loading

1. Base foundations must be proportioned so that the area of the base is greater than the total column load plus the weight of the concrete pier divided by the allowable soil bearing pressure.
2. By EIA, RS-222, bearing pressure for normal soil is 4,000 psf.
3. Applied column load = 5,230 lb
   Weight of concrete pier 44.3 cu ft at 140 lb/cu ft = 6,200 lb
   Total load on base = 11,430 lb
   Bearing pressure $= \dfrac{11{,}430}{3 \times 3} = 1{,}270$ psf
4. Bearing pressure is considerably less than 4,000 psf, and the pier has a large factor of safety.

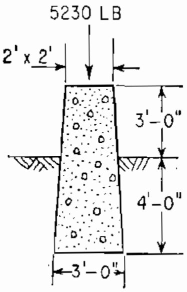


FIG. 2-73. Base-foundation analysis.

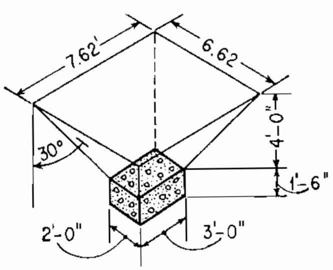


FIG. 2-74. Guy-anchor analysis.

Guy Anchors

1. Guy anchors are designed for the resultant load of guys when the wind is blowing in the critical direction.
2. Vertical load is resisted by weight of concrete and earth overburden. EIA specifies in uplift that the foundations shall be designed to resist two times more than the applied load assuming that the pier engages a 30° frustrum as an earth overburden. Resistance to horizontal load is provided by friction on the base of the anchor and by lateral resistance of soil on the face of the anchor. Friction on the base is usually small and is neglected. Lateral resistance can be obtained by Rankine's formula for passive resistance:

$$P = wh \frac{1 - \sin \phi}{1 + \sin \phi}$$

where P = resistance, psf
W = unit weight of earth – 100 lb/cu ft
h = depth to point considered – 4.75 ft
ϕ = angle of internal friction of soil assumed to be 30°

$$P = 100h \frac{1 + 0.5}{1 - 0.5} = 300h = 300(4.75) = 1{,}425 \text{ psf}$$

3. Allowable uplift on anchors:

$$\begin{aligned}
\text{For weight of earth: } \tfrac{4}{3}(6 + 50.4 + \sqrt{302.4}) &= 98.5 \text{ cu ft} \\
98.5 \text{ cu ft} \times 100 \text{ lb/cu ft} &= 9{,}850 \text{ lb of earth} \\
\text{For weight of concrete: } 2 \text{ ft} \times 3 \text{ ft} \times 1.5 \text{ ft} &= 9 \text{ cu ft} \\
9 \text{ cu ft} \times 140 \text{ lb/cu ft} &= 1{,}260 \text{ lb of concrete} \\
\frac{9{,}850 \text{ lb}}{11{,}110 \text{ lb}} \text{ of earth} \times \tfrac{1}{2} &= 5{,}555 \text{ lb allowable uplift}
\end{aligned}$$

4. Allowable horizontal load on anchor

$$\begin{aligned}
&= \text{resistance psf} \times \text{frontal area} \\
&= 1{,}425 \text{ psf} \times 3 \text{ ft} \times 1.5 \text{ ft} \\
&= 6{,}420 \text{ lb}
\end{aligned}$$

Part 3

STANDARD BROADCAST ANTENNA SYSTEMS

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PREFACE

The purpose of this section is to furnish useful information to the engineer, technician, and operator in a broadcasting station. The material is divided into text and handbook types of presentation. An effort has been made to approach each new subject gradually in the text, while in the appendices, design equations and data have been presented in handbook style with the aim of making them most useful to the technician and operating engineer.

First, the single tower is analyzed. It is then used as elements in a two-tower directional-antenna array before going to the more complicated arrays.

Antennas form the dominant theme supported by other items such as coupling networks and monitoring circuits. The topics of adjustments and field measurements are treated in a way thought to be most useful to a man in the field.

INTRODUCTION

The chief purpose of a radio-broadcasting antenna is to radiate the energy supplied by the transmitter efficiently. A simple antenna can do this job quite well. It is usually a vertical tower that radiates the energy equally in all directions along the ground.

A secondary purpose of the antenna system may be to concentrate the amount of radiation in the directions that it is wanted and to restrict the radiation in the directions it is not wanted. This may require a very complicated directional-antenna system if the requirements are great.

The antenna is the last point in the system under the control of the radio-broadcasting station. Radio waves radiated from the transmitting antenna are propagated through space to the receiving antenna. The only control over these propagated waves is in the selection of the antenna site, the polarizations, and the strength of the signals leaving the transmitting antenna. The selection of the antenna site is determined by many considerations, such as ground constants, terrain, distance and direction to populated areas to be served, distance and direction to the areas to be protected, and last but not least the availability of a suitable land area to install the necessary towers and ground system.

For standard broadcast stations, vertical polarization is used because of its superior ground-wave-propagation characteristics and the simplicity of antenna design. The strength of the signal from the transmitting antenna, in any given direction, depends upon the output power of the transmitter and the antenna design. Since the output power is regulated by the Federal Communications Commission for the class of stations involved, the only factors remaining under the engineer's control are the antenna location and design. These factors go hand in hand when designing directional antennas for broadcast purposes.

THE SINGLE-TOWER NONDIRECTIONAL ANTENNA

Current and Voltage Distribution

The vast majority of radio-broadcasting stations have single-tower antennas that are neither top-loaded nor sectionalized. Most of them have an insulator near the ground. Such towers all have a current distribution with a zero value at the top as shown in Fig. 3-1. The maximum value of current is 90° down from the top on a theoretical

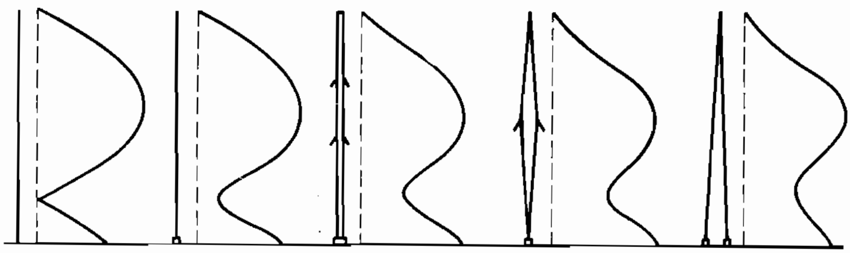


Fig. 3-1. Practical compared with theoretical current distribution on vertical radiator.

antenna, while on all practical antennas it is less than 90° down from the top. This is owing to the fact that the velocity of propagation slows down as the cross section of the tower is increased. For the average uniform-cross-section tower the current maximum is about 84° down from the top.[*,1]

The general shape of the current distribution on a tower is that of a sine wave given by

$$i_a = I_a \sin (G - y) \tag{3-1}$$

where i_a = current amplitude at distance y above the ground as shown in Fig. 3-2*a*, amp
I_a = maximum current amplitude, amp
G = height of antenna, deg
y = height of current element i_a, deg

For most purposes it is entirely satisfactory to consider the current distribution as an exact sine wave through this equation. This is practically true for a vertical wire as shown in Fig. 3-1*b*. It is also a good approximation for a uniform-cross-section tower as illustrated in Fig. 3-1*c*. For the diamond and tapered types as shown in Fig. 1*d* and *e*, the approximation may not be satisfactory.

* Superscript numbers refer to References on page 2-110.

The general shape of the voltage distribution is very nearly that of a cosine wave as shown in Fig. 3-2 for the theoretical case and is expressed by the equation

$$e_a = E_a \cos (G - y) \tag{3-2}$$

where e_a = voltage amplitude at distance y above the ground as shown in Fig. 3-2*b*, volts

E_a = maximum voltage amplitude, volts

and G and y are as defined in Eq. (3-1). If the tower is not tall enough for the current distribution to have a minimum below the top of the tower, then the maximum value of voltage will be at the top of the tower. It is necessary to visualize the shape of the

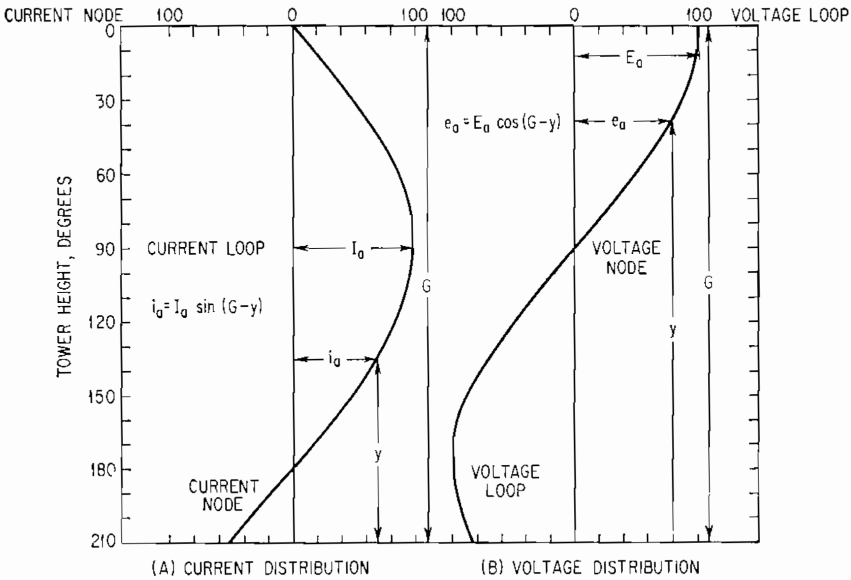


FIG. 3-2. Theoretical current and voltage distribution on a vertical radiator.

voltage distribution along the tower because of the need of good insulators at the high-voltage points. If sufficient insulation is not provided in the guy cables or at the tower base, the current may arc-over at these points and disrupt the broadcasting service. If the initial design has poor insulation, then redesign with adequate insulation should be considered.

Some towers are not insulated at the base. Such towers are shunt-fed at some point above the base. This type of tower is less expensive, has no dangerous base voltage, and is less vulnerable to lightning. The feed line can be used to some extent as the matching network to couple the transmitter or transmission line to the tower. The current distribution above the feed point is essentially the same as for a base-insulated tower.[1] The current below the feed point deviates materially from a sine wave as shown in Fig. 3-3. This is of little consequence in nondirectional operations. It cannot be tolerated in critical directional-antenna systems because of its effect on deep minima of the radiation pattern.

By proper design the coupling can consist of a slant feed cable with a series capacitor to couple into the transmission line. In general, as the height of the feed point on the tower is raised, the resistance and positive reactance increases. When the horizontal distance to the feed point from the tower base is increased, the resistance and positive reactance decreases. The exact position of the shunt feed line can best be determined by experiment.

The slant cable can consist of two parallel cables properly insulated and having the proper physical dimensions. Such an arrangement can be adjusted to couple directly into a transmission line.

Another method which eliminates the undesirable radiation effects of the slant line is to connect several cables to the tower one-quarter wave ($\lambda/4$) from the base and stretch them down to the ground with insulators at the lower end. These cables form a short-circuited one-quarter-wave ($\lambda/4$) transmission line which is open-circuited at the base, thus making it possible to feed the tower through these cables connected in parallel.

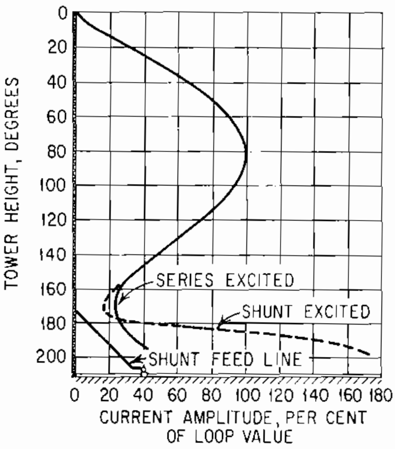


FIG. 3-3. Experimental current distribution on shunt- and series-fed tower. (*Morrison and Smith, Proc. IRE, June, 1937.*)

Sectionalized towers have been used for some time and have taken on added importance with the advent of FM and TV broadcasting. A sectionalized tower, in addition to the ordinary base insulator, has one or more insulators in the tower above the base. Very tall towers are often used to support FM and TV antennas in order to achieve the desired height above average terrain for maximum coverage of the FM or TV station. If this is the sole objective, the tower does not have to be sectionalized with insulators.

In some cases a tall tower is sectionalized for the purpose of preventing undesired reradiation when in the vicinity of AM towers, particularly if the other towers are elements of a directional-antenna array. In other cases it is desired to use part or all of the sectionalized tower as active AM radiating elements. This may not be so easy to accomplish as one would expect. Moreover, it requires considerable effort and planning to design the system properly. The Federal Communications Commission will require proof that the antenna system is operating properly, especially if the sectionalized tower is near or part of a directional-antenna array.

Sometimes a tall sectionalized tower is constructed for the purpose of obtaining greater AM broadcast coverage by properly controlling the current distribution on the tower.[2,3] When towers are sectionalized for this purpose, considerable attention is given to the current distributions on the various sections of the tower. This is necessary because the radiation from the current elements on each section must add properly to produce the greatest or optimum field-strength effects. It is well worthwhile to look seriously into these possibilities, even if the tower is to be used for FM and TV operations in addition to AM operation.

Vertical-radiation Characteristic

A nondirectional tower, whether series- or shunt-fed, sectionalized or nonsectionalized, top-loaded or without top loading, has its own vertical-radiation pattern sometimes called its vertical-radiation characteristic. This is simply the amount of signal radiated at all elevation angles above the horizontal plane with respect to the horizontal-plane radiation. Its calculation is usually made using the assumption of sinusoidal current distribution on the radiating portion of the tower.

The current distribution can be controlled by the height and shape of the tower. On a sectionalized tower the magnitude and phase of the current on the lower sections can be controlled with respect to the current on the top section. This permits such a tower to possess a family of vertical-radiation characteristics.[2,3]

The vertical-radiation characteristic of a vertical nonsectionalized, base-insulated tower is given by

$$f(\theta) = \frac{\cos(G \sin\theta) - \cos G}{(1 - \cos G)\sin\theta} \tag{3-3}$$

where $f(\theta)$ = vertical radiation characteristic
G = electrical height of antenna, deg
θ = elevation of observation point, deg

The derivation of Eq. (3-3) is given in Appendix A as a special case for a sectionalized tower when the top section is zero. The curves showing $f(\theta)$ as a function of height were published in several forms in the 4th edition of the "NAB Engineering Handbook."[4] The most useful form is reproduced in Appendix A.

Self-impedance

A radio tower has a different impedance at every point along its height. Two points are of special interest. One is at the current loop which is the current maximum approximately 90° down from the top of the tower if it is not top-loaded, and the other is at the point where the tower is fed at the base.

Much effort has been made in recent years to find a reliable means of calculating the base impedance of a tower. The average characteristic impedance, usually called Z_0 of the tower appears to play an important role in such calculations.[4]

Assuming a sinusoidal current distribution and the conservation of power between the loop and the base for a simple tower without top loading, the base and loop radiation resistances can be related by the simple equation

$$R_{\text{base}} = \frac{R_{\text{loop}}}{\sin^2 G} \tag{3-4}$$

where R_{base} = base radiation resistance, ohms
R_{loop} = loop radiation resistance, ohms
G = height of tower, deg

This equation for base resistance is quite reliable for antenna heights up to 120°. The loop and base radiation resistance along with the theoretical field strength, assuming a perfect ground, are shown in Appendix A.

It should be remembered that any set of calculations may not and usually will not agree with the actual values determined from measurement after the tower has been constructed. For this reason about the best that one can hope for is to make as intelligent an estimate as possible. The base impedance is affected by stray capacity and inductance effects and may be considerably different from the approximate theory when the tower is of the order of a half wave ($\lambda/2$) high.

The loop impedance of a single tower serves an important role by virtue of the fact that the calculated base impedance usually disagrees with the measured value and also because some towers are fed at or near the loop point. For example, a 90° tower fed at its base is also approximately fed at its loop; thus

$$Z_{\text{base}} = Z_{\text{loop}} = 36.6 + j21.3 \tag{3-5}$$

where Z_{base} = base impedance, ohms
Z_{loop} = loop impedance, ohms
$j = \sqrt{-1}$, making the second term an inductive reactance

This means that the antenna is series resonant, without reactance, when the height G is slightly less than 90°.

Ground System

A single AM tower is not complete without a ground system. To feed power into such a tower it is common practice to couple the output of the transmitter across the base insulator. The tower base forms one terminal, and the ground system forms the other terminal. Simple antenna theory assumes the ground plane to be a perfect conductor which acts like a mirror plane to the radio waves. In practice it is not a perfect conductor and may introduce a series-ground-loss resistance from a fraction of an ohm to several ohms.

A rather common rule of thumb is to use 2 ohms' loss resistance for the copper-wire ground system consisting of 120 radials 90° long. This ground-loss resistance can be

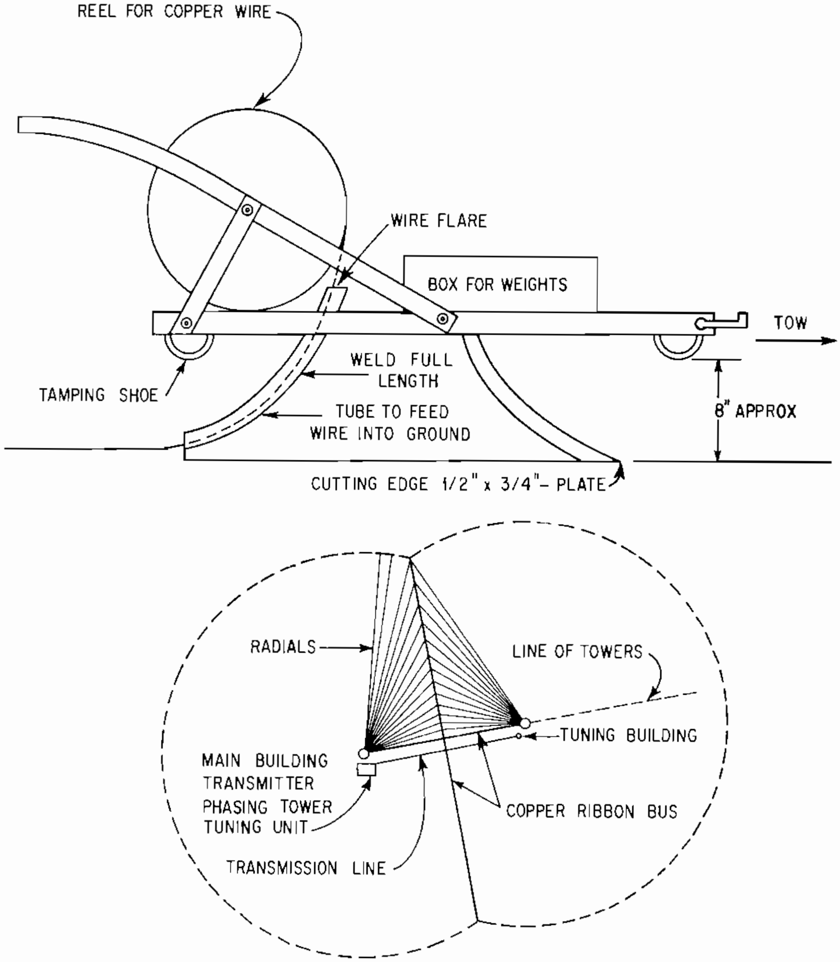


FIG. 3-4. Design of plow for laying ground wires and typical two-tower ground system.

decreased by reducing the E loss due to the electric field and the H loss due to the magnetic field.

When the tower is near a half wavelength in height, there is a voltage maximum at the base with a resulting strong electric field that results in high E losses owing to the displacement current passing from the antenna through the earth to the radial ground wires. This loss can be materially reduced by using an expanded copper screen around the antenna base or increasing the number of radial conductors and placing them very near the surface or under a layer of asphalt pavement which has very low loss for the electric displacement current.

The H loss due to the magnetic field extends out a considerable distance. This loss is due to the radial current which divides between the ground conductors and the earth. It can be decreased by increasing the number of conductors and extending their length. This will cause a larger portion of the current to be in the copper radials where the resistance is very low.

A typical ground system may consist of No. 10 copper wire buried 4 to 12 in. deep. Usually this area is made into meadow or grassland that is mowed often enough to prevent tall grass that may cause considerable E loss under certain conditions. If it is necessary to till the soil, the wires must be buried deep enough to avoid mechanical injury.

It is common practice to use a wire plow, as shown in Fig. 3-4, to lay the ground system. The wire plow consists of a thin vertical steel blade to cut a slit in the ground. At the rear edge of the blade there is a small tube through which the copper wire passes from a wire reel into the ground. The depth of the ground wire can be controlled by the adjustment of the vertical blade with respect to horizontal sled runners or wheels which support the plow mechanism. Soft- or medium-hard-drawn copper wire is easier to handle in the field than hard-drawn copper wire. It can also stand more mechanical stretching before breakage occurs.

The radial wires are usually plowed in, starting from the tower, and driving a tractor pulling the plow toward a guidepost at the edge of the ground system. It is convenient to provide a copper wire or cable ring around the tower base to which each radial ground wire can be mechanically fastened while the radial is being installed. The radial wires must then be soldered or brazed to this ring to provide a good electrical connection. Copper ribbon can then be bonded to the copper ring and run to the ground-system terminal of the antenna. Copper-clad stakes are commonly used to hold the copper ring in place and act as a lightning ground. These stakes are driven down level with the copper ring, and the two are brazed together to form a good electrical connection.

Expanded copper mesh is commonly used inside the copper tie ring or square. Its primary purpose is to terminate the E field. Its secondary job is to carry the radial ground-system current. However, if the amount of copper in the mesh is inadequate, then radial copper straps can be added in this area and bonded to the expanded copper mesh.

Tower Lighting and Painting

The Federal Communications Commission has rules for suitably lighting and painting radio towers so they can be seen from aircraft, thus minimizing their hazard. They are also marked on the aeronautical charts used by aircraft pilots. Part 17, Construction, Lighting and Marking of Antenna Structures, of the FCC Rules and Regulations covers this subject thoroughly.

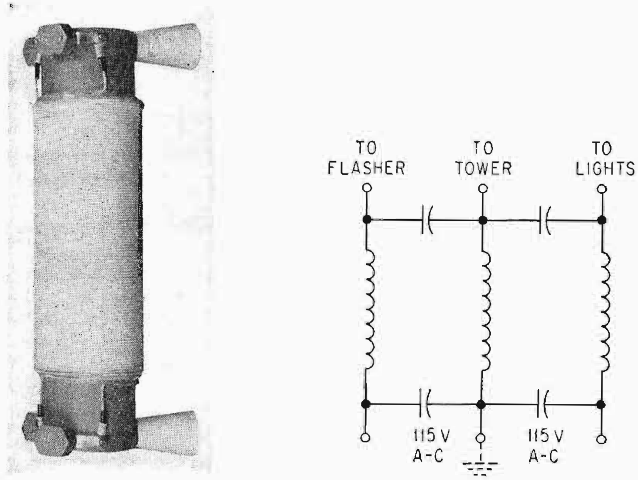
In brief, it is necessary to provide warning lights at the top and fractional elevation levels of the tower. For tall towers flasher beacons are required at the top and some intermediate levels. For base-insulated towers it is necessary to transfer the a-c power across the base insulator. This is commonly done by RF choke coils, Austin-type power transformers, or the use of quarter-wave ($\lambda/4$) isolating stubs.

Radio towers must be painted with alternate strips of international orange and white paint. The number and width of the strip are covered in the above regulations.

Lightning Protection

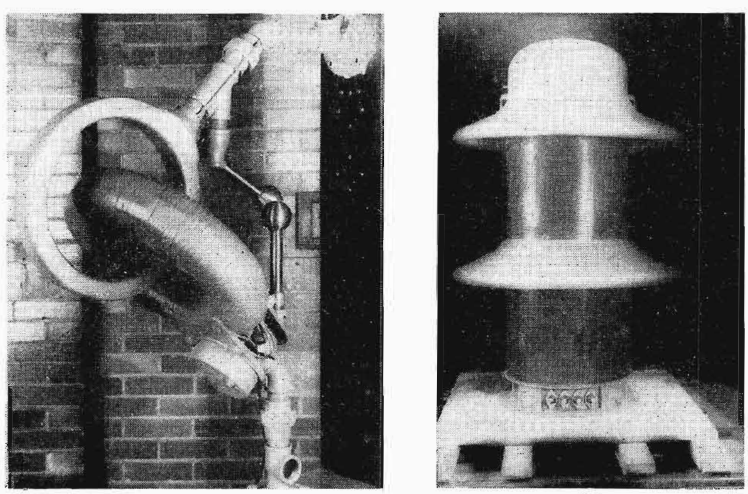
Radio towers are vulnerable to lightning; hence it is very important to provide the necessary protection. Lightning rods should be provided at the top of the tower to protect the flasher beacon. Choke coils, large values of resistance, oil-filled insulators, or isolation stubs should be used to drain the static charges across the sectionalizing and base insulators. Ball gaps or horn gaps should be placed across the insulators to carry the high current surges.

The ground system around the tower base should have nonfusible cable or conductor. It is good practice to terminate these cables in copper-clad ground rods not far from the tower base. In some cases the radial ground system itself may be adequate to handle the lightning surges.



(A) PHOTOGRAPH (B) WIRE DIAGRAM

FIG. 3-5. Antenna-lighting choke coil.



(*a*) (*b*)

FIG. 3-6. Austin-type transformers: (*a*) Air-insulated. (*b*) Oil-insulated.

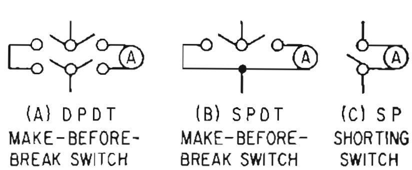


FIG. 3-7. Typical antenna meter switching circuits.

An important consideration is the protection of the base current antenna meter and the RF coupling equipment. It is good practice to provide a tower-grounding disconnection switch on the antenna side of the RF coupling equipment for the protection of technical personnel that must maintain it. During operation the antenna terminal of the RF coupling equipment should have a horn-gap path so lightning discharges can be bypassed directly to ground. The lightning paths should be as direct and short as possible to ground

With regard to the RF antenna meter the best practice is to connect it into the circuit with a double-pole-double-throw (DPDT), make-before-break switch, as shown in Fig. 3-7*a*. The meter can then be inserted or removed completely from the circuit during operation. When removed from the circuit, there is very little chance for lightning to injure it because there are no metallic connections to it. The meter is always removed from the circuit except when it is necessary to make a reading. It is sometimes necessary to adjust the length of the shorting loop so it will have the same inductance as the meter loop.

A less expensive and less desirable method is to use a single-pole-double-throw (SPDT), make-before-break switch as shown in Fig. 3-7*b*. The least expensive and least desirable method is to use a single-pole (SP) shorting switch as shown in Fig. 3-7*c*. The shorting switch shunts most of the current around the RF meter; however, a lightning surge may be sufficient to injure it.

It is difficult to predict what a lightning stroke will do, particularly if it is a direct hit on the tower. The stroke may jump to the transmission-line side of the coupling network; hence it is advisable to provide lightning-protection gaps at the tower end of the transmission line.

Adjustments

A transmission line can usually be coupled into a tower by the use of a series and shunt element. If the tower is in a directional-antenna array, then three tuning components are usually employed so the phase can also be controlled at this point.

Usually it is necessary to design and order the coupling network components before the tower and ground system are installed. In this case sufficient latitude must be allowed for variations of the inductive and capacitive components to match into the tower impedance from the transmitter or transmission line. If the tower and ground system are already installed, antenna input impedance measurements can be made at the operating frequency. It is therefore possible to determine, quite accurately, the value of the components required, but even in this case it is advisable to provide a reasonable tolerance for adjustment in the field.

The problem of coupling a transmission line to a sectionalized tower is usually much more involved. The sectionalized tower is, in effect, a collinear vertical directional-antenna system and therefore should be provided with both magnitude and phase control for each of the several elements. For this type of antenna it is usually desired to obtain the optimum vertical-radiation characteristic. If this is done, the results should be checked by field-strength measurements. In this type of antenna it is desirable to provide considerable latitude in variations of the adjustment components.[2,3]

The design information necessary for matching from the transmission line into the antenna is covered in Appendix B.

Inverse Field Strength at 1 Mile

The inverse field strength at 1 mile, sometimes referred to as the unattenuated field strength at 1 mile, is the field strength at 1 mile when the only attenuation is that of distance. It is a theoretical value and is considered primarily for comparison purposes. This concept removes the frequency and ground attenuation effects. Nondirectional- and directional-antenna patterns can be compared on this basis.

The vertical-radiation characteristic, for example, is merely a comparison of the inverse field strength at 1 mile at all elevation angles above the horizontal plane with the inverse field strength at 1 mile in the horizontal plane. When it is necessary to express the radiation from an antenna the value is usually given as the horizontal-plane inverse field strength at 1 mile. It can be expressed either with or without the inherent losses of the antenna system.

When submitting inverse-field-strength information to the Federal Communications Commission it is common practice to include the antenna-system losses. Nondirectional antennas produce but one such value, since the input power is determined by direct input-power measurements. In other words, the input power is determined by multiplying the measured input resistance by the square of the antenna current measured at the same point. In equation form,

$$P_a = I_a^2 R_a \tag{3-6}$$

where P_a = antenna power input, watts
I_a = antenna current, amp
R_a = antenna resistance, ohms

A nondirectional antenna theoretically produces only one value of inverse field strength at 1 mile, which is the same at all horizontal bearings from the antenna. Nondirectional-antenna patterns are graphically described by a circle, the radius of which is the inverse field strength at 1 mile. The pattern of a single-tower radiator is usually considered to be nondirectional. If the feeder is nonsymmetrical, such as in the case of a shunt-fed antenna, or if there are objects which reradiate in the vicinity of the tower, the horizontal pattern will not be circular or nondirectional but will have some directivity.

If the horizontal pattern is directional or nondirectional, its equivalent nondirectional effectiveness can be expressed as the root-mean-square (rms) inverse field strength at 1 mile, or simply its rms value. The rms value is the radius of a circle which has the same area as the pattern formed by all the inverse-field-strength values at 1 mile in all horizontal directions.

A directional-antenna pattern can be quite well described by plotting the inverse-field-strength values at 1 mile at intervals of 10° on polar graph paper. The rms value of the pattern can be obtained by taking the square root of the sum of the squares divided by the number of squared values, thus

$$E_0 = \sqrt{\frac{E_{10}{}^2 + E_{20}{}^2 + E_{30}{}^2 + \cdots + E_{360}{}^2}{36}} \tag{3-7}$$

where E_0 = rms field strength, mv/m
E_{10} = inverse field strength at azimuth angle of 10°, mv/m
E_{20} = inverse field strength at azimuth angle of 20°, mv/m, etc.

The rms value can also be obtained by using a polar planimeter to measure the area and determining the radius of the circle having the same area. This radius is the rms value of the pattern in the same units used to plot the directional pattern. It is common practice to measure the field strength and plot patterns in millivolts per meter, abbreviated mv/m.

The Federal Communications Commission does not normally require proof of performance measurements on single-tower nondirectional antennas. Therefore measured values of inverse field strength of nondirectional antennas are not in general available to the public at the reference room of the FCC, Washington, D.C. The description of existing towers of nondirectional radio stations is usually not complete except as to height and type. In most directional-antenna proof-of-performance reports it is required to show nondirectional measurements on a single tower in the array either before the other towers are erected or when the other towers are detuned so they will contribute a minimum of reradiation. This information is available at the reference room of the FCC.

Attenuated Field Strength

The attenuated field strength is the amount of signal left after it has been diminished by distance, ground conductivity, ground inductivity, and all other effects encountered by the signal between the antenna and the point of measurement. The field strength is also a function of the operating frequency and unattenuated field strength at 1 mile in the direction from the antenna toward the measuring point.

Only after a tower is constructed is it possible to determine the actual attenuated field strength at any point. Sometimes a test antenna and transmitter are installed at a proposed site to determine more precisely the coverage or interference to be expected. The attenuated field strength is determined by measurement with a field-strength meter properly calibrated and operated.

When the unattenuated rms field strength is needed to prove compliance with minimum requirements, it is necessary to make proof-of-performance measurements on a nondirectional antenna. This consists of a set of attenuated field strength measurements made on each of eight or more radials. The attenuated measurements are then used to determine the unattenuated field strength at 1 mile in the direction of each radial. The manner of taking measurements and the means of analysis are fully described in the Technical Standards of Part 3, Radio Broadcast Services, of the FCC Rules and Regulations.

TWO-TOWER DIRECTIONAL ANTENNA

Radiation-pattern Shape

One purpose of a directional antenna is that of producing a greater radiation in one or more directions than a nondirectional antenna would produce with the same power. Another purpose is to produce a small radiation in one or more directions. The latter consideration is more often required than the former because it is the rule rather than the exception that when a directional antenna is required, its radiation pattern must be so designed that it will not cause interference in any area, thereby depriving that area of one or more existing services. Or if this is not possible, the interference that is created must be limited to population that would feel the impact of losing service least. In other words if interference must be caused to some population, it is more desirable that it be caused to population that already has plenty of service rather than to population that has a meager amount of service or no service at all.

An existing radio station is faced with the same type of interference problem if it desires to change its directional-antenna pattern or if its directional antenna gets out of adjustment. A careful theoretical study of the two-tower directional antenna provides the owner and operator with a very useful tool for maintaining the correct operation.

The two-tower directional antenna, besides being the simplest of directional antennas, if often a basic unit of a three-tower or more array. It may be compared with a single tower in the following respects: The signals produced are but one signal as far as the receiver is concerned. Each tower produces a pattern having an rms value that must be above a specified minimum value according to the FCC rules. The current and voltage distributions on the towers in a directional-antenna array are usually assumed to be sinusoidal and cosinusoidal, respectively, just as they are on a nondirectional antenna. The vertical-radiation characteristic of each tower is defined in exactly the same way. The two-tower operation converges to a single-tower operation if the tower heights are equal, the phasing of the currents in the towers are the same, and the spacing of the two-tower array approaches zero.

This is as far as one can go in comparing the single- and two-tower operations. The two-tower operations are different in the following respects: The spacing of the towers in the two-tower array makes the instantaneous signal of one tower out of phase with the corresponding instantaneous signal for the other tower. This means that the towers can be spaced so that the signal can be made to add or subtract as desired. This, of course, cannot be done with a single tower. Also by means of phasing circuits it is possible to control the instantaneous signals from each of the towers in the two-tower array. Usually the phasing circuit is placed in only one of the tower circuits, since the object of interest is to control the phase of the current in one tower with respect to the phase of the current in the other tower. Furthermore, the magnitude of the current in one tower can be controlled with respect to the magnitude of the current in the other tower. This permits the control of minima depth in the directional antenna pattern. Thus, the spacing, phase, and current ratio controls available in the two-tower array are not available in the single tower, which must have a circular pattern.

To understand better the two-tower directional antenna, consider the following description. Let one tower, say tower 1, be the reference tower and fixed in location. Let the other tower 2 be free to move on a straight line, say due north from tower 1. Let us also by means of the phasing and coupling circuits maintain the same electrical phasing and current magnitude in the two towers. Let us further assume that a person P_n is due north of tower 1 and that another person P_s is due south of tower 1. Now, if tower 2 is gradually moved north, P_n will note that the signal from tower 1 is being received at the same time as before but that the signal from tower 2 is being received sooner. The person P_s will note that the signal from tower 1 is being received at the same time as before but that the signal from tower 2 is being received later. The person P_n might say that the signal from tower 2 leads the signal from tower 1, while the person P_s will say that the signal from tower 2 lags the signal from tower 1.

Actually the persons P_n and P_s can observe only the combination signal from towers 1 and 2. When tower 2 is moved 180° north of tower 1, the person P_n will note an absence of signal. This means that the signal from tower 2 leads the signal from tower 1 by 180°, and since the signals are the same magnitude, they cancel and produce a null effect. The person P_s will also note a null effect which is due to the signal from tower 2 lagging the signal from tower 1 by 180°.

Now, consider person P_e due east and person P_w due west from tower 1 and observing the resulting signal in these directions. They will both note at all times, regardless of the location of tower 2, that both signals arrive at the same time. Hence, the signals are always in phase and add completely. When the towers are spaced 180° and are in phase, it is therefore seen that the pattern has the shape of a figure eight with the lobes east and west and the nulls north and south. This case is illustrated in column 1 of Figs. B-3 and B-9.

One other pattern will be similarly described. Let all the above assumptions hold except that tower 2 is now always phased by means of the electrical phasing circuits to be 90° ahead of tower 1. Now when tower 2 is 90° north of tower 1, the person at P_n will note that the signal from tower 2 leads the signal from tower 1 by 180° and therefore complete cancellation occurs, with the result of a null. The person P_s will note that the signal from tower 2 is exactly in phase with the signal from tower 1 and therefore they completely add to form a lobe. The persons P_e and P_w will receive a signal 41 per cent greater than the individual signal from tower 1 or 2 because these signals are 90° out of phase. This pattern has the shape of a cardioid with the lobe to the south and the null to the north. This fact can be further explored by referring to column 3, Fig. B-3, or column 2, Fig. B-8.

The above two patterns just described serve to illustrate the effect of both spacing and phasing. From this it is seen that the pattern shape is affected both by the spacing and phasing. The above discussion pertains only to the pattern shape in the horizontal plane. For the more general case see Appendix B, Two-tower Directional Antennas.

Radiation-pattern Size

The Federal Communications Commission provides specific amounts of power for the various classes of radio-broadcasting stations. The rules permit the following amounts of power; 100, 250, 500, 1,000, 5,000, 10,000, 25,000, and 50,000 watts. It is therefore necessary to select the value of power to be used and make sure the individual towers will produce enough inverse field strength at 1 mile so the rms of the directional-antenna array will meet minimum radiation requirements of the rules. The pattern used for rms size consideration is the one in the horizontal plane. If the directional antenna is inefficient, the rms pattern may be too small. It is therefore important to be able to determine pattern size.

There are many factors involved in determining the pattern size of a directional-antenna array. The principal ones are phasing, spacing, and height of the towers and the ground-system resistance losses. The pattern size can first be determined assuming no loss in the directional-antenna system. This value is computed from a formula which is based on one tower operating alone, the self-resistance of both towers, the mutual impedance between the two towers, the current ratio, and the relative current phase. The total resistance losses of the directional-antenna system are commonly computed by assigning a series loss resistance to each tower.

The mutual impedance between two towers can be calculated from cumbersome formulas, or it can be found more quickly by graphical means. The mutual impedance between equal-height towers for various spacings is given in Fig. B-14. The mutual impedance is referred to the loop, or maximum current position. It is convenient to use the loop values for computation but necessary to use the base mutual-impedance values when tuning up a directional-antenna array.

The procedure for determining pattern size is to use the above factors in the formula, as given in Appendix B, page 2-118, to calculate the field strength of the reference tower when operating in the directional-antenna array. The field strength from the other tower can then be obtained by applying the field ratio that was used to determine the pattern shape in the horizontal plane. The use of these values of E_1 and E_2 in the horizontal-pattern formula results in the correct-sized pattern.

RMS Field Strength at 1 Mile

It is now possible to calculate the rms field strength of the directional-antenna pattern in the horizontal plane. The appropriate formula in Eq. (B-14) is easy to apply, and the results are accurate. Moreover, these calculations serve as an excellent check on the rms of the plotted pattern which can be measured by using a polar planimeter or Eq. (3-7).

Monitoring System

Practically all directional antennas have monitoring systems consisting of individual antenna current meters, a common-point input current meter, and a phase monitor to give the relative phase between the towers. Most directional antennas have antenna meters at each tower base and corresponding remote meters in the transmitter operating room. This makes it possible for the operator on duty to observe the operating conditions continually and make the necessary log entries.

Usually, when the directional antenna is installed, all the antenna meters are calibrated against a meter of known accuracy. Sometimes RF meters are injured in shipment or for some other reason will not give accurate readings. It is good practice to retain an accurate meter so the calibration of all the RF meters can be checked from time to time as needed. The antenna meters at the towers are read daily or weekly, and the remote meters checked for accuracy. Most remote meters are provided with an adjustment so their reading can be made to correspond exactly to the antenna meter.

The calibration of the phase monitor at the time of the antenna installation is as a rule adequate as long as the monitoring loops and phase-monitoring lines stay in good physical and electrical condition. It is important to have a phase-monitoring system that is more reliable than the directional-antenna system. If the phase readings vary from the licensed value and there is no noticeable change in the antenna current readings, it is advisable to question the phase monitor before making any readjustments on the directional-antenna system. In such cases the field strength at the monitoring points should be checked. If these readings are normal, the trouble is probably in the phase-monitor system.

Feeder System

All that is required for a single tower is to match the antenna to the transmission line, and in turn the transmission line must be matched to the transmitter. In most cases the transmitter will match directly into the transmission line, and if the tower is next to the transmitter building, a transmission line is not required. In some cases it is possible to excite the antenna directly from the transmitter output without a transmission line or coupling circuits.

In a directional-antenna feeder system, power-dividing and -phasing networks are required in addition to transmission lines and matching networks. A typical two-tower directional-antenna feeder system is shown in Fig. 3-8. At least one tower of a two-tower array must have its driving-point impedance transformed to match into a transmission line. The other tower, if not located close to the transmitter, must also be excited through a transmission line.

In a two-tower directional antenna it is necessary to have the required total phase shift from the common point at the transmitter output to each of the towers. The phase shift must be such that the phase of the tower currents meets the design requirements. When a phasing network is employed, it should operate over a favorable control range so the current in tower 2 with respect to the current in tower 1 can be adjusted and maintained at the proper value. In Fig. 3-8 the current ratio of tower 2 to tower 1 can be adjusted and maintained by the power-dividing network.

It should be pointed out that the phase- and power-division controls are usually not independent because of the mutual-impedance coupling effects between the towers. In other words a change in the phase control may have more effect on the current ratio

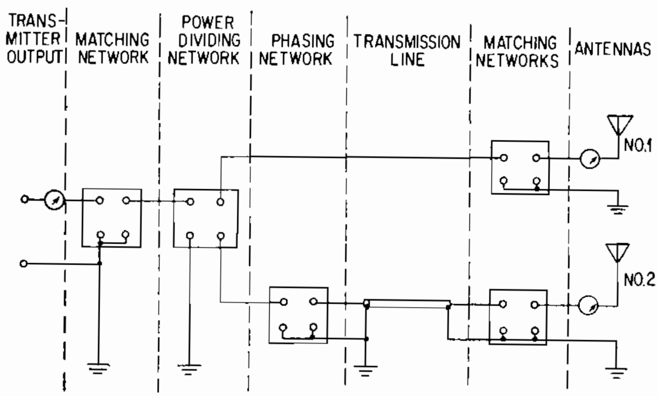


Fig. 3-8. Block diagram of a directional-antenna feeder system.

than on the phase-monitor reading. The person that must keep the directional-antenna system in adjustment should therefore operate the various controls and obtain a feel of how the system reacts. Before moving any controls, however, the settings should be noted and recorded so it is possible to return to the original operating condition. Here it is assumed that the feeder system is already operating properly. Only persons with the responsibility of operating and maintaining the directional-antenna system need to have this experience.

If the feeder system has been designed and the antenna system is to be tuned up, it is desirable first to determine the feed-point driving-point impedance values. This can be done by following the procedure in Appendix B. It is then necessary to set up the tower coupling networks so they will match into the driving-point impedances determined above. In addition they should have the correct value of phase so the phasing control will be near the center of its range for proper phase of tower 2 with respect to tower 1. The power-dividing network can then be set up to give the approximate division of power, and if there is a matching network between the transmitter and the power divider, it can be set up to give the proper impedance for the transmitter.

A small amount of RF power can now be fed in at the common point, and adjustments made to approximate the required current ratio and phasing between the two towers. If the driving-point impedances at the towers were computed correctly and the tower matching networks were set up properly, it should not be necessary to make any further adjustments at this point other than to add or subtract phase shift.

It should be observed that the driving-point impedances at the towers will not have their correct values until the feeder system is in final adjustment. Therefore, improper meter readings and standing waves on the transmission lines are to be expected until the final adjustment is approached.

When a directional-antenna array has been correctly adjusted, complete measurement data should be taken before it is turned over to the new user. These data should include not only RF bridge measurements of all components but similar static measurements at several points in the feeder system. These measurements should be made, for example, at the input to each tower impedance-matching network by opening up the transmission line and connecting the RF bridge at this point. Also record open- and short-circuit measurements of all transmission lines.

These measurements can be further supplemented by making dynamic RF voltage readings to ground at a number of points in the feeder system. Also RF current readings should be taken in all network branches.

Then in the event there is a departure from normal performance, the above static and dynamic measurements can be duplicated to assist in the restoration of the feeder system to normal service. This information is particularly helpful if a component becomes defective or is destroyed by lightning.

It is also good practice to make a record of all capacitor and inductor adjustments. It is advisable to mark all coil taps and capacitor settings with lacquer paint. Fingernail polish can be used for this purpose.

Particular attention should be given to make sure that the phase-monitoring system is in good condition and properly installed. If the phase-monitor lines are of equal length and some of the line must be coiled up, this should be done so that, as nearly as possible, equal lengths are outside the building and will therefore be equally affected by temperature variations. Otherwise, phase variations may occur owing to unequal temperatures of the phase-monitoring lines.

The feeder system should be inspected and cleaned regularly. It is advisable to use insectproof screens over any openings in the housing of feeder system networks. If pressure gauges are used on capacitors or coaxial transmission lines, they should be checked occasionally. These components may be injured if operated without pressure even though the gauge reading appears to be satisfactory.

In the day-to-day operation of a directional-antenna system it should not be necessary to move any controls or make any adjustments. Sometimes temperature and weather conditions will cause slight excursions of the phase and current ratio values. If the tolerance limits are exceeded, then the problem should be analyzed and appropriate corrective measures taken.

DIRECTIONAL ANTENNAS HAVING MORE THAN TWO TOWERS

Comparison with Two-tower Array

Many directional antennas consist of more than two towers because a two-tower array cannot produce the pattern shape required. It often happens that a two-tower pattern could be used, or it may even be that a nondirectional pattern could be employed if the pattern size were small. Such patterns may be ruled out by the owner because of prestige as to power statements and lack of good service over the urban and rural areas to be covered.

General Case

A general treatment of directional antennas of more than two towers can be limited to an explanation of one tower with respect to a reference point because all other towers are treated in exactly the same manner, since no specific information can be given to distinguish one tower from another. The only facts that need be known about a tower are that it has height, it is sectionalized or not, top-loaded or not, that it has a certain cross-sectional shape and size for each distance above the ground, and that it has a ground system of a specified efficiency. Most of these items have already been discussed.

The important considerations for a general tower in a directional-antenna system are its spacing, phasing, current, and height with respect to the other towers in the array. These four items define its contribution to the radiation characteristics of the array once its individual or single tower characteristics are defined. Hence this general treatment must conclude with an expression that describes the radiation of any tower of a multielement array. This expression is called a vector and is written

$$\dot{E}_k = E_k f_k(\theta) \underline{|S_k \cos \phi_k \cos \theta + \Psi_k} \tag{3-8}$$

where $\dot{E}_k$ = vector unattenuated inverse field strength at 1 mile for the kth tower while in operation, mv/m

E_k = magnitude of horizontal field strength of kth tower, mv/m

$f_k(\theta)$ = vertical-radiation characteristics of kth tower—always unity y along ground

$\underline{|}$ = vector angle terms are placed in this position. Vector magnitude terms are placed ahead of this angle sign

S_k = spacing of kth tower, deg

ϕ_k = azimuth angle measured clockwise from reference through kth tower, deg

θ = elevation angle from ground or horizontal plane, deg

Ψ_k = electrical phase of current in kth tower, deg

The subscript k was used in this equation to distinguish the radiated field strength of this tower from the other towers in the array. The sum of the vector fields from all the towers gives the total field strength in any direction from the array.

Dropping the subscripts in the above equation for simplicity, the product $Ef(\theta)$ is the magnitude of the vector and $S \cos \phi \cos \theta + \Psi$ is the phase of the vector. The only real value of this general treatment is the meaning it lends to the over-all theory. In fact its understanding is so vital that a clear concept of directional antennas must come from its meaning. As a matter of fact one can treat the whole matter of pattern shape from the vector concept directly without other mathematical complications. If this is done, it is, of course, necessary to know how to add, subtract, multiply, and divide vectors. On the other hand if the mechanism of vectors is not known, one is at a great disadvantage from the start in acquiring a thorough understanding of directional antennas. It is therefore recommended that at least the rudiments of vector analysis be learned by anyone desiring really to understand directional antennas.

Before leaving the general case attention is called to the fact that any directional antenna must be treated as a unit such that the whole operation is considered when any part of the antenna system is changed. For example, it is very important to know how a change in the magnitude or phase of each tower current affects the shape of the pattern, but at the same time it cannot be forgotten that the efficiency is also a factor that must be considered.

The perfect pattern shape and the most efficient operation are seldom attained at the same time. Theoretically this may be possible, but actually the number of towers may be limited or the coverage and protection requirements may have changed after the directional-antenna system was put into operation. Suffice it to say that it is the rule rather than the exception that one or more compromises are necessary before the final operation is attained, and it is best to understand the peculiarities of any particular array so that these compromises can be recognized and dealt with in the most intelligent manner.

Special Cases

Two-tower Pattern

The simplest equation for a two-tower pattern is

$$E = 2E_2 \cos \left(\frac{S_2}{2} \cos \phi + \frac{\Psi_2}{2} \right) \tag{3-9}$$

where E = inverse field strength at 1 mile, mv/m

E_2 = inverse field strength at 1 mile for each tower acting alone, mv/m

$S_2/2$ = spacing from a reference point midway between the two towers, deg

ϕ = azimuth angle measured clockwise from line of towers, deg

$\Psi_2/2$ = electrical time phase of tower 2 and the negative electrical time phase of tower 1, deg

This equation is for the horizontal plane only, and the terms are especially defined to make the equation simple. The tower heights and current values are assumed to be equal or such that $E_1 = E_2$ along the ground. The spacing S_2 is from tower 1 to tower 2, and the phase Ψ_2 is the phase of the current in tower 2 taken with respect to tower 1 (see Fig. 3-9).

Since a two-tower pattern is symmetrical with respect to the line of towers, it is necessary to compute the values for only one side of the line of towers, that is, ϕ from 0 to 180°, and these same values can be used on the other side of the line of towers. For example, cos 10° = cos 350°, and hence the value of E will be the same in these two directions.

The shape of the pattern is controlled by proper selection of spacing S_2 and phasing Ψ_2, while the pattern size is controlled by E_2. For null filling or to determine the radiation above the ground plane, it is necessary to use a more general formula.

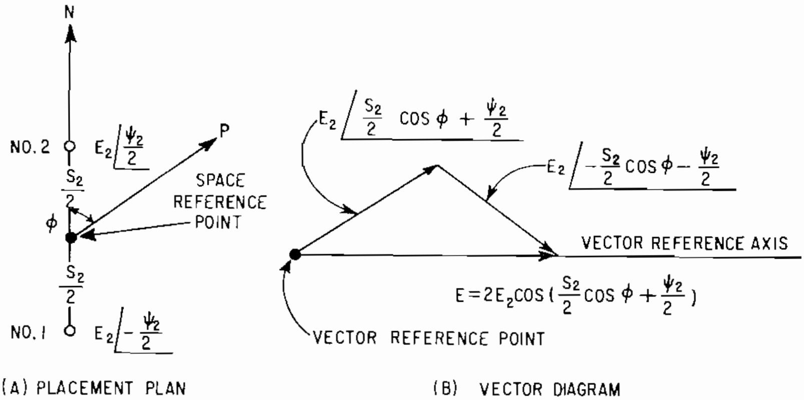


FIG. 3-9. Simple two-tower case.

Three Towers in Line

A three-tower array will be considered from the simultaneous points of view of theory and practical operation. Three towers are either in line or not in line. If they are in line, as in the case of all two-tower patterns, the three-tower pattern must be symmetrical about the line of towers. Consequently, the pattern shape needs to be computed only on one side of the line of towers.

The three towers may be equally spaced or not equally spaced. If vectors alone are used to analyze the operation, it makes little difference where the towers are located, especially if the current values are not chosen for mathematical simplicity. If simplicity is desired, as it often is, the tower spacings should be made equal. This is covered more thoroughly in Appendix C, Fig. C-1.

To relate theory and practice consider an array of three towers in line. The field strength produced by each tower can be represented by a vector at any point in space. The sum of the three vectors at the point is the total field strength produced by the entire array. This sum, or resultant field strength, is itself a vector and can be determined mathematically when all the parameters of the three-tower array are known. The size, or magnitude, of the resultant vector is the all-important part of the resultant field strength as far as the radio receiver is concerned. This is because the receiver does not detect the phase angle; it simply responds to the magnitude of the resultant vector and detects the information on it. The magnitude of the resultant vector at the receiver depends upon the magnitude and phase of the current on each of the three towers, which amounts to a total of six parameters.

The observation that there are six parameters in a three-tower array, which can vary independently of one another, makes it clear that it is necessary to understand which ones are being changed when the array is being adjusted. Otherwise, the possibility of making the wrong adjustment is very great. On the other hand when a desired correction is made by changing the appropriate parameter, the result cannot be wrong. This view is somewhat optimistic because theory does not hold exactly in practice where actual conditions involve the necessity of making compromises. For example, it is not difficult to change a parameter to get a certain field strength at a given point but in so doing the field strength may be adversely affected elsewhere.

An understanding of the directional antenna is quite easily acquired through vector analysis, but in actual field practice it is almost always more efficient to convert the vectors to an ordinary algebraic expression of the field strength at 1 mile. When this is done, the theoretical effects of a change in any one parameter can be quickly determined. The algebraic equations for a three-tower-in-line array are given in Appendix C, Fig. C-3.

Three Towers Not in Line

The above treatment of three towers in a straight line should and did receive first consideration because of the number of such directional-antenna arrays in existence. Three towers not in line, sometimes referred to as a dog-leg array, deserves serious consideration because of the number of such arrays that are in existence and because such three-tower patterns naturally fit the predominately unsymmetrical requirements.

There are a number of ways to select the reference point and the reference line in the three-tower array. Only one will be treated here for the sake of clarity and briefness. It is believed to have more significance than other choices because it can be related to the two-tower treatment already covered and to the four-tower paralellogram array.

Further discussion of three towers not in line follows the treatment of the four-tower parallelogram array; hence it is treated as a corollary in Appendix C, Fig. C-4.

Four-tower Parallelogram

Many directional-antenna systems have four towers located at the corners of a parallelogram. The chief reason for the popularity of this type of array is the ease with which the pattern shape can be designed to meet complicated requirements. The design procedure is straightforward, and the computations are relatively easy. Because of these advantages it is surmised that some four-tower arrays have been designed and constructed where three-tower arrays would do the job. This does not necessarily imply that the three-tower array would do a better job. The four-tower array may have better stability in operation and make it possible to modify the pattern without change in tower location, and the efficiency may be better.

When the multiplication form of the four-tower array is used, it can be designed piecemeal by first selecting one two-tower design that will provide the necessary protection in two directions. Then another two-tower array can be selected to protect in two other directions. If the parallelogram design is used, these patterns can be multiplied together and achieve the necessary protection in all four specified directions. The design details are given in Appendix C, Fig. C-2.

Arrays of More than Four Towers

It is not believed advisable to go further into the discussion of special cases where more than four towers are involved. If an owner or operator of a multielement array desires to adjust or understand a specific directional-antenna system, it is anticipated that he will take one of two courses: employ a competent consultant to do the work or become sufficiently proficient himself to do the job.

Suffice it to say here that in general the adding of more towers in an array permits protection in more directions or greater protection over wider angles and may in some cases be used to increase the field strength in some directions. The more complicated arrays are usually made up of combinations of two-tower units, and in some cases three-tower units are used. For example, an eight-tower array may be made up of four two-tower units, or a nine-tower array may be made up of three three-tower units.

GENERAL CONDITIONS AND PLANT LAYOUT

The entire plant should be considered from a number of points of view prior to detail study if an existing broadcast station is in need of adjustments or if the broadcast plant is to be built from its beginning.

The location of the transmitter building with respect to the towers is important from the standpoint of access to the transmitter from the road, and if the common point of the directional-antenna system is in the transmitter building, the building should be close to the towers to minimize RF transmission-line losses. If the transmitter building must be located some distance from the towers, it is advisable to feed the RF power over a transmission line to a common point located so that the RF lines from this point to the towers will have a minimum of loss.

The ground-system design for a new directional-antenna array should be laid out such that the copper will be used to best advantage to minimize E and H losses. This does not necessarily mean that a radial system under each tower is the best layout. A study of the H field or ground-current direction at a number of points will help decide how the copper wire should be placed. If the ground system has been installed for some time, it may have deteriorated somewhat. In such cases it is advisable to check for corrosion and mechanical failure of the conductors. The extent of the ground system should be checked against the original construction permit for completeness.

The transmission line, if above the ground, should have a ground strap buried in the ground below it, and this strap should be tied into the ground conductor system. This buried ground strap should be bonded to the ground side of the transmission line at regular intervals.

A general survey of the feeder system in an existing plant will involve not only the location of the matching, phasing, and power-division networks but obtaining information concerning possible inefficiencies and inconveniences in operating arrangements and adjustment controls.

The phase monitor should be the most reliable indicator of the current of the various towers. If this is not the case, steps should be taken to improve its operation. The location of remote indicating meters should be checked along with their calibration against the antenna ammeters. If any question exists about the current magnitudes, then all the antenna and common-point meters should be calibrated against a meter of known accuracy.

It is good practice to become familiar with the procedure for warming up the transmitter, including starting and stopping operations. This will protect the equipment. Safety precautions, especially when high power is involved, should be obeyed rigorously. It is much better to spend a little more time than to have someone injured or killed.

All tuning controls, including variable capacitors and inductors, should be noted. All taps and settings should be recorded. A complete set of meter and phase-monitor readings should be recorded before any adjustments are made on an existing system.

The tower lighting, tower insulation, lighting-control circuits, or the phase-monitoring system may require preliminary alterations before tower-impedance or common-point-impedance measurements are made.

The number of transmitters available for regular, auxiliary, or emergency operation should be inspected with regard to switching circuits and studied with regard to the possibility of improvements in convenience and efficiency.

REQUIRED PREADJUSTMENT INFORMATION

Preliminary Computations

Base Driving-point Impedance

The loop impedance values can be computed or estimated, and from this information the base driving-point impedances of all towers can be estimated as outlined in Appendix B.

Base Driving-point Currents

Knowing the power and driving-point impedances it is possible to estimate the base driving-point currents. Consideration should be given to the conservation of power principle between the loop and base values as discussed in Appendix B.

Characteristic Impedance of Transmission Lines

In a new or old system it is good practice to measure the characteristic impedance of all transmission lines. This can sometimes be done by measuring the open- and short-circuit impedances and determining the characteristic impedance from the equation

$$Z_0 = \sqrt{Z_{oc}Z_{sc}} \tag{3-10}$$

where Z_0 = characteristic impedance, ohms
Z_{oc} = open-circuit impedance, ohms
Z_{sc} = short-circuit impedance, ohms

These values may all contain resistance terms when measured with an RF bridge. When the transmission line is near 90° in length, this method gives very good results. However, when the line is near 180° in length, the open-circuit values will be very large and the short-circuit values will be very small, with the result that Z_0 from the above equation may not be very accurate.

Another method, quite good and acceptable in practice, is to use a decade resistance box at one end of the line and measure the impedance looking in at the other end of the line. Then plot the decade box resistance along the x axis of graph paper and the measured RF bridge input impedance magnitude along the y axis. Where this curve intersects a 45° diagonal line in the first quadrant is located the characteristic impedance magnitude.

This method works quite well for any length of line. Of course, as the line becomes very long, the variation of resistance at the far end will have less and less effect, because if the line is of infinite length, the input impedance will look like the characteristic impedance regardless of the value of load resistance.

This method can be refined in accuracy by first measuring with the RF bridge the values of the decade box resistance. Usually decade resistance boxes have an inductive reactance component that may vary with resistance-value settings. In such cases it may be desirable to parallel the decade resistance box with a small variable capacitor that is adjusted to make the load terminals of the decade box look like a pure resistance. With such refinements it is usually possible to obtain very good results in the field.

Matching Networks

With the above information at hand the transmission line to tower matching networks can be adjusted to transfer the transmission-line-impedance to the driving-point-impedance value. An L section is usually adequate unless the design requires a different amount of phase shift.

The system should be designed for the least amount of phase shift possible consistent with good operating practice because in this way the system efficiency can be maximized.

If it is not convenient to set up dummy driving-point impedances and measure the network from the transmission-line end, then a resistor equal to the characteristic impedance of the transmission line can be connected across the line side of the matching network. The network can then be adjusted until the RF bridge looking in at the tower terminals sees the conjugate value of the driving-point impedance. This means that when the network is connected at this point in a normal fashion, the reactance of the driving-point impedance will be resonated with the reactance of its conjugate value. The resistance of the conjugate impedance is equal to the resistance of the driving-point impedance. Hence the condition for maximum power transfer is achieved.

Probably the only other matching network will be between the power divider and the transmitter. This is the last network to be adjusted. It may be either before or after the common point where the power input to the directional antenna is measured. Usually it is after the common point in order that the common-point input will be a pure resistance at the operating frequency. The loss in this network is then charged against the directional-antenna system, since it is beyond the common point of power measurement.

Phase-shifting Networks

Usually the phase-shifting networks are designed to operate into the characteristic impedance of the transmission line. Hence, they can be connected directly and maintain an impedance match. It is rather common practice to place the phase-shifting networks in the lines that handle the least amount of RF power, thus minimizing the RF power loss of the feeder system. The transmission line or tower that takes the most power can be run directly to the power-dividing network.

It is usually easier to vary the phase by ganging the rollers of coils rather than using variable capacitors. For this condition a T section would be chosen for a $90° \pm 10°$ phase-retarding network and a π section would be chosen for a $90° \pm 10°$ phase-advancing network as shown in Appendix B, Fig. B-26.

If it is necessary to vary a capacity element, it is sometimes more convenient to place a small fixed capacitor in series with a variable coil so that the series combination will have the correct value at the operating frequency. If the filtering or harmonic properties also have to be considered, this combination may not be satisfactory.

It is important to make sure that the rotating wiping contacts on the phase shifters are in good mechanical condition to wipe smoothly and make good electrical contact continuously. The contacts should feel nearly as cool as the other parts after the equipment has been in operation; otherwise there is too much resistance at the contacts.

Power-dividing Networks

The power-dividing network usually accepts power from the transmitter output and feeds the proper amounts into transmission lines and phase-shifting networks. For maximum efficiency it is good practice to feed the largest amount of power directly into the transmission line, thus avoiding the power loss in the phase-shifting network.

If power-handling dummy driving-point-impedance loads are used the power divider can be adjusted approximately before connecting to the towers. If this procedure is followed, the approximate value of phase can be inserted if the phase sampling is done at the input to the dummy loads. For L sections in parallel the resistance input to the individual L sections must have the value of resistance needed to absorb the correct ratio of the total power delivered from the common point.

For example, in a two-tower array, the L section resistance inputs can be written

$$R_1 = \frac{V^2}{P_1} \tag{3-11}$$

$$R_2 = \frac{V^2}{P_2} \tag{3-12}$$

where R_1 = resistance into L section leading to tower 1, ohms
R_2 = resistance into L section leading to tower 2, ohms
V = voltage between common point and ground, volts
P_1 = power to tower 1, watts
P_2 = power to tower 2, watts

The common-point resistance can be written

$$R = \frac{R_1 R_2}{R_1 + R_2} \tag{3-13}$$

where R is the common-point resistance in ohms

Component Ratings

The current through and the voltage across each component in the feeder system should be computed to determine the required rating. This information provides a means of choosing the most economically sized component in a new installation. These computations will show up components in an existing system which are underrated and should be changed.

The current rating of capacitors are given by the manufacturer and should not be exceeded during operation for the most adverse temperature and poor adjustment conditions. The voltage ratings are also given by the manufacturer and should be high enough to comply with any surges that may arise, including lightning. The lightning-protection devices should be good enough to allow for reasonable economy in deciding the maximum voltage rating.

The current and voltage rating of coils are related to the voltage gradient between turns of the coil. The distance between conductor centers in adjacent turns should be roughly twice the diameter of the conductor, and the conductor diameter must comply with good engineering standards as to coil losses.

Coarse Adjustments

Meter Calibrations

All meters should be checked for accuracy against meters which are of known accuracy. Calibration charts should be made up for meters that do not register correctly. The current-sampling system on each tower should be checked for accuracy.

Phase-monitor System

The phase monitor should be checked for accuracy. The tower-sampling loops can be placed in parallel and checked for zero phase when the same field is sampled. If tower input currents are sampled, the same current can be sampled by two sampling units to check for accuracy.

Another method is to establish a null off the end of two towers and read the phase which is known quite accurately by theory for this condition. This can be done by setting up a field strength set at some distance and walk the two-tower phase and power-division controls to give a deep null. This also gives an excellent check on unity field-strength ratio. It is helpful to have two-way communication to expedite these measurements.

Common-point Impedance

After the array is approximately adjusted, it is advisable to measure the common-point input impedance. It may be desired at this time to make input matching network adjustments so a pure resistance load will be presented to the transmitter at the operating frequency.

After final adjustment of the array the common-point input impedance must be measured across a band of frequencies to meet FCC requirements and check on characteristics that may cause objectionable distortion. It is desirable to have a relatively constant value of resistance over the modulation-frequency range.

Low-power Operation

After the common-point impedance has been adjusted properly, low power can be fed into the system and all meters checked for predicted readings. If errors have been made in the computations, the adjustment will probably be incorrect.

Field-strength Check

After the array is in reasonable adjustment, it is timely to check the field strength. Usually a nondirectional proof is made by running at least eight radials to determine the rms value and the attenuation in the various directions and establish suitable monitoring points in critical directions.

These measurements will probably indicate what changes are necessary to meet the requirements in the construction permit. Any change in adjustment should be followed by appropriate field-strength measurements properly logged so that further adjustments are always in the correct direction.

As the desired pattern is approached and the feeder system comes into proper adjustment, the full input power can be used.

Fine Adjustments

These adjustments are simply a continuation of the tuning to arrive at the final values. More exact and extensive information is gathered with regard to how the controls affect the field-strength measurements, particularly along radials in the direction of the various minima.

The final adjustment of the array is decided upon after enough information is gathered to show what adjustment of the array gives the desired over-all results. The final adjustment may involve compromises in optimum field strength between the various minima and critical bearings concerned with protection.

During this phase the monitoring points are usually selected. The value of monitoring-point readings should be recorded along with the other meter readings of the system.

When the final pattern adjustments have been made, careful attention is given to establishing the exact power at the common point. The resistance and reactance vs. frequency measurements are then run for the common point.

Final Operating Adjustment

With the antenna system operating properly, all meter readings are recorded and maintained while the field-strength measurements are made to prove the shape and size of the horizontal pattern.

The monitoring points have to be photographed in order to provide a reliable means of finding their exact location in the future. The field strength at the monitoring points should be checked at least daily while making the proof of performance field-strength measurements.

The field-strength radial measurements are plotted on FCC logarithmic paper and analyzed to determine the unattenuated field strength at 1 mile. These values are then plotted on polar coordinate paper, and a planimeter can then be used to determine the rms value. This should agree closely with the predicted value.

If only a skeleton or partial proof is required, sufficient directional measurements must be made at points used in the original proof to show by means of ratios between the two measurements at each location that the pattern is basically unchanged. If the average of the ratios for each radial, usually about 5, is between 0.8 and 1.2, it is considered that the pattern is unchanged. If the average deviates outside this range on two or more radials, the array probably needs further adjustment.

MULTIPURPOSE ANTENNA SYSTEMS

Two-pattern Arrays

Many directional-antenna systems have a different day and night pattern. Usually the nighttime pattern requires deeper minima and in many cases different locations of the towers or more towers in the array.

In the layout and design of such a system the problem should be carefully analyzed and the simplest layout used consistent with good engineering practice. Many times the same matching networks can be used with a day-night transfer relay to change coil turns and capacity values as required for the two conditions of operation.

It is good practice to provide pilot-light circuits to indicate when all RF relays are in their correct positions. If power is applied to a system with the relays not in proper positions, some components may be injured and the transmitter may not be working into a matched load.

Two Transmitters Using Same Towers

There are a number of cases where an antenna system is used by more than one station. If, for example, two radio transmitters use the same towers, it is necessary to add RF filter circuits so energy will not be fed from the output of one transmitter back to the output of the other transmitter and produce cross-modulation products. If this happens, the program of the other radio station will be heard in the background.

In the feeder-system design for two transmitters using the same towers it is usually possible to design the networks such that the T, π, or L sections perform the necessary filtering action in addition to the required impedance transformation and phase-shift functions.

The metering circuits must also be filtered so they will not respond to the undesired frequency. If a meter has two RF currents of different frequencies, it will give an rms response providing it is not frequency-sensitive.

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APPENDIX A. SINGLE-TOWER ANTENNAS

Theoretical Vertical-radiation Characteristics

Formulas

Sectionalized Top-loaded Tower. The current distribution on the bottom section of the tower as shown in Fig. A-1 is given by

$$i_a = I_a \sin (G - y) \tag{A-1}$$

The current distribution on the top section is given by

$$i_c = I_c \sin (H - y) \tag{A-2}$$

At the insulator height $y = A$, $I_c = i_a$, $G - A = B$, and

$$I_c \sin (H - A) = I_a \sin B \tag{A-3}$$

or

$$I_c = \frac{\sin B}{\sin (H - A)} I_a \tag{A-4}$$

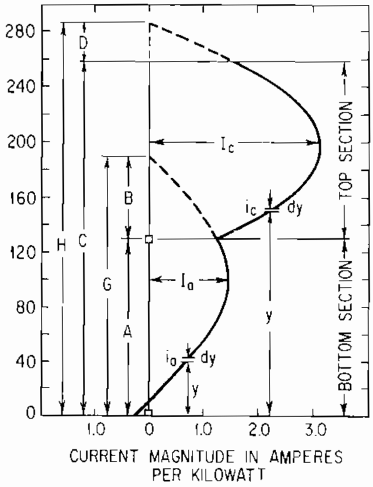


FIG. A-1. Theoretical current distribution on a top-loaded sectionalized tower.

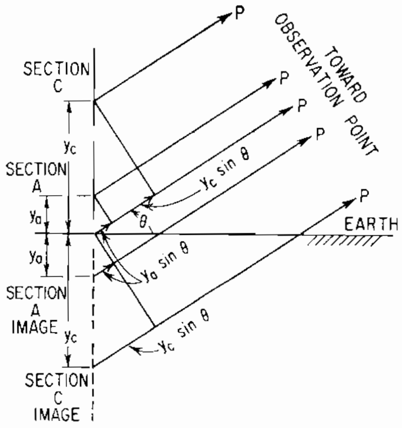


FIG. A-2. Geometry to determine field from sectionalized tower with images.

The inverse field or unattenuated field strength toward 1 mile at the observation point P at an elevation angle θ produced by a vertical element dy at the base of the antenna would be $dy \cos \theta$. The field from any other similar element of the antenna or its image would have a phase different from zero as depicted in Fig. A-2. The addition of these vector fields from an element and its image on sections A and C is shown in Fig. A-3*a* and *b*, respectively. It is noted that the sine components cancel. The total field at the point P is, therefore,

$$E_\theta = K2I_a \cos \theta \left[\int_0^A i_a \cos (y \sin \theta)\, dy + \int_A^C i_c \cos (y \sin \theta)\, dy \right] \tag{A-5}$$

where K is a constant such that E_θ will be in the units desired. K cancels out in $f(\theta)$. Substituting from Eqs. (A-1), (A-2) and (A-4), performing the indicated integration, and dividing the result by itself when $\theta = 0$ give

$$f(\theta) = \frac{\cos B \cos (A \sin \theta) - \cos G + \dfrac{\sin B \cos (H - C) \cos (C \sin \theta)}{\sin (H - A)} - \dfrac{\sin B \sin \theta \sin (H - C) \sin (C \sin \theta)}{\sin (H - A)} - \dfrac{\sin B \cos (H - A) \cos (A \sin \theta)}{\sin (H - A)}}{\cos \theta \{\cos B - \cos G + [\sin B / \sin (H - A)](\cos \overline{H - C} - \cos \overline{H - A})\}} \tag{A-6}$$

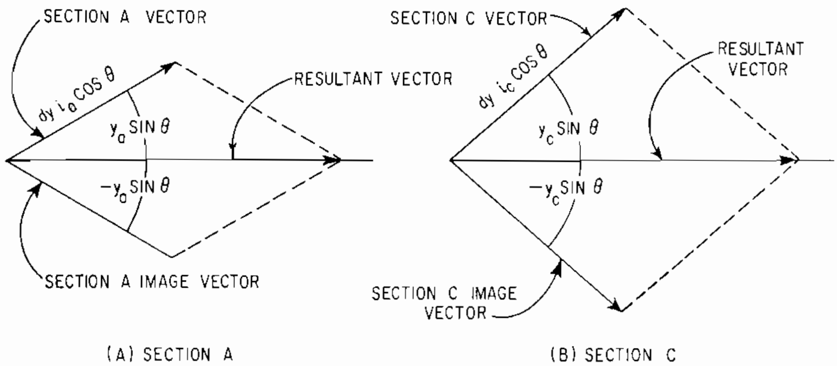


FIG. A-3. Vector diagrams of field strength at point *P*.

This is the vertical-radiation-characteristic equation for a two-section sectionalized tower. The same procedure can be applied if more than two sections are involved.

Top-loaded Tower. Referring to Fig. A-1 it is noted that the sectionalized antenna can be reduced to a nonsectionalized top-loaded antenna by making the top section of zero length but at the same time arranging for top loading such that B is unchanged. This can be done by letting $C = A$ and $H = C$ in Eq. (A-6), which then reduces to

$$f(\theta) = \frac{\cos B \cos (A \cos \theta) - \cos G - \sin B \sin \theta \sin (A \sin \theta)}{\cos \theta (\cos B - \cos G)} \tag{A-7}$$

This is the vertical-radiation characteristic for a top-loaded tower of height A and top-loaded to a height of $C = A + B$.

Ordinary Vertical Tower. The ordinary tower without top loading can be obtained from Eq. (A-6) by letting $C = A$, $H = C$, and $B = 0$ or in Eq. (A-7) by letting $A = G$ and $B = 0$ to obtain

$$f(\theta) = \frac{\cos (G \sin \theta) - \cos G}{\cos \theta (1 - \cos G)} \tag{A-8}$$

This is the same as Eq. (3-3) in the text. Table A-1 gives values of $f(\theta)$ for a useful range of tower heights, and Fig. A-4 gives this information in graphical form.

Theoretical Self-impedance and Radiation

It is useful to know the theoretical loop and base resistance of a vertical radiator. This information is presented graphically in Fig. A-5 along with the theoretical inverse field strength at 1 mile.

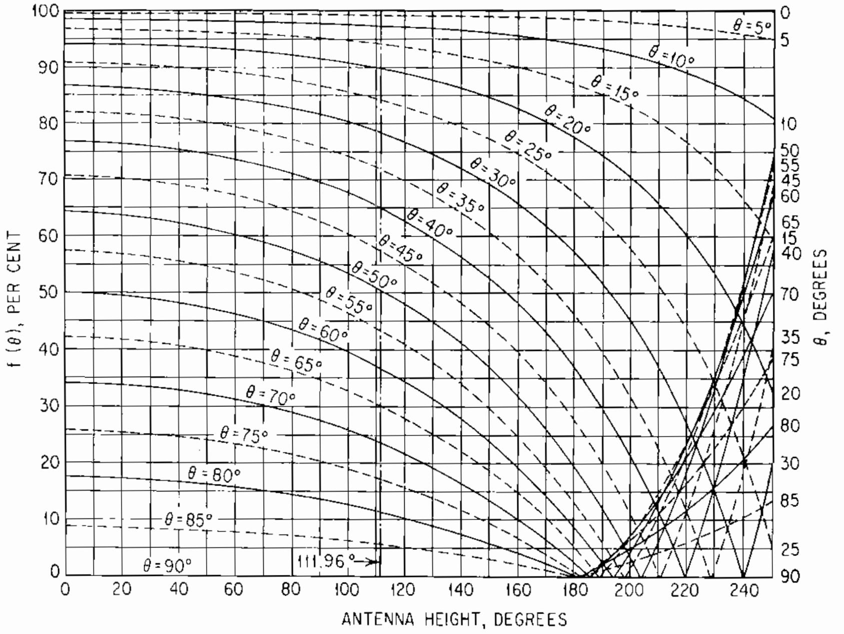


FIG. A-4. Vertical-radiation characteristic as a function of electrical tower height for various values of elevation angle.

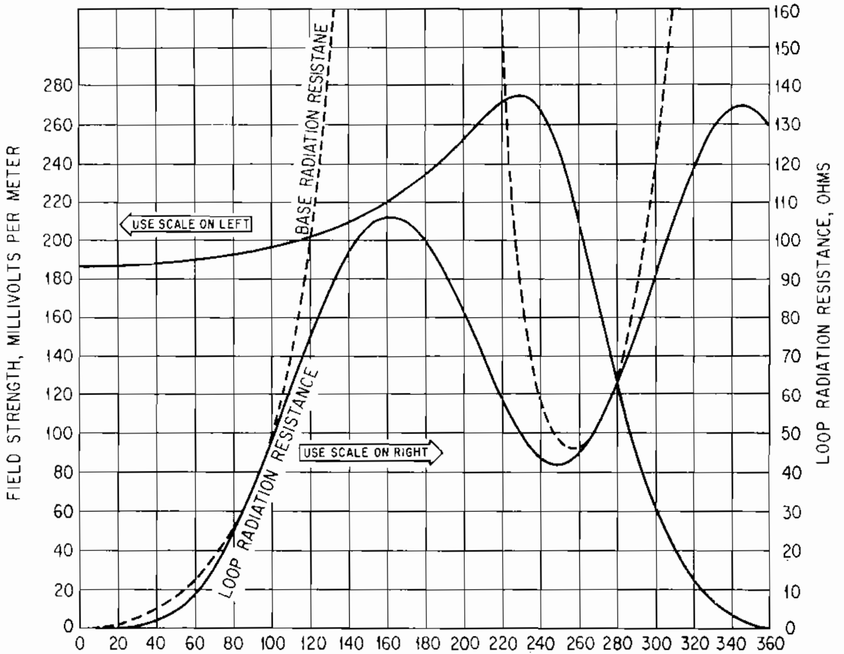
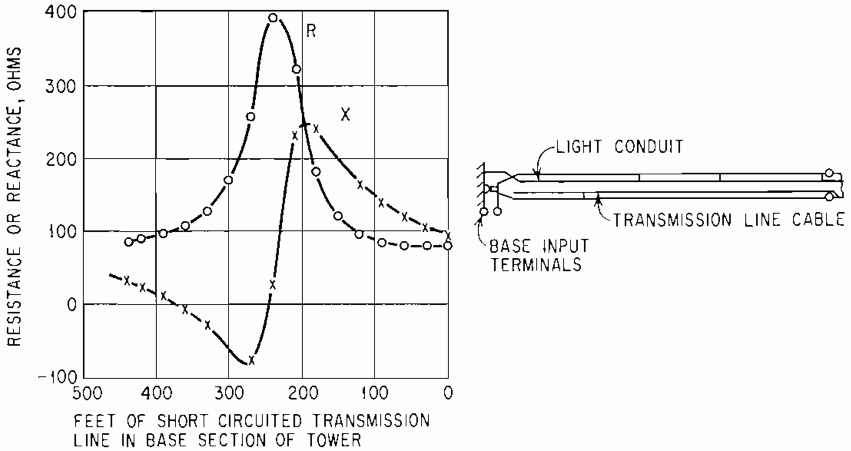
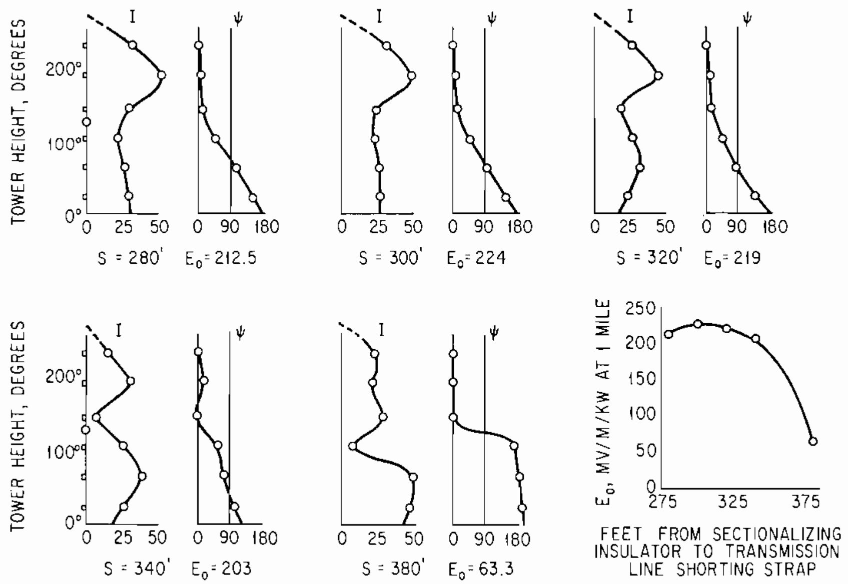


FIG. A-5. Inverse field strength at 1 mile for 1 kw, loop and base radiation resistance as a function of tower height over a perfectly conducting earth.



(A)- BASE IMPEDANCE OF 258° TOWER AS A FUNCTION OF LOADING REACTANCE ACROSS SECTIONALIZING INSULATOR



(B)- CURRENT AND PHASE DISTRIBUTION ON 258° TOWER AS FUNCTION OF LOADING REACTANCE ACROSS SECTIONALIZING INSULATOR IN TERMS OF SHORTED TRANSMISSION LINE LENGTHS

Fig. A-6. Performance of sectionalized tower with top section excited through reactance element from bottom section.

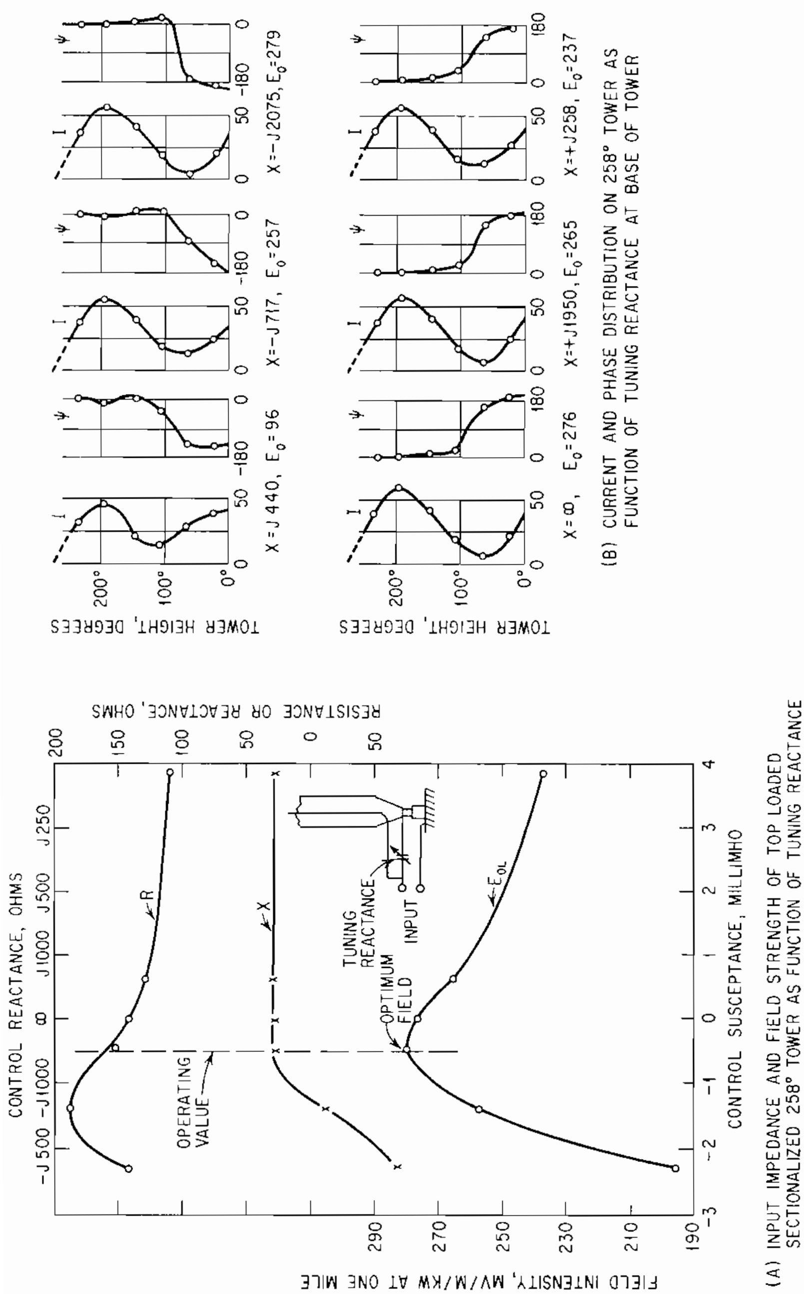


Fig. A-7. Performance of sectionalized tower with top and bottom sections excited independently.

Table A-1. Vertical-radiation Characteristic $f(\theta)$

$\theta°$	Tower height, $G°$								
	0	5	10	15	20	25	30	35	40
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5	0.9962	0.9962	0.9962	0.9961	0.9961	0.9961	0.9960	0.9960	0.9959
10	0.9848	0.9848	0.9847	0.9846	0.9845	0.9843	0.9841	0.9839	0.9836
15	0.9659	0.9659	0.9657	0.9655	0.9653	0.9649	0.9644	0.9639	0.9632
20	0.9397	0.9394	0.9393	0.9390	0.9386	0.9379	0.9372	0.9362	0.9351
25	0.9063	0.9062	0.9058	0.9054	0.9047	0.9037	0.9026	0.9012	0.8996
30	0.8660	0.8658	0.8654	0.8648	0.8638	0.8626	0.8610	0.8592	0.8571
35	0.8192	0.8188	0.8186	0.8176	0.8164	0.8148	0.8129	0.8106	0.8080
40	0.7660	0.7658	0.7653	0.7642	0.7628	0.7610	0.7587	0.7561	0.7530
45	0.7071	0.7069	0.7062	0.7051	0.7035	0.7014	0.6989	0.6960	0.6925
50	0.6428	0.6423	0.6418	0.6406	0.6390	0.6368	0.6341	0.6309	0.6272
55	0.5736	0.5732	0.5726	0.5714	0.5697	0.5674	0.5647	0.5615	0.5577
60	0.5000	0.4947	0.4990	0.4979	0.4961	0.4940	0.4914	0.4882	0.4846
65	0.4226	0.4222	0.4217	0.4203	0.4191	0.4171	0.4143	0.4117	0.4084
70	0.3420	0.3412	0.3412	0.3404	0.3390	0.3372	0.3351	0.3325	0.3297
75	0.2588	0.2579	0.2584	0.2575	0.2564	0.2550	0.2533	0.2513	0.2490
80	0.1736	0.1695	0.1732	0.1727	0.1720	0.1710	0.1697	0.1684	0.1668
85	0.0871	0.0844	0.0869	0.0869	0.0864	0.0858	0.0852	0.0844	0.0836

$\theta°$	45	50	55	60	65	70	75	80	85
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5	0.9958	0.9957	0.9956	0.9955	0.9953	0.9952	0.9950	0.9948	0.9946
10	0.9832	0.9830	0.9824	0.9819	0.9815	0.9809	0.9804	0.9795	0.9788
15	0.9625	0.9617	0.9607	0.9597	0.9585	0.9573	0.9559	0.9544	0.9527
20	0.9339	0.9325	0.9309	0.9289	0.9272	0.9251	0.9227	0.9200	0.9173
25	0.8978	0.8957	0.8934	0.8908	0.8879	0.8848	0.8813	0.8776	0.8735
30	0.8546	0.8519	0.8487	0.8453	0.8416	0.8375	0.8328	0.8278	0.8224
35	0.8050	0.8015	0.7977	0.7934	0.7887	0.7836	0.7779	0.7718	0.7651
40	0.7485	0.7449	0.7410	0.7358	0.7305	0.7244	0.7180	0.7109	0.7103
45	0.6886	0.6769	0.6791	0.6735	0.6675	0.6608	0.6536	0.6457	0.6372
50	0.6230	0.6186	0.6130	0.6073	0.6009	0.5936	0.5862	0.5777	0.5686
55	0.5535	0.5486	0.5427	0.5373	0.5308	0.5236	0.5159	0.5075	0.4984
60	0.4804	0.4759	0.4705	0.4648	0.4587	0.4518	0.4441	0.4361	0.4271
65	0.4042	0.4002	0.3954	0.3898	0.3843	0.3779	0.3710	0.3630	0.3556
70	0.3263	0.3216	0.3190	0.3141	0.3089	0.3031	0.2970	0.2906	0.2842
75	0.2463	0.2433	0.2400	0.2363	0.2323	0.2279	0.2232	0.2181	0.2127
80	0.1649	0.1629	0.1622	0.1576	0.1557	0.1515	0.1492	0.1457	0.1408
85	0.0826	0.0816	0.0804	0.0791	0.0777	0.0761	0.0739	0.0726	0.0707

$\theta°$	90	95	100	105	110	115	120	125	130
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5	0.9944	0.9942	0.9939	0.9937	0.9934	0.9931	0.9927	0.9923	0.9919
10	0.9781	0.9770	0.9760	0.9749	0.9738	0.9725	0.9712	0.9697	0.9681
15	0.9509	0.9489	0.9468	0.9445	0.9420	0.9393	0.9363	0.9337	0.9297
20	0.9143	0.9110	0.9074	0.9035	0.8993	0.8947	0.8898	0.8845	0.8788
25	0.8691	0.8642	0.8590	0.8534	0.8473	0.8407	0.8336	0.8259	0.8175
30	0.8165	0.8102	0.8033	0.7959	0.7878	0.7791	0.7698	0.7597	0.7489
35	0.7579	0.7501	0.7417	0.7320	0.7228	0.7122	0.7000	0.6886	0.6754
40	0.6946	0.6855	0.6759	0.6656	0.6541	0.6420	0.6288	0.6157	0.5999
45	0.6279	0.6180	0.6073	0.5958	0.5834	0.5702	0.5560	0.5408	0.5245
50	0.5591	0.5487	0.5373	0.5253	0.5124	0.4987	0.4838	0.4689	0.4511
55	0.4886	0.4781	0.4669	0.4548	0.4419	0.4281	0.4134	0.3977	0.3809
60	0.4178	0.4078	0.3969	0.3854	0.3730	0.3600	0.3460	0.3310	0.3151
65	0.3470	0.3378	0.3279	0.3174	0.3061	0.2942	0.2813	0.2680	0.2536
70	0.2766	0.2687	0.2598	0.2509	0.2413	0.2311	0.2203	0.2091	0.1969
75	0.2067	0.2007	0.1937	0.1866	0.1790	0.1709	0.1623	0.1533	0.1437
80	0.1377	0.1331	0.1281	0.1237	0.1180	0.1130	0.1064	0.1005	0.0941
85	0.0686	0.0664	0.0640	0.0614	0.0588	0.0559	0.0529	0.0497	0.0464

Table A-1. Vertical-radiation Characteristic $f(\theta)$ (*Continued*)

$\theta°$	Tower height, $G°$							
	135	140	145	150	155	160	165	170
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5	0.9915	0.9910	0.9905	0.9899	0.9893	0.9886	0.9878	0.9870
10	0.9663	0.9645	0.9624	0.9602	0.9577	0.9551	0.9522	0.9491
15	0.9259	0.9219	0.9175	0.9127	0.9075	0.9019	0.8956	0.8889
20	0.8725	0.8657	0.8584	0.8504	0.8418	0.8324	0.8222	0.8110
25	0.9085	0.7988	0.7883	0.7769	0.7645	0.7511	0.7366	0.7207
30	0.7372	0.7245	0.7108	0.6961	0.6801	0.6628	0.6440	0.6237
35	0.6612	0.6460	0.6293	0.6118	0.5926	0.5720	0.5496	0.5254
40	0.5837	0.5664	0.5477	0.5276	0.5060	0.4828	0.4577	0.4305
45	0.5070	0.4882	0.4681	0.4466	0.4235	0.3979	0.3719	0.3432
50	0.4330	0.4137	0.3932	0.3710	0.3473	0.3219	0.2948	0.2657
55	0.3631	0.3440	0.3237	0.3020	0.2786	0.2542	0.2278	0.1996
60	0.2981	0.2802	0.2611	0.2407	0.2190	0.1960	0.1713	0.1451
65	0.2382	0.2222	0.2051	0.1867	0.1675	0.1469	0.1256	0.1019
70	0.1838	0.1716	0.1555	0.1399	0.1237	0.1065	0.0881	0.0687
75	0.1335	0.1227	0.1114	0.0994	0.0866	0.0732	0.0590	0.0439
80	0.0868	0.0796	0.0719	0.0634	0.0547	0.0458	0.0359	0.0256
85	0.0428	0.0390	0.0351	0.0309	0.0265	0.0218	0.0169	0.0117

$\theta°$	175	180	185	190	195	200	205	210
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5	0.9861	0.9851	0.9840	0.9828	0.9815	0.9801	0.9784	0.9766
10	0.9455	0.9418	0.9375	0.9330	0.9278	0.9222	0.9159	0.9089
15	0.8815	0.8733	0.8645	0.8547	0.8438	0.8319	0.8186	0.8038
20	0.7988	0.7855	0.7708	0.7548	0.7370	0.7175	0.6958	0.6718
25	0.7034	0.8845	0.6638	0.6412	0.6168	0.5888	0.5585	0.5250
30	0.6015	0.5774	0.5510	0.5222	0.4907	0.4561	0.4179	0.3757
35	0.4991	0.4706	0.4395	0.4057	0.3687	0.3283	0.2839	0.2350
40	0.4013	0.3696	0.3353	0.2979	0.2573	0.2129	0.1645	0.1112
45	0.3122	0.2788	0.2427	0.2036	0.1612	0.1152	0.0650	0.0103
50	0.2344	0.2008	0.1646	0.1256	0.0834	0.0378	−0.0118	−0.0657
55	0.1658	0.1370	0.1022	0.0649	0.0247	−0.0186	−0.0655	−0.1161
60	0.1171	0.0873	0.0553	0.0211	−0.0155	−0.0550	−0.0973	−0.1431
65	0.0772	0.0509	0.0228	−0.0071	−0.0391	−0.0733	−0.1100	−0.1494
70	0.0481	0.0261	0.0029	−0.0220	−0.0483	−0.0765	−0.1065	−0.1388
75	0.0280	0.0111	−0.0069	−0.0259	−0.0461	−0.0676	−0.0905	−0.1150
80	0.0148	0.0033	−0.0089	−0.0218	−0.0354	−0.0499	−0.0633	−0.0818
85	0.0062	0.0004	−0.0057	−0.0122	−0.0191	−0.0264	−0.0341	−0.0424

$\theta°$	215	220	225	230	235	240	245	250
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5	0.9746	0.9723	0.9697	0.9668	0.9635	0.9597	0.9551	0.9504
10	0.9011	0.8925	0.8826	0.8580	0.8586	0.8442	0.8275	0.8084
15	0.7873	0.7689	0.7481	0.7247	0.6981	0.6679	0.6333	0.5935
20	0.6450	0.6151	0.5815	0.5438	0.5010	0.4525	0.3970	0.3334
25	0.4877	0.4462	0.3997	0.3475	0.2887	0.2220	0.1462	0.0593
30	0.3291	0.2772	0.2188	0.1548	0.0821	0.0000	−0.0931	−0.1992
35	0.1810	0.1214	0.0551	−0.0188	−0.1016	−0.1946	−0.2997	−0.4191
40	0.0529	−0.0117	−0.0814	−0.1620	−0.2501	−0.3489	−0.4599	−0.5853
45	−0.0498	−0.1156	−0.1881	−0.2683	−0.3572	−0.4562	−0.5671	−0.6917
50	−0.1243	−0.1885	−0.2588	−0.3363	−0.4216	−0.5163	−0.6216	−0.7394
55	−0.1711	−0.2310	−0.2962	−0.3677	−0.4462	−0.5327	−0.6285	−0.7351
60	−0.1924	−0.2461	−0.3040	−0.3674	−0.4364	−0.5125	−0.5958	−0.6882
65	−0.1918	−0.2375	−0.2880	−0.3406	−0.3989	−0.4625	−0.5322	−0.6089
70	−0.1733	−0.2107	−0.2503	−0.2935	−0.3402	−0.3909	−0.4463	−0.5069
75	−0.1411	−0.1691	−0.1992	−0.2315	−0.2664	−0.3042	−0.3452	−0.3899
80	−0.0992	−0.1182	−0.1380	−0.1600	−0.1826	−0.2079	−0.2346	−0.2639
85	−0.0511	−0.0605	−0.0705	−0.0812	−0.0927	−0.1051	−0.1185	−0.1330

Sectionalized Tower Measurements

Two cases of interest are presented in Figs. A-6 and A-7. In Fig. A-6, it will be noted that the maximum field strength is 224 mv/m for 1-kw input when the tower is driven at the base and an inductive reactance in the form of a short-circuited transmission line is connected across the sectionalizing insulator. The current and phase distribution are of particular interest for this condition. A standing wave of varying amplitude exists on the top section with very little phase shift, while on the lower section a traveling wave characterized by a constant amplitude and progressive phase shift is evident.

When both the upper and lower tower sections are driven as shown in Fig. A-7, the maximum inverse field strength for 1-kw input is 279 mv/m. In this case there is a very rapid phase shift of 180° and the current drops to a very low value. At the bottom of the tower there is a build-up of current that is approximately 180° out of phase with the current on the top section. It is this combination that reduces high angle radiation and is responsible for the strong ground-wave field strength.

APPENDIX B. TWO-TOWER DIRECTIONAL ANTENNAS

Pattern Formulas

General Equation

The inverse field strength from a two-tower directional antenna as shown in Fig. B-1 is given by

$$E = E_1 f_1(\theta)\sqrt{2F}\sqrt{\frac{1+F^2}{2F} + \cos\left(S\cos\phi\cos\theta + \Psi\right)} \qquad \text{(B-1)}$$

where E = inverse field strength at 1 mile, mv/m
E_1 = inverse field strength at 1 mile from tower 1 when operating in array, mv/m
$f_1(\theta)$ = vertical-radiation characteristic of tower 1

$$F = \frac{E_2 f_2(\theta)}{E_1 f_1(\theta)} \qquad \text{(B-2)}$$

= ratio of field strength from tower 2 to tower 1

where E_2 = inverse field strength at 1 mile from tower 2 when operating in array, mv/m
$f_2(\theta)$ = vertical-radiation characteristic of tower 2
S = spacing between tower 2 and tower 1, deg
ϕ = azimuth angle from line of towers, deg
θ = elevation angle, deg
Ψ = electrical phase angle of current in tower 2 with respect to tower 1, deg

The above terms as shown in Fig. B-2 are written without subscripts where possible for a simple two-tower array. When more than two towers are involved, the term F in Eq. (B-2) is written F_{21} to designate the ratio between tower 2 and tower 1. Similarly, the spacing would be marked S_{21}, which is the distance from tower 2 to tower 1 that is located at the space reference point. The electrical phase in general is written Ψ_{21} to designate the phase of the current in tower 2 with respect to tower 1.

Minimum-depth Term

The minimum-depth term by definition is

$$\frac{1+F^2}{2F} \qquad \text{(B-3)}$$

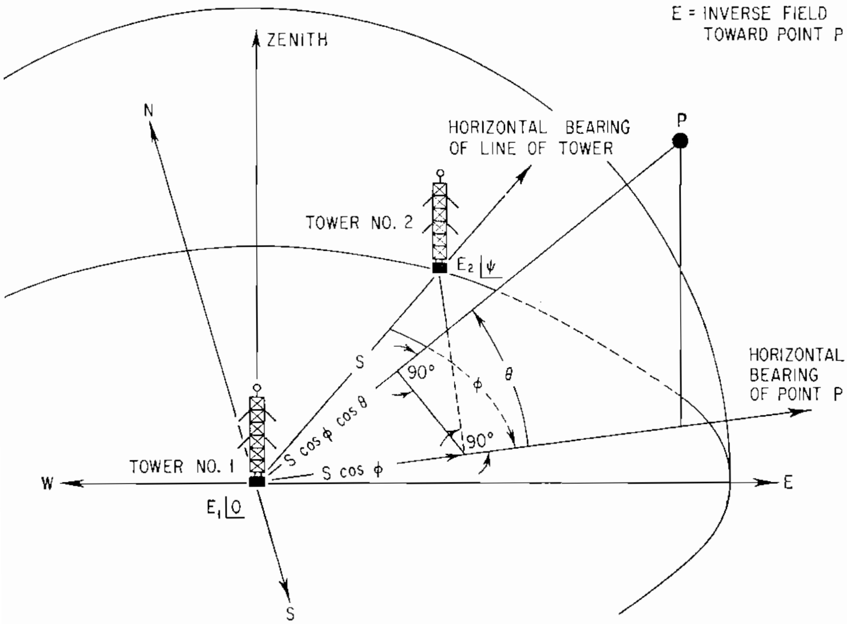


Fig. B-1. Space view of two-tower directional antenna.

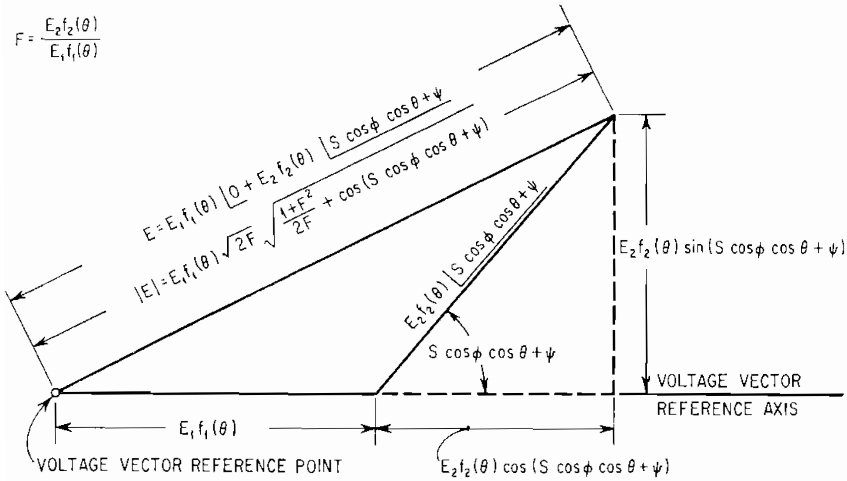


Fig. B-2. Voltage vector diagram for two-tower directional antenna.

Because of its significance in Eq. (B-1), Table B-1 has been prepared. This table lists the values of F, $1/F$, F^2, and the minimum-depth term. The minimum-depth term is unchanged if $1/F$ is used in the place of F.

An inspection of the radicand in Eq. (B-1) shows that E in the minima can be made larger than zero providing the minimum-depth term is not completely canceled by the cosine term. The exact size of E in the minima can be fixed by choice of the value of the minimum-depth term. Conversely, if the equation for E is in the form of Eq. (B-1) and if F is also given, then Table B-1 can be used to check the accuracy of the formula quickly. If F is not given, it can be found from the table.

General Value of Field Ratio

The general form of F is given in Eq. (B-2). The values of $f(\theta)$ for various tower heights are given in Fig. A-4 and Table A-1. Hence, in the design of a two-tower directional antenna, it is convenient first to select the value of the minimum-depth term. The corresponding value of F can be found in Table B-1, and by Eq. (B-2) the ratio of E_2 over E_1 can be determined. This procedure can be reversed to check a given equation.

For pattern computations, it is convenient to fix θ and vary ϕ; thus the information can be used to meet the requirement in Paragraph 3.150 of Part 3, FCC Rules. The data required are field strength E as a function of azimuth angle ϕ for 5° intervals of elevation angle θ from 0 to 60°.

Horizontal-plane Equation

In the ground plane Eq. (B-1) reduces to

$$E = E_1\sqrt{2F}\sqrt{\frac{1 + F^2}{2F} + \cos(S\cos\phi + \Psi)} \qquad \text{(B-4)}$$

where F is the ratio of E_2 over E_1 for equal or unequal height towers. Thus Eq. (B-4) can be used for $\theta = 0$ and Eq. (B-1) can be used at elevation angles up to 60° as required by the above rules.

If the ratio of E_2 over E_1 is given but E has not been expressed in the form of Eq. (B-1) or (B-4), it is convenient to use Table B-1 to obtain the values to be used in the above equations.

The minimum-depth term usually appears more than once in directional-antenna-pattern equations for arrays having more than two towers. Three towers in line and parallelogram arrays can use two or more of the multiplication radicands given in Eq. (B-1).

Systematization of Two-tower Patterns

The systematization has been divided into relatively large steps of 45° for phasing and spacing in Figs. B-3 to B-6. The spacing extends to four wavelengths or 1,440°. The more useful range of spacing up to one wavelength is given in small steps of 15° for both spacing and phasing in Figs. B-7 to B-12.

Pattern Size

Field Strength of Reference Tower

In order to determine the pattern size, it is rather common practice to compute the value of field strength that the reference tower will radiate when operating in the directional-antenna array. This value can then be used in Eq. (B-1) to determine the pattern shape at the correct size. The value of E_1 can be computed from the following

(*Continued on page 2-131.*)

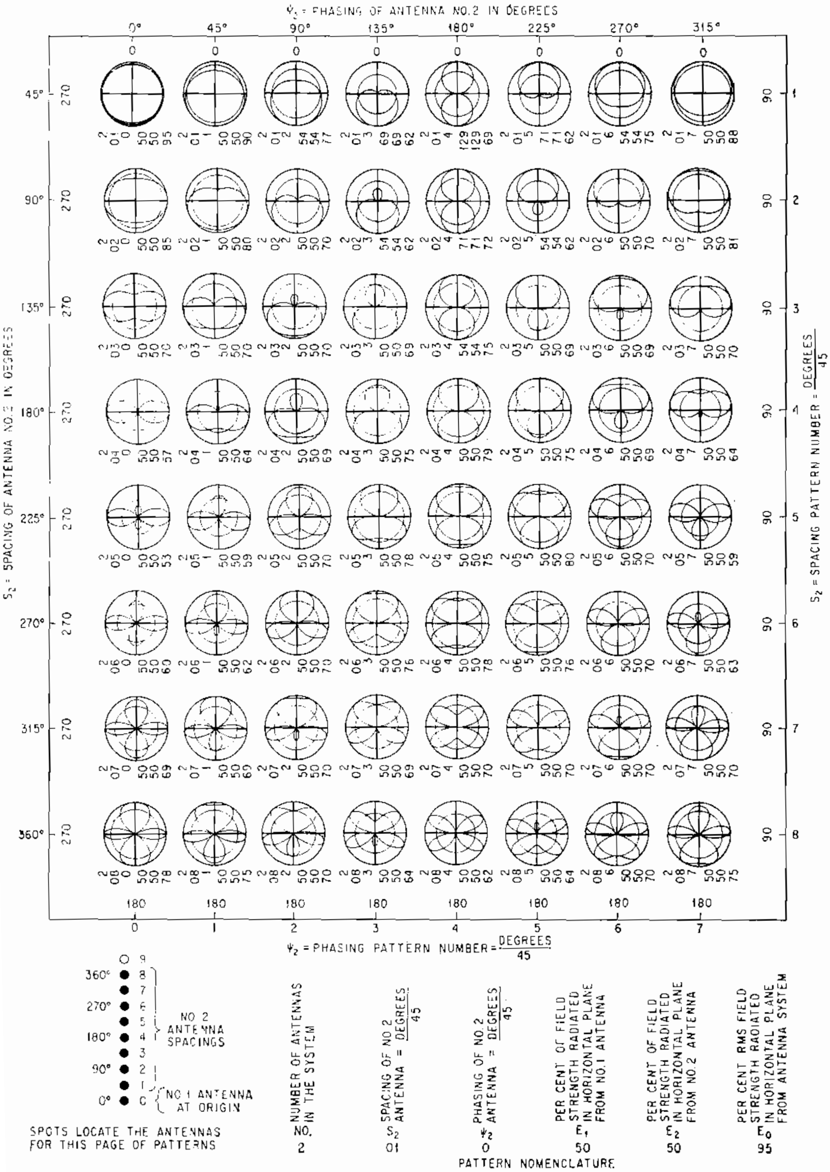


FIG. B-3

FIGS. B-3 to B-6. Systematization of two-tower patterns in steps of 45 to 1,440°.

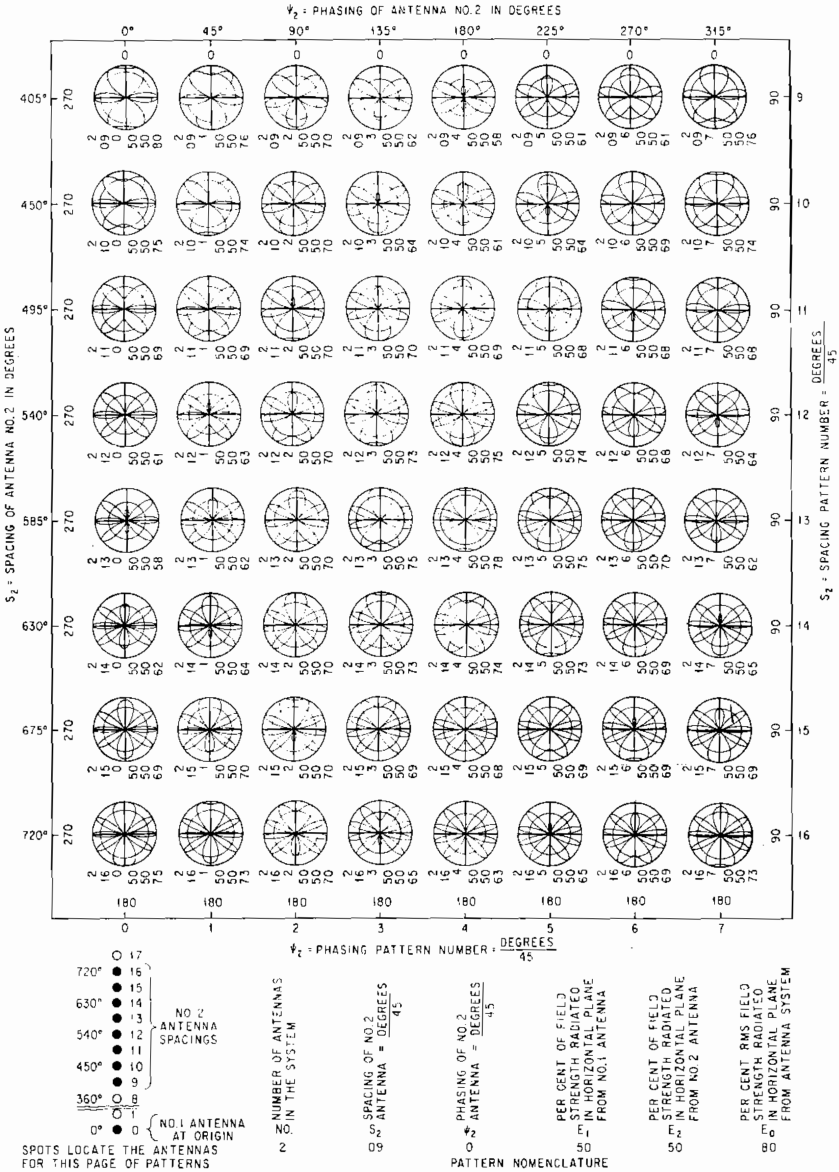

ψ_2 = PHASING OF ANTENNA NO. 2 IN DEGREES
0° 45° 90° 135° 180° 225° 270° 315°
S_2 = SPACING OF ANTENNA NO. 2 IN DEGREES
405° 450° 495° 540° 585° 630° 675° 720°
S_2 = SPACING PATTERN NUMBER = DEGREES / 45
9 10 11 12 13 14 15 16
ψ_2 = PHASING PATTERN NUMBER = DEGREES / 45
0 1 2 3 4 5 6 7
NO. 2 ANTENNA SPACINGS
NO. 1 ANTENNA AT ORIGIN
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS
NUMBER OF ANTENNAS IN THE SYSTEM
NO.
2
SPACING OF NO. 2 ANTENNA = DEGREES / 45
S_2
09
PHASING OF NO. 2 ANTENNA = DEGREES / 45
ψ_2
0
PER CENT OF FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA
E_1
50
PER CENT OF FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 2 ANTENNA
E_2
50
PER CENT RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM
E_0
80
PATTERN NOMENCLATURE

FIG. B-4

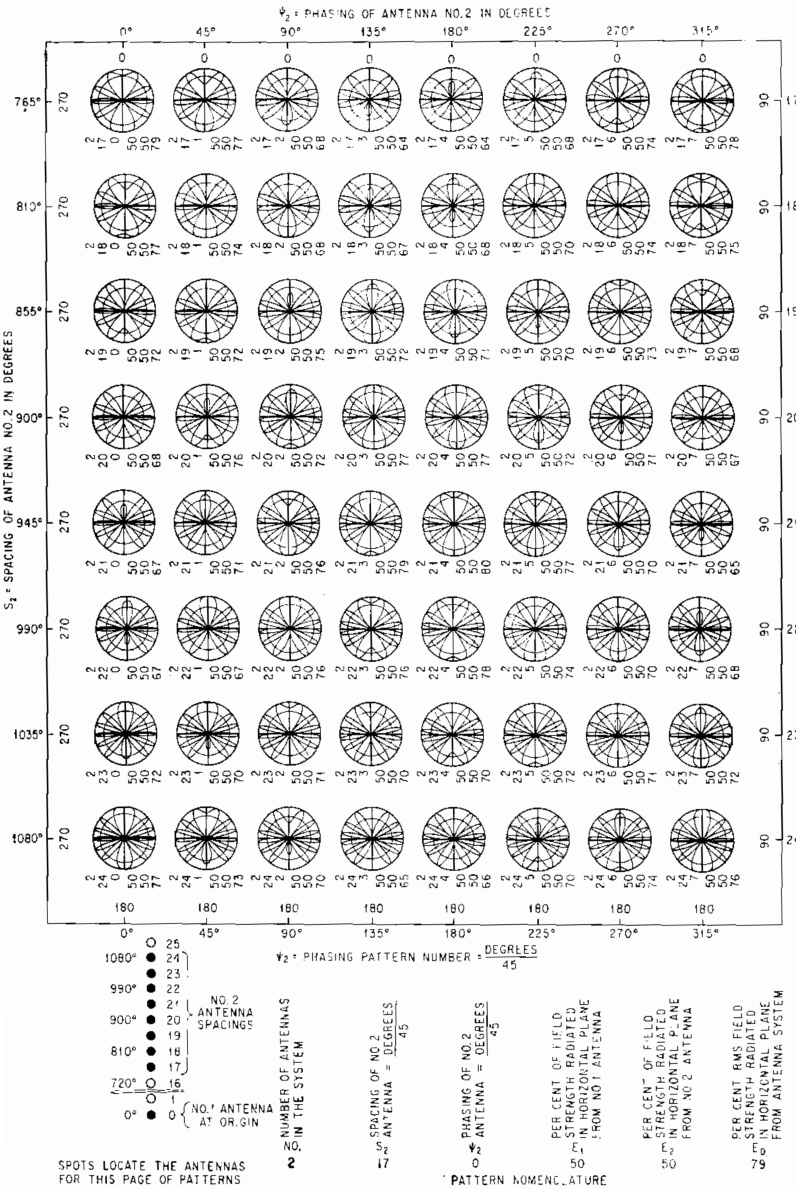
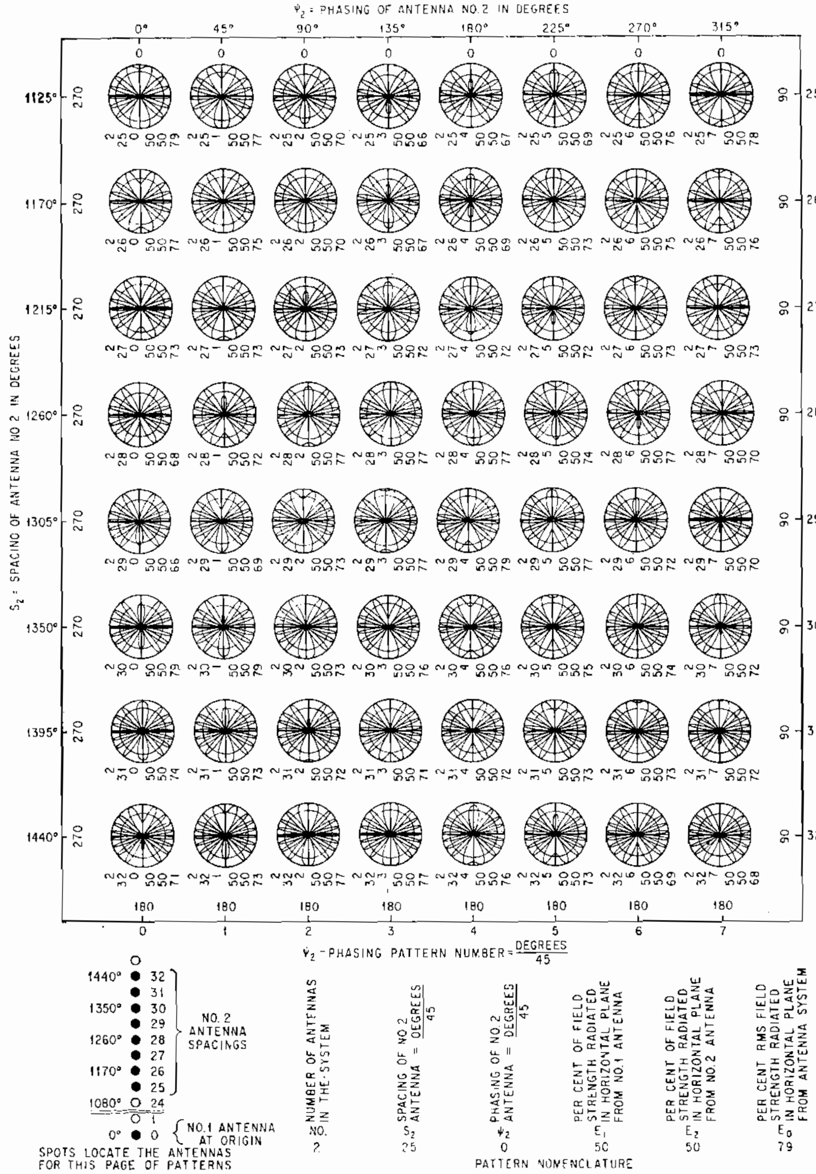


FIG. B-5



ψ_2 = PHASING OF ANTENNA NO. 2 IN DEGREES
0° 45° 90° 135° 180° 225° 270° 315°
S_2 = SPACING OF ANTENNA NO. 2 IN DEGREES
1125° 1170° 1215° 1260° 1305° 1350° 1395° 1440°
S_2 = SPACING PATTERN NUMBER = DEGREES/45
25 26 27 28 29 30 31 32
ψ_2 – PHASING PATTERN NUMBER = DEGREES/45
0 1 2 3 4 5 6 7
NO.1 ANTENNA AT ORIGIN
NO. 2 ANTENNA SPACINGS
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS
NUMBER OF ANTENNAS IN THE SYSTEM
SPACING OF NO.2 ANTENNA = DEGREES/45
PHASING OF NO.2 ANTENNA = DEGREES/45
PER CENT OF FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO.1 ANTENNA
PER CENT OF FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO.2 ANTENNA
PER CENT RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM
NO. 2
S_2 25
ψ_2 0
E_1 50
E_2 50
E_0 79
PATTERN NOMENCLATURE

FIG. B-6

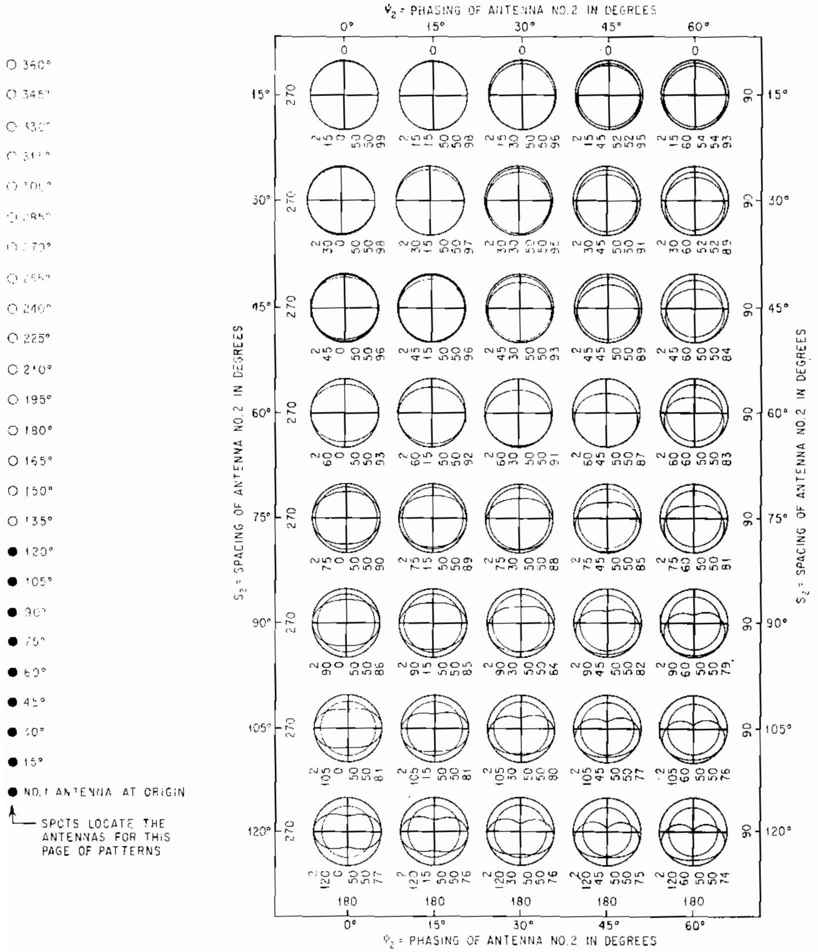
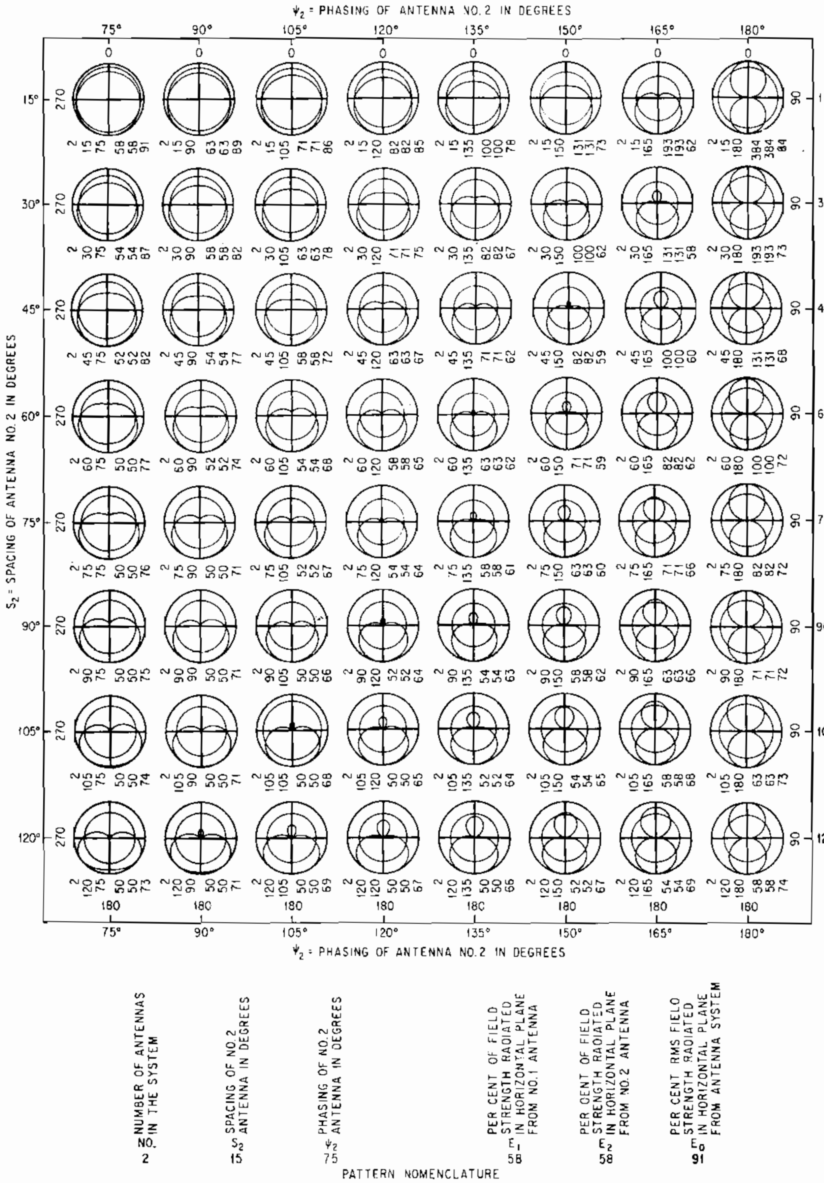


FIG. B-7

FIGS. B-7 to B-12. Systematization of two-tower patterns in steps of 15 to 360°.



ψ_2 = PHASING OF ANTENNA NO. 2 IN DEGREES
75° 90° 105° 120° 135° 150° 165° 180°
S_2 = SPACING OF ANTENNA NO. 2 IN DEGREES
15° 30° 45° 60° 75° 90° 105° 120°
NO. 2 NUMBER OF ANTENNAS IN THE SYSTEM
S_2 15 SPACING OF NO. 2 ANTENNA IN DEGREES
ψ_2 75 PHASING OF NO. 2 ANTENNA IN DEGREES
E_1 58 PER CENT OF FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA
E_2 58 PER CENT OF FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 2 ANTENNA
E_0 91 PER CENT RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM
PATTERN NOMENCLATURE

FIG. B-8

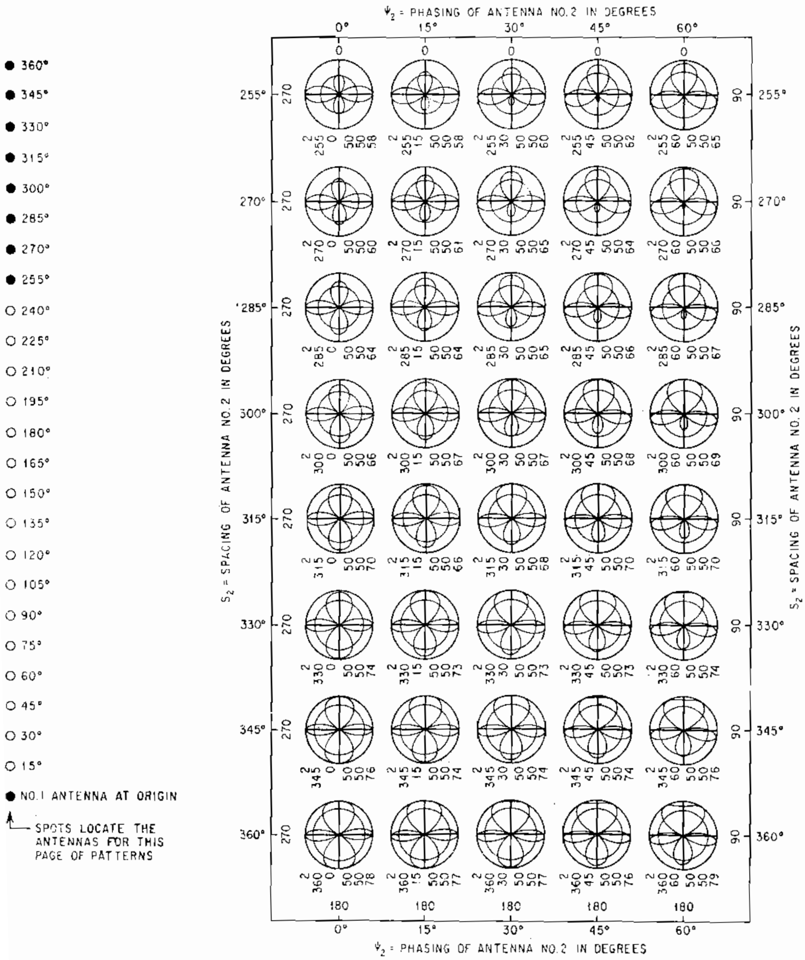

● 360°
● 345°
● 330°
● 315°
● 300°
● 285°
● 270°
● 255°
○ 240°
○ 225°
○ 210°
○ 195°
○ 180°
○ 165°
○ 150°
○ 135°
○ 120°
○ 105°
○ 90°
○ 75°
○ 60°
○ 45°
○ 30°
○ 15°
● NO. 1 ANTENNA AT ORIGIN
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS
Ψ_2 = PHASING OF ANTENNA NO. 2 IN DEGREES
S_2 = SPACING OF ANTENNA NO. 2 IN DEGREES

FIG. B-9

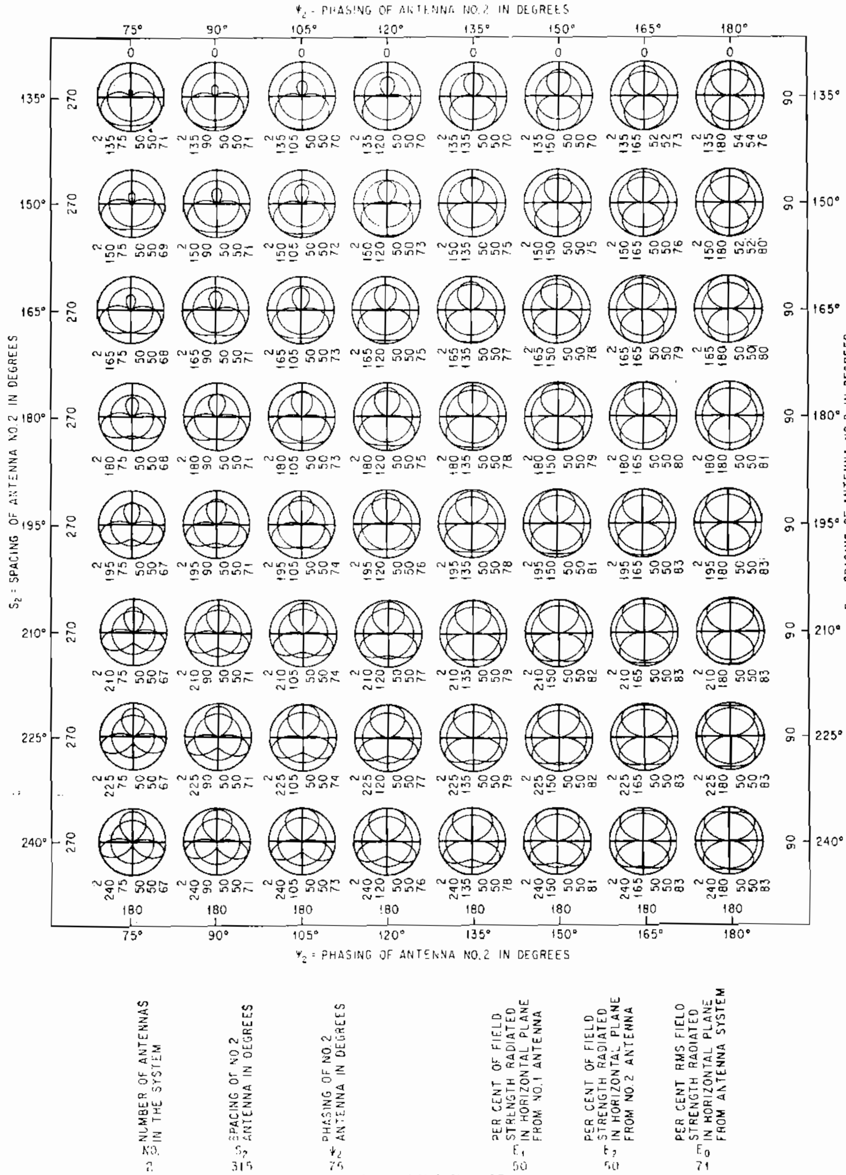

Ψ2 = PHASING OF ANTENNA NO.2 IN DEGREES
75° 90° 105° 120° 135° 150° 165° 180°
S2 = SPACING OF ANTENNA NO.2 IN DEGREES
135° 150° 165° 180° 195° 210° 225° 240°
0
90
180
270
NUMBER OF ANTENNAS IN THE SYSTEM
SPACING OF NO.2 ANTENNA IN DEGREES
PHASING OF NO.2 ANTENNA IN DEGREES
PER CENT OF FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO.1 ANTENNA
PER CENT OF FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO.2 ANTENNA
PER CENT RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM
NO. S2 Ψ2 E1 E2 E0
2 315 75 50 50 71
PATTERN NOMENCLATURE

Fig. B-10

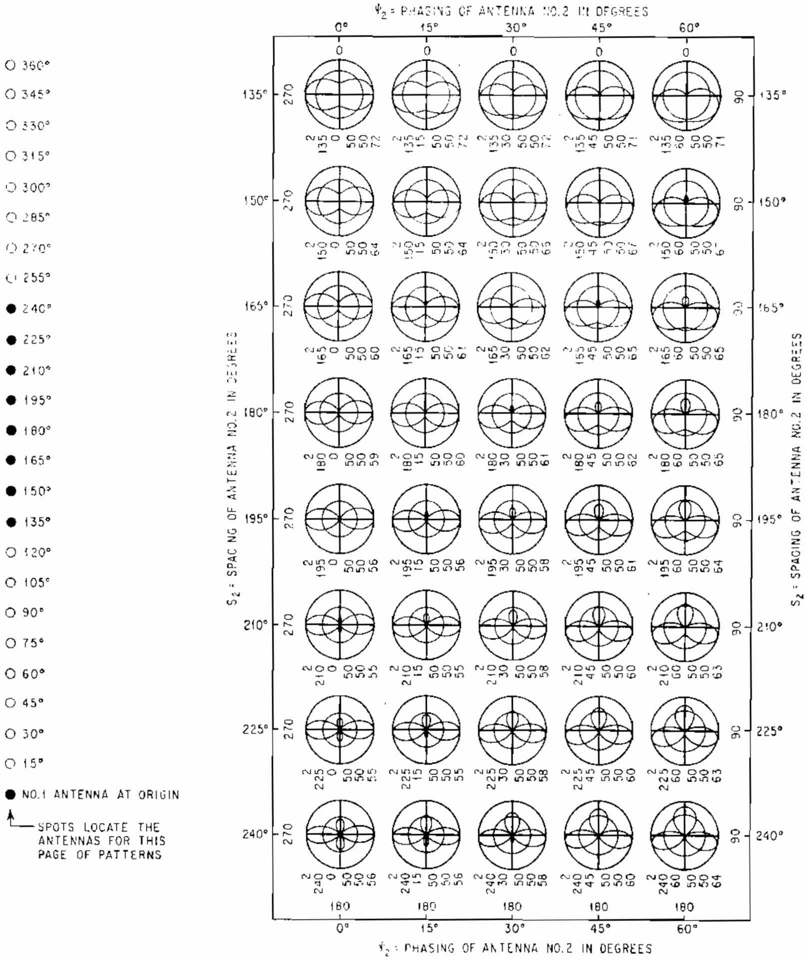
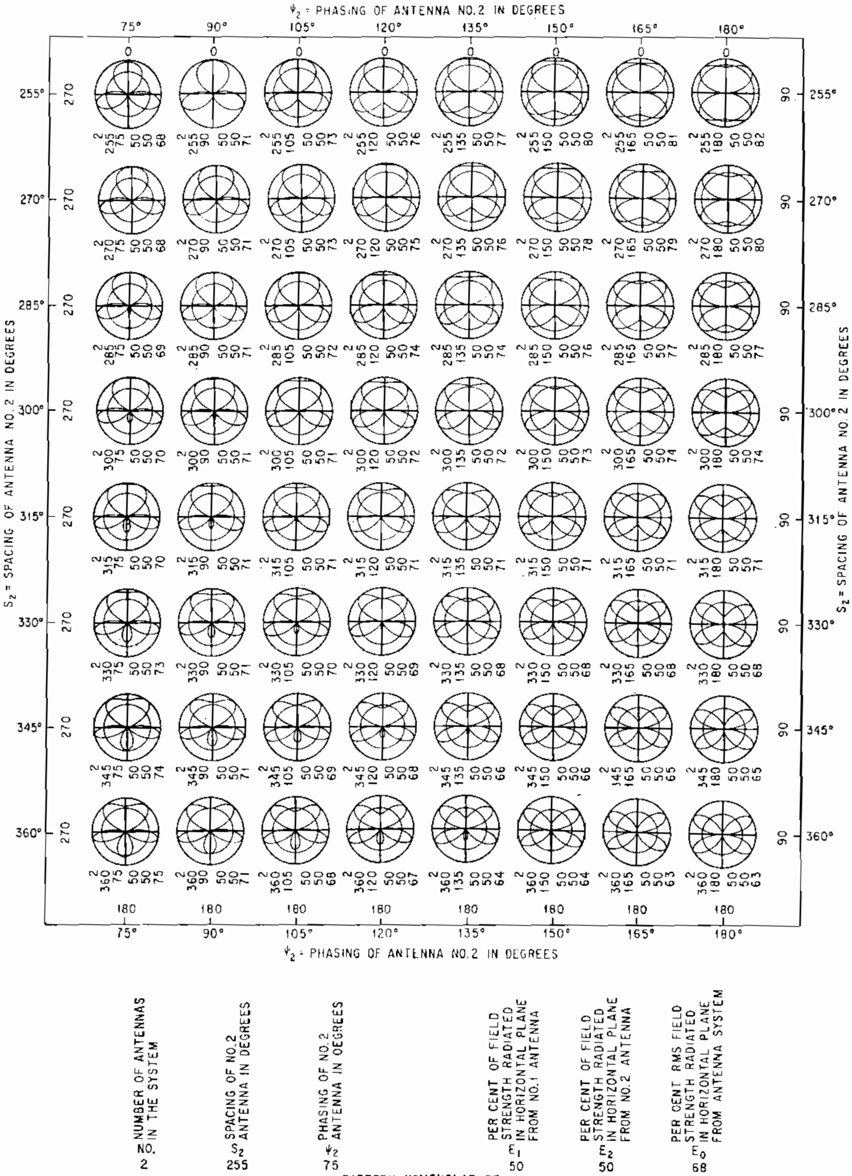

Ψ2 = PHASING OF ANTENNA NO.2 IN DEGREES
0° 15° 30° 45° 60°
S2 = SPACING OF ANTENNA NO.2 IN DEGREES
135° 150° 165° 180° 195° 210° 225° 240°
○ 360°
○ 345°
○ 330°
○ 315°
○ 300°
○ 285°
○ 270°
○ 255°
● 240°
● 225°
● 210°
● 195°
● 180°
● 165°
● 150°
● 135°
○ 120°
○ 105°
○ 90°
○ 75°
○ 60°
○ 45°
○ 30°
○ 15°
● NO.1 ANTENNA AT ORIGIN
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS

FIG. B-11



Ψ_2 = PHASING OF ANTENNA NO.2 IN DEGREES
75° 90° 105° 120° 135° 150° 165° 180°
S_2 = SPACING OF ANTENNA NO.2 IN DEGREES
255° 270° 285° 300° 315° 330° 345° 360°
0
270
90
180
PATTERN NOMENCLATURE
NO. 2 NUMBER OF ANTENNAS IN THE SYSTEM
S_2 255 SPACING OF NO.2 ANTENNA IN DEGREES
Ψ_2 75 PHASING OF NO.2 ANTENNA IN DEGREES
E_1 50 PER CENT OF FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO.1 ANTENNA
E_2 50 PER CENT OF FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO.2 ANTENNA
E_0 68 PER CENT RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM

Fig. B-12

equation, sometimes called the loop impedance formula, thus

$$E_1 = E_{1s}\sqrt{\frac{R_{11}}{R_1 + M^2R_2}}$$

$$= E_{1s}\sqrt{\frac{R_{11}}{(R_{11} + R_{L1} + R_{C1}) + M^2(R_{22} + R_{L2} + R_{C2})}} \qquad \text{(B-5)}$$

where E_1 = inverse field strength at 1 mile for tower 1 while operating in the array, mv/m
E_{1s} = inverse field strength at 1 mile for tower 1 operating alone as a standard reference antenna, mv/m
R_{11} = loop self-resistance of tower 1, ohms
R_{L1} = loss resistance assumed at loop of tower 1, ohms
R_{C1} = coupled resistance at loop of tower 1 from other towers while array is in operation, ohms
R_{22} = loop self-resistance of tower 2, ohms
R_{L2} = loss resistance assumed at loop of tower 2, ohms
R_{C2} = coupled resistance at loop of tower 2 from other towers while array is in operation, ohms
M = ratio of current at loop of tower 2 divided by current at loop of tower 1

The values of E_{1s}, R_{11}, and R_{22} can be obtained from Fig. A-5 for simple towers that are not sectionalized or top-loaded. For other types of towers these values must be assumed or calculated. The values of R_{L1} and R_{L2} are usually assumed to be 2 ohms each.

Coupled-resistance Formula

The values of coupled resistance from the other towers are given by

$$R_{C1} = MZ\cos(\Psi + \gamma) \qquad \text{(B-6)}$$

$$R_{C2} = \frac{Z}{M}\cos(-\Psi + \gamma) \qquad \text{(B-7)}$$

where Z = magnitude of loop impedance between the two towers, ohms
M = magnitude of current ratio of loop current in tower 2 divided by tower 1
γ = angle of loop mutual impedance, deg
Ψ = electrical phase angle of current in tower 2 with respect to tower 1, deg

These equations can be used with reasonable accuracy for simple nonloaded towers.

The above equations are written without the use of magnitude signs and subscripts for the sake of simplicity. The exact vector expressions are

$$Z_{21} = |Z_{21}|\underline{/\gamma_{21}} \qquad \text{(B-8)}$$

and

$$M_{21} = \frac{I_2}{I_1} = |M_{21}|\underline{/\Psi_{21}} \qquad \text{(B-9)}$$

where the currents are vector values having magnitude and phase angle. The current values in this equation are determined when the directional antenna is designed.

Mutual-impedance Curves

The value of mutual impedance for most tower heights and spacing is given in Fig. B-13. The loop mutual impedance between quarter-wave towers is shown in Fig. B-14. These values can be used in the above equations for coupled resistance. For towers of unequal height the mutual impedance can be computed or reference can be made to curves already computed.[4]

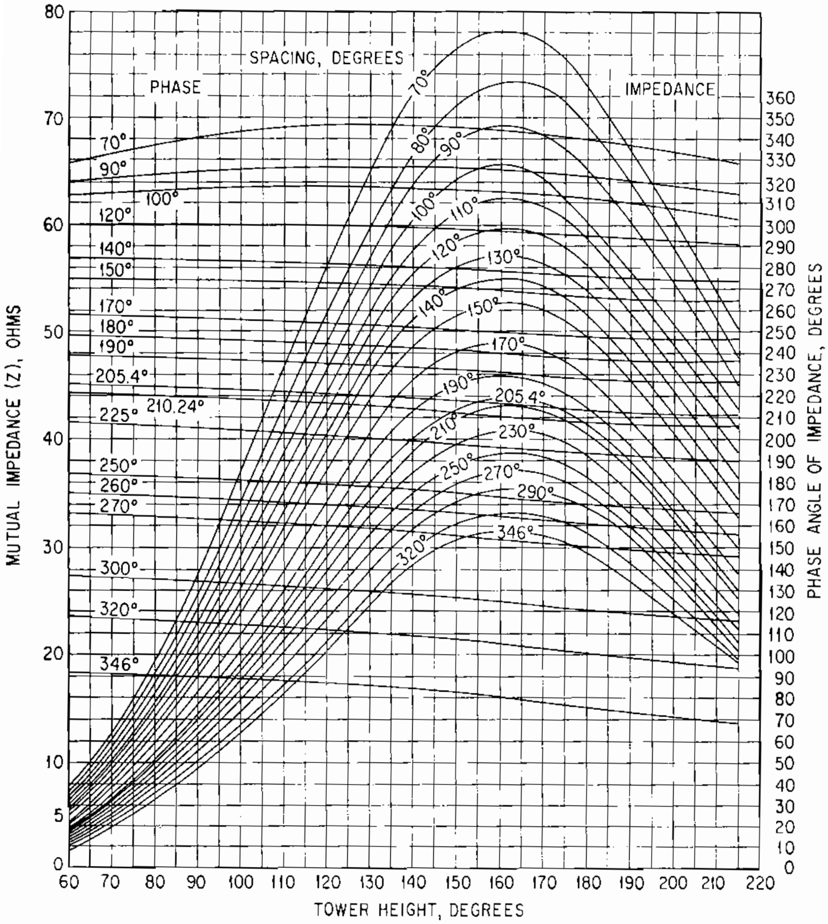


FIG. B-13. Loop mutual impedance and phase angle between two towers of equal height.

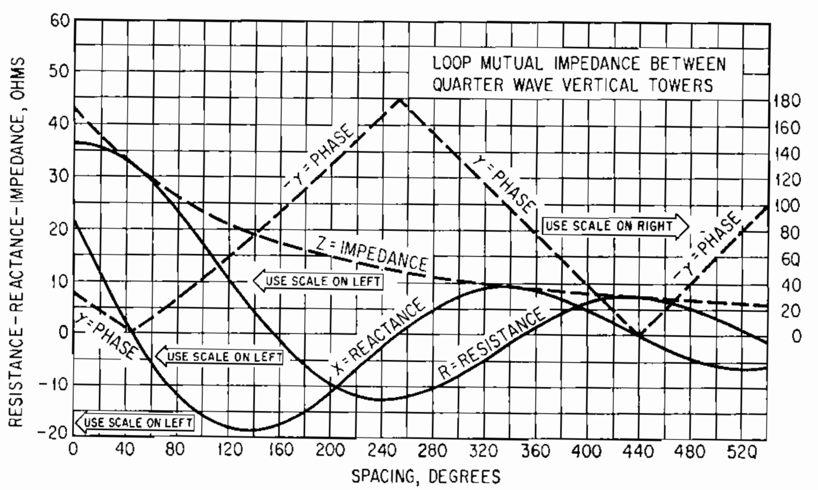


FIG. B-14. Loop mutual impedance between quarter-wave vertical towers.

Top-loaded and Sectionalized Towers

The preceding equations can be applied to top-loaded and sectionalized towers but with considerable complication. The field strength E_{1s} and the self-resistance R_{11} are in general not available. They can be found in the literature for a few special cases.[3] The mutual impedance between sectionalized towers likewise is not readily available. It must be calculated for any special case if it is to be determined accurately. It is easier to determine the mutual effects by graphical solutions to the necessary accuracy.

Horizontal-plane RMS Field Strength

The rms field strength for a two-tower array can be determined from

$$E_0 = E_1\sqrt{1 + F^2 + 2F \cos \Psi J_0(S)} \qquad \text{(B-10)}$$

where E_0 = rms inverse field strength at 1 mile, mv/m
E_1 = inverse field strength at 1 mile for reference tower 1 while operating in array, mv/m
F = ratio of magnitude of field strength from tower 2 divided by tower 1
Ψ = electrical phase of field from tower 2 with respect to tower 1, deg
$J_0(S)$ = Bessel function of first order for tower spacing S

Usually the terms F and M are identical. However, with unequal-height towers and top-loading or sectionalized towers these ratios may have different values. Table B-2 can be used to obtain the desired Bessel-function values. Interpolation can be used if necessary.

Horizontal RMS Field-strength and Power Gain

The field-strength gain of any directional-antenna array can be written

$$\sqrt{g_0} = \frac{E_0}{E_{1s}} \qquad \text{(B-11)}$$

where $\sqrt{g_0}$ = field-strength gain by definition in the horizontal plane
E_0 = rms inverse field strength at 1 mile, mv/m
E_{1s} = inverse field strength at 1 mile for tower 1 operating alone as a standard reference antenna, mv/m

The power gain for a two-tower array is given by

$$g_0 = \frac{1 + F^2 + 2F \cos \Psi J_0(S)}{1 + F^2 + 2F \cos \Psi (R_{12}/R_{11})} \qquad \text{(B-12)}$$

where g_0 = directivity or power gain
F = ratio of magnitude of field strength from tower 2 divided by tower 1
Ψ = electrical phase of field from tower 2 with respect to tower 1, deg
$J_0(S)$ = Bessel function of first kind and zero order for tower spacing S
R_{12} = mutual loop resistance between towers, ohms
R_{11} = loop-radiation self-resistance of tower 1, ohms

It is of interest to know whether a particular antenna system is a gainer or a loser as compared with a standard reference antenna. This can be determined by the following:

$$E_0 = E_{1s}\sqrt{g_0} \qquad \text{(B-13)}$$

Now, if 90° towers are used and the field ratio $F = 1$, Eq. (B-12) substituted in Eq. (B-13) gives

$$E_0 = 195\sqrt{\frac{1 + \cos \Psi J_0(S)}{1 + \cos \Psi (R_{12}/36.6)}} \qquad \text{(B-14)}$$

The solution of this equation is shown in Fig. B-15 for various values of tower current phasing and tower spacing. It gives the theoretical field without loss for 1-kw operation.

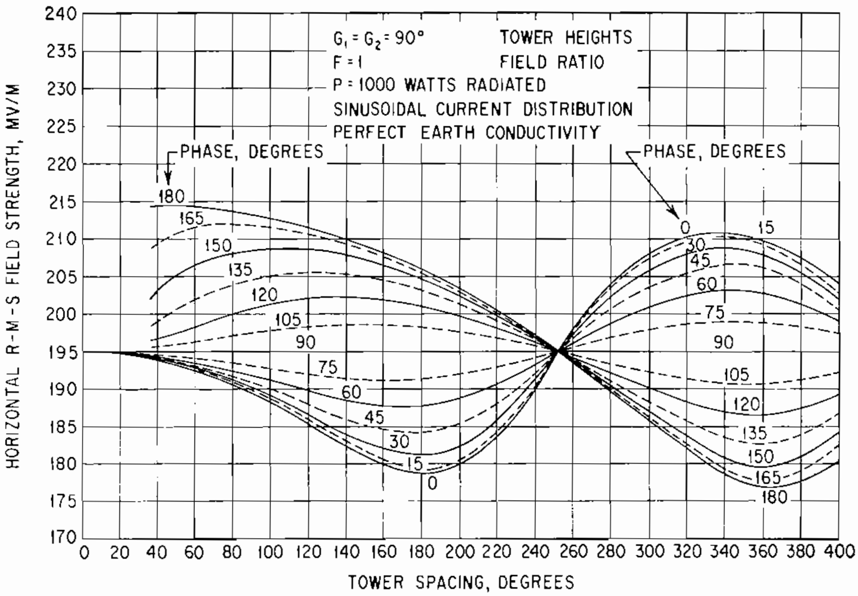


FIG. B-15. Horizontal rms field strength of two-tower directional antenna.

Power to Provide System Losses

Because of losses in the transmission lines and matching, phasing, and power-division networks, plus other losses in the system such as resistance losses in the tower and ground system and dielectric losses in the insulators, an overfeeding of power is allowed by FCC at the common point.

The calculation of the amount of overfeeding of power at the common point is made as follows:

For stations with directional antennas authorized to radiate 5 kw of power or less, the measured common-point resistance is assumed to be 92.5 per cent of its measured value, and for all other directional antennas, it is assumed to be 95 per cent. This arbitrary reduction in resistance amounts to increasing the current at the common point by $1/\sqrt{0.925} = 1.0389$, or approximately a 4 per cent increase for values of transmitter power up to and including 5 kw. For transmitters with power above 5 kw the antenna current can be increased $1/\sqrt{0.95} = 1.0252$, or approximately a 2.5 per cent increase.

Another way of saying this is that for a 1-kw station 1,081 watts can be fed in at the common point, while for a 50-kw station 52,105 watts can be fed in at the common point. For the 1-kw station there is 81 watts available for feeder-system loss, and in the 50-kw station there is 2,105 watts available for feeder-system loss.

Feeder System

Loop and Base, Impedance and Current

The first approximation of the base resistance of an ordinary base-insulated tower that is not top-loaded or sectionalized is given by

$$R_b = \frac{R_a}{\sin^2 G} \tag{B-15}$$

where R_b = base resistance of tower, ohms
R_a = loop resistance of tower, ohms
G = electrical height of tower, deg

The first approximation of the base current for the above tower is

$$I_b = I_a \sin G \tag{B-16}$$

where I_b = base current of tower, amp
I_a = loop current of tower, amp

These equations are consistent with the theory that the power at the loop is equal to the power at the base; that is,

$$I_b{}^2 R_b = I_a{}^2 R_a \tag{B-17}$$

These equations are most accurate for single towers operating alone where the cross section is small and uniform so the current distribution will be approximately sinusoidal.

A second approximation of the base impedance depends upon the tower acting like a transmission line from the loop to the base and is given by

$$Z_b = Z_0 \frac{Z_a \cos (G - 90) + jZ_0 \sin (G - 90)}{Z_0 \cos (G - 90) + jZ_a \sin (G - 90)} \tag{B-18}$$

where Z_b = base impedance of tower, ohms
Z_a = loop impedance of tower, ohms
Z_0 = average characteristic impedance of tower, ohms
G = electrical height of tower, deg

A second approximation for the base current also depends upon the tower acting like a transmission line and is written

$$I_b = |I_a| \left[\sin G + j \frac{R_a}{2Z_0} (1 - \cos G) \right] \tag{B-19}$$

where I_b = complex value of tower base current, amp
$|I_a|$ = magnitude of tower loop current, amp
R_a = loop resistance of tower, ohms

Z_0 and G are defined following Eq. (B-18). The first term in this equation is a sinusoidal term corresponding to Eq. (B-16), which corresponds to the antenna current that causes the radiation. The second term is the feed current which supplies the radiated power from the base to the loop. It should be noted that this equation does not give the phase of the base current with respect to the loop current. This change in phase between the loop and base current is expressed by the more general equation

$$I_y = |I_a| \left[\sin (G - y) + j \frac{R_a}{2Z_0} (\cos y - \cos G) \right] \tag{B-20}$$

where Iy is the current at any height y on the tower in amperes. The other terms are defined in Eq. (B.19). Equation (B-20) reduces to Eq. (B-19) when $y = 0$. It gives the phase as well as the magnitude of the current at any point on the tower; hence at the current loop,

$$I_a = |I_a| \left[1 + j \frac{R_a}{2Z_0} (\cos y - \cos G) \right] \tag{B-21}$$

The difference in the phase of the current I_a in Eq. (B-21) and the current I_b in Eq. (B-19) is the additional phase shift that must be provided for in the feeder system.

Conservation of power between the loop and base may not exist in Eqs. (B-18) and (B-19) as it does in Eqs. (B-15) and (B-16). However, Eqs. (B-18) and (B-19) usually give a better answer for the base impedance values when the towers are operating in a directional-antenna system.

These equations can be used in the feeder-system design. However, it is advisable to provide adequate range so proper adjustments can be made when the system is put into operation.

Networks for Matching Impedances

General. A directional-antenna system usually requires impedance-matching networks at several points such as from the transmission lines to the towers and perhaps from the transmitter to the common point of the antenna feeder system. These networks are usually made up of lumped constants in the form of L, T, or π sections.

If an impedance load is not a pure resistance, it can be made to look like a pure resistance by adding a reactance element in series or parallel that will make the load either series- or parallel-resonant. If this is done, the treatment of the impedance-matching networks can be simplified. Therefore in this section networks to match between pure resistance values of R_1 and R_2 will be treated.

L Sections. An L section is the simplest way to match between two resistors R_1 and R_2. It is made up of an inductor for Z_2 and a capacitor for Z_3 with a small, fixed phase lag depending upon the ratio $r = R_1/R_2$. Or it can be constructed with a capacitor for Z_2 and an inductor for Z_3 with a small phase advance as shown in Figs. B-16 and B-17.

The phase shift in an L section is fixed by the ratio $r = R_1/R_2$. This is because there are only two reactance elements. The size of the shunt element across R_1 controls the size of R_2, while the series element is used to resonate the circuit so only resistance appears at the R_2 terminals.

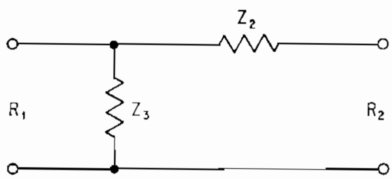


FIG. B-16. General L-section impedance-matching network.

The design equations for an L section matching between resistors R_1 and R_2 are

$$Z_2 = \pm jR_2\sqrt{r-1} = \pm j\frac{R_1}{a} \quad \text{(B-22)}$$

$$Z_3 = \mp j\frac{R_1}{\sqrt{r-1}} = \mp j\frac{R_1}{b} \quad \text{(B-23)}$$

$$\cos\beta = \frac{1}{\sqrt{r}} \quad \text{(B-24)}$$

where Z_1 = reactance of series arm, ohms
Z_2 = reactance of shunt arm, ohms
R_1 = larger terminating resistance, ohms
R_2 = smaller terminating resistance, ohms
r = R_1/R_2 ratio
β = phase shift, deg

The $\pm j$ in Eq. (B-22) and $\mp j$ in Eq. (B-23) means simply that if $+j$ or an inductor is used for Z_1, then $-j$ or a capacitor must be used for Z_3.

T and π Sections. T and π sections made up of reactance arms are widely used in the directional-antenna feeder systems. With the three reactance elements it is possible to control the amount of phase shift in addition to the input and output resistance values.

The efficiency of such a network is implicitly determined by the ratio $r = R_1/R_2$ and the phase shift β. There is no choice between T and π sections, whether advancing or retarding the phase, as far as efficiency is concerned. The loss increases with the ratio r and tends to increase for very small or very large phase shifts. For very high transformation ratios r of, say, 10 or more, it is advisable to use two or more sections in tandem. This will increase the stability and reduce the loss.

The design equations for a T or π section are

$$a = \frac{r\sin\beta}{\sqrt{r} - \cos\beta} \quad \text{(B-25)}$$

$$b = \sqrt{r}\sin\beta \quad \text{(B-26)}$$

$$c = \frac{\sqrt{r}\sin\beta}{1 - \sqrt{r}\cos\beta} \quad \text{(B-27)}$$

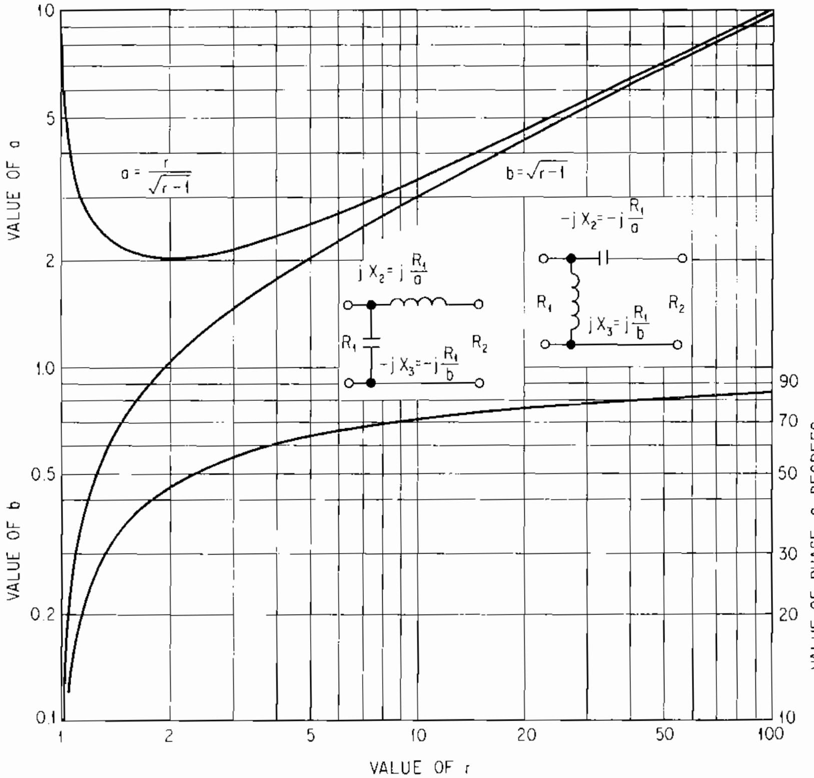


FIG. B-17. L-section design chart.

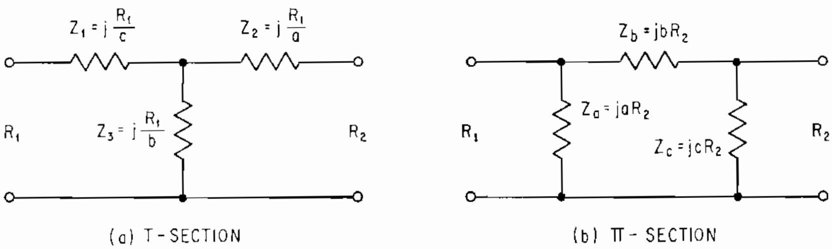


FIG. B-18. General T- and π-section impedance-matching network.

where a = design factor as shown in Figs. B-18 and B-19
b = design factor as shown in Figs. B-18 and B-19
c = design factor as shown in Figs. B-18 and B-19
$r = R_1/R_2$, ratio, greater than 1
β = phase shift, deg

The graphs of a, b, and c are shown in Figs. B-20 through B-24 where r is assumed to be equal or greater than unity. The terminals at R_1 can be placed at either the load or generator end of the section; hence the above equations can be applied to any case.

It is interesting to note that these design curves also apply for the L section where $a = r/\sqrt{r-1}$, $b = \sqrt{r-1}$, and $c = \infty$.

Transmission Lines

General. Most directional antennas require one or more RF transmission lines. They are usually operated nonresonant, which means that the load is made equal to the characteristic impedance of the transmission line. In this case the wave travels from the transmitter end to the load end and is completely absorbed by the load; therefore, there are no standing waves on the line. For this condition of operation the power loss and standing waves on the line are a minimum.

The general equations for the voltage and current at the sending and receiving end of a transmission line are

$$E_s = E_r \cosh \sqrt{ZY}\, l + I_r Z_0 \sinh \sqrt{ZY}\, l \tag{B-28}$$

$$I_s = I_r \cosh \sqrt{ZY}\, l + \frac{E_r}{Z_0} \sinh \sqrt{ZY}\, l \tag{B-29}$$

where E_s = sending end voltage, volts
E_r = receiving end voltage, volts
$Z = R + j\omega L$ = series impedance per unit length, ohms
$\gamma = G + j\omega C$ = shunt admittance per unit length, ohms
l = length of line in same units as Z and γ
$Z_0 = \sqrt{Z/Y}$ = characteristic impedance, ohms
$\gamma = \sqrt{ZY}$ = propagation constant, or hyperbolic angle per unit length, radians

Characteristic Impedance. The characteristic impedance at radio frequency can be taken as a pure resistance,

$$Z_0 = \sqrt{\frac{L}{C}} \tag{B-30}$$

where L = inductance per unit length, henrys
C = capacitance per unit length, farads

For a single coaxial transmission line this equation can be written

$$Z_0 = \frac{138}{\sqrt{\epsilon}} \log_{10} \frac{D}{d} \tag{B-31}$$

where ϵ = dielectric constant
D = inside diameter of outer conductor
d = outside diameter of inner conductor in the same units as D

For a parallel two-wire transmission line the characteristic impedance is

$$Z_0 = 120 \cosh^{-1} \frac{D}{d} \tag{B-32}$$

where D = spacing between conductor centers
d = diameter of conductors in same units as D

The characteristic impedance of coaxial and two-wire transmission lines is shown in Fig. B-25.

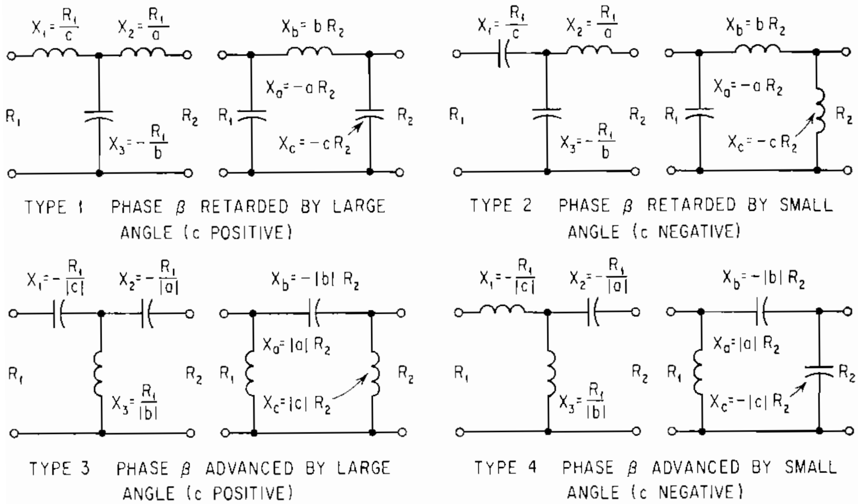


FIG. B-19. Specific three-element reactance networks.

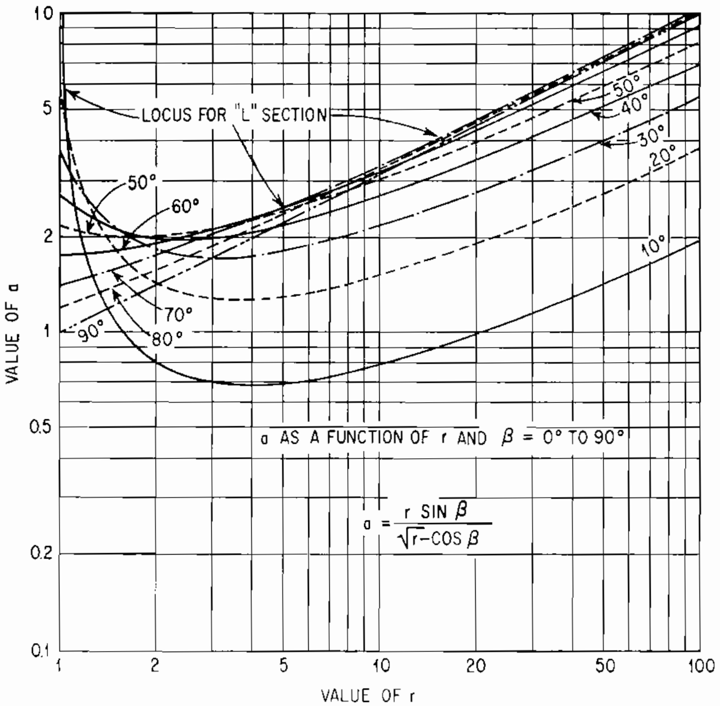


FIG. B-20. Design chart for a as function of r and $\beta = 0$ to 90°.

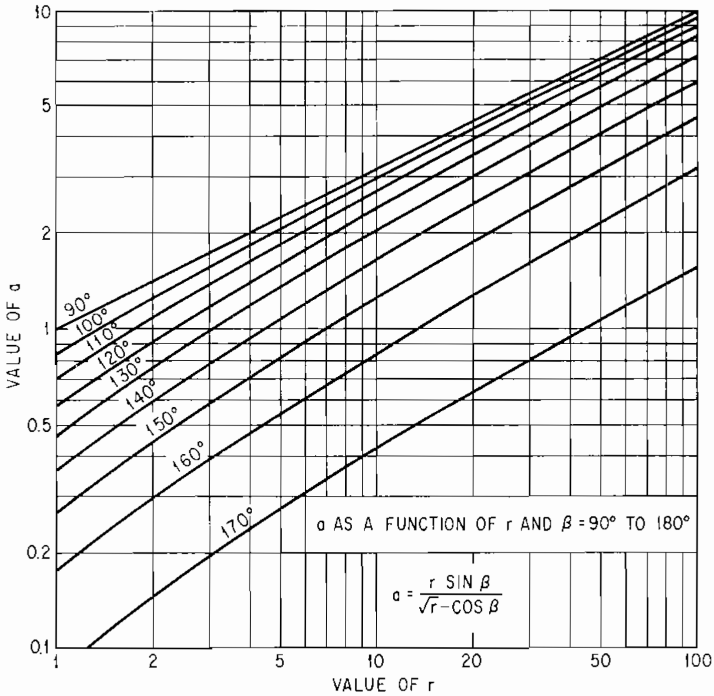


Fig. B-21. Design chart for a as function of r and β = 90 to 180°.

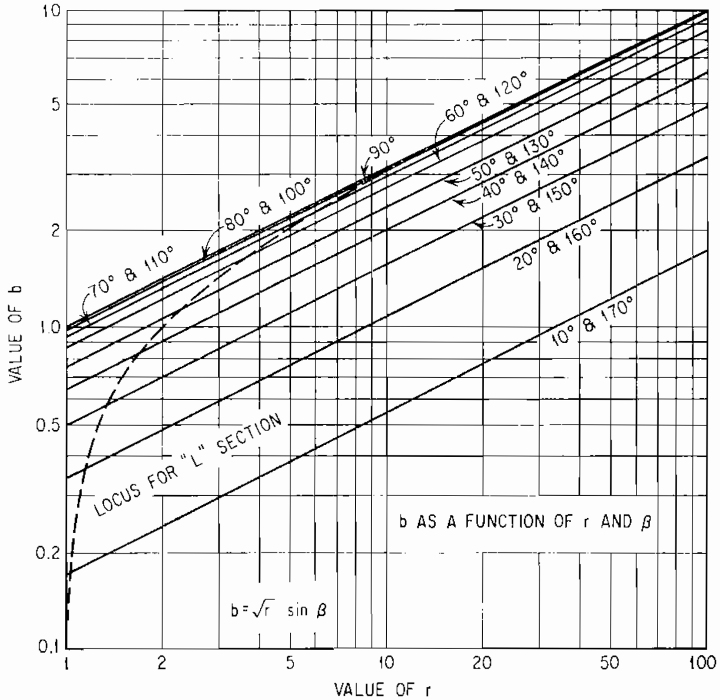


Fig. B-22. Design chart for b as function of r and β.

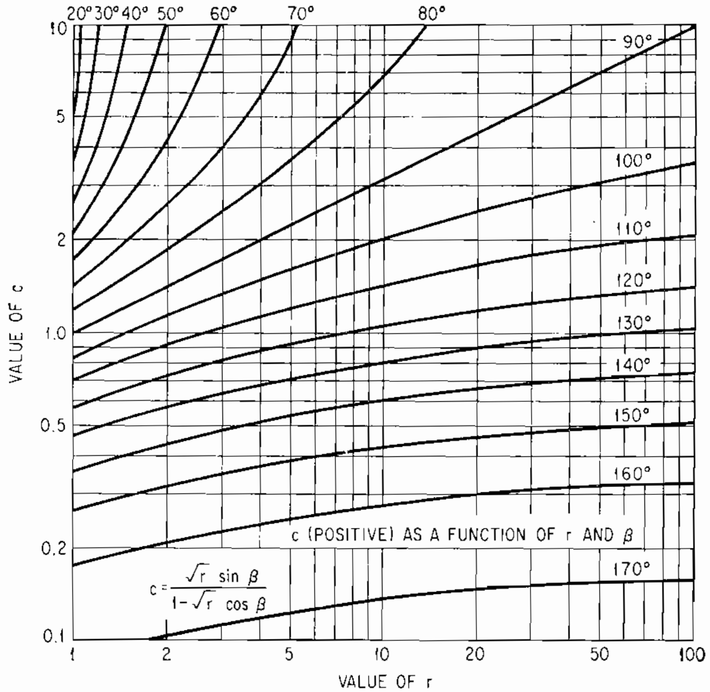


FIG. B-23. Design chart for c (positive) as function of r and β.

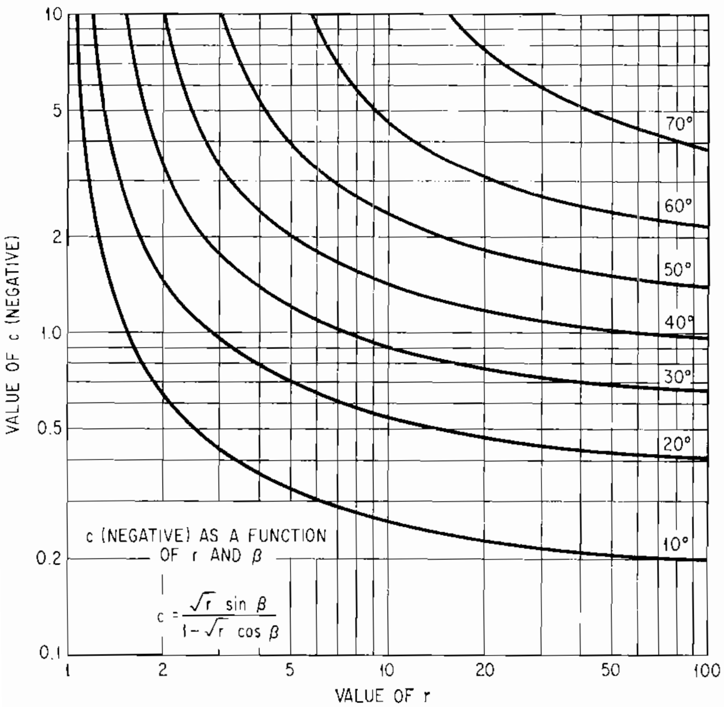


FIG. B-24. Design chart for c (negative) as function of r and β.

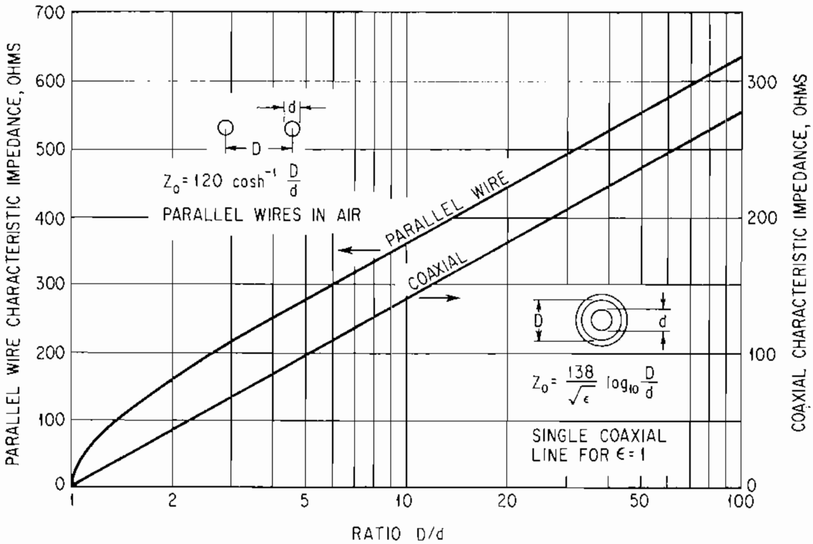


FIG. B-25. Characteristic impedance of coaxial and two-wire transmission lines.

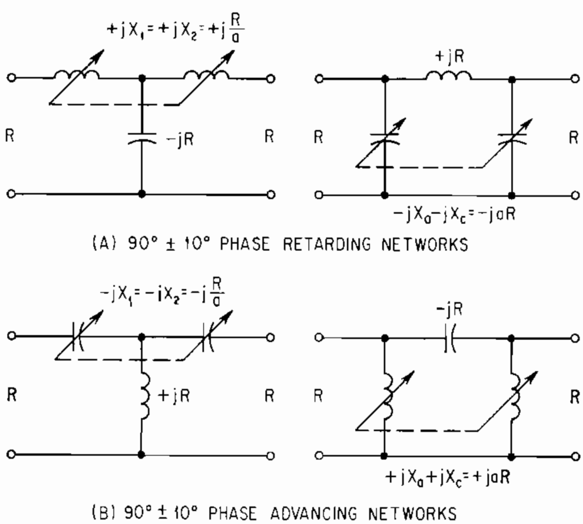


FIG. B-26. Phase-shifting networks.

Propagation Constant. The other factor of interest is the propagation constant given by

$$\sqrt{ZY} = \gamma = \alpha + j\beta \tag{B-33}$$

where γ = propagation constant, radians per unit length
α = attenuation constant, nepers per unit length
β = phase constant, radians per unit length

Usually the attenuation in the line can be neglected in the design of directional antennas, particularly if the line is designed for low loss and is operated nonresonant.

The phase shift in an air-dielectric line will be only a few per cent less than would occur in free space. For a coaxial line with ceramic beads the velocity factor is 0.85, while with solid polyethylene insulation the velocity factor is approximately 0.66. For two-wire lines insulated with ceramic spacers at intervals of a few feet the velocity factor is about 0.975. These factors must be taken into consideration when determining the phase shift in transmission lines of a directional-antenna system.

Phase-shifting Networks

In addition to the necessary phase shift in the networks and transmission lines of a feeder system, it is usually desirable to have a phase-shift network the control on which shifts the phase with little or no impedance transformation. This is readily accomplished in a 90° T or π section that has unity impedance transformation, $r = 1$, between input and output terminals.

In such a 90° T or π section the reactance arms all have the same magnitude and are equal to $R = R_1 = R_2$. The shunt arm in the T section or the series arm in the π section is held constant while the other two arms are varied in unison to shift the phase (see Figs. B-26 and B-27).

The value of the reactance in the series arms of a T section is

$$Z_1 = Z_2 = \pm jR \frac{1 - \cos\beta}{\sin\beta} = \pm j\frac{R}{a} \tag{B-34}$$

where $Z_1 = Z_2$ = series-arm reactance, ohms
$R = R_1 = R_2$ = terminating resistances, ohms
β = phase shift, deg

and the shunt arm of the T section is

$$Z_3 = \mp jR \frac{1}{\sin\beta} = \mp j\frac{R}{b} \tag{B-35}$$

where Z_3 is the shunt-arm reactance in ohms and the other values are given above.

The value of the resistance in the shunt arms of a π section is

$$Z_a = Z_c = \pm jR \frac{\sin\beta}{1 - \cos\beta} = \pm jaR \tag{B-36}$$

where $Z_a = Z_c$ = shunt-arm resistance, ohms
$R = R_1 = R_2$ = terminating resistances, ohms
β = phase shift, deg

and the series arm of the π section is

$$Z_b = \mp jR\sin\beta = \mp jbR \tag{B-37}$$

where Z_b is the series-arm reactance in ohms and the other values are defined above.

The phase shift for the approximation that $b = 1$ gives good answers for ±10° and can be written

$$\beta = \cos^{-1}\left(1 - \frac{R}{X_1}\right) = \cos^{-1}\left(1 - \frac{R}{X_a}\right) \tag{B-38}$$

where X_1 and X_a are the reactance values as shown in Fig. B-27 and the other values are defined above for the T- and π-section phase-shifting network.

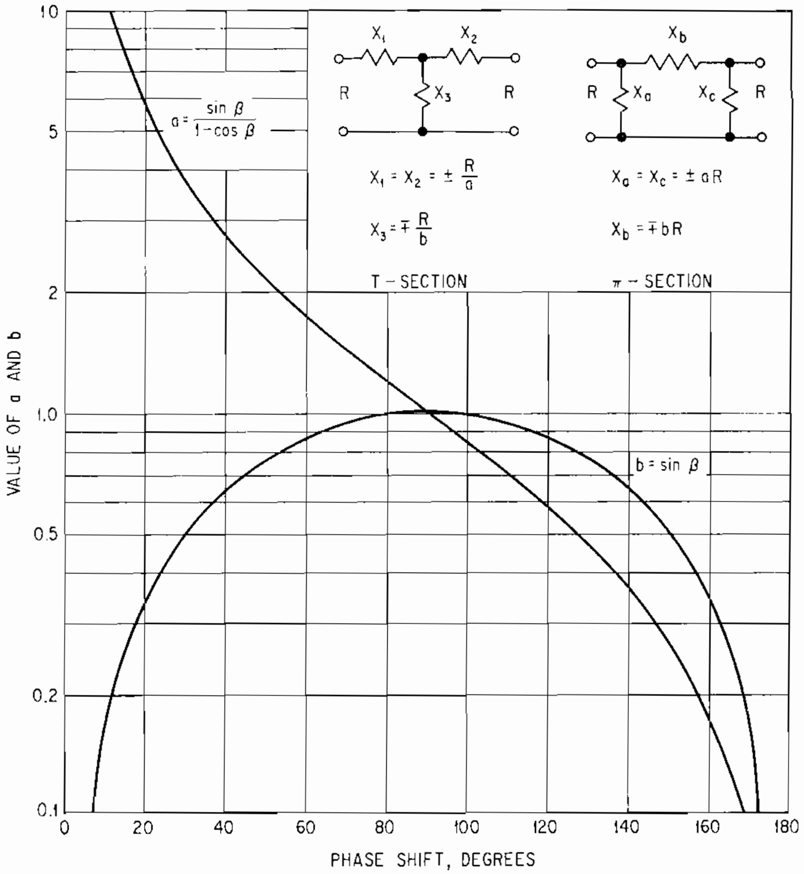


FIG. B-27. Phase-shifting-network curves.

Power-dividing Networks

The driving-point impedance at the base of each tower in a directional-antenna system must be fed the correct amount of power to make the array operate properly. The usual practice is to provide a power-dividing network near the common-point input to the feeder system as shown in Fig. 3-8.

Typical power-dividing networks are shown in Fig. B-28. Terminals 1 and 2 are the output terminals to towers 1 and 2, respectively. The transmitter is connected directly or through a matching section to the terminals marked IN. A common practice is to start with the phase at the antenna loop current and compute the phase shift back through the matching networks, transmission lines, and phase shifters to the output of the power divider. In case the power division is nearly equal and the feed lines need to be out of phase, the push-pull circuit in Fig. B-28*a* may be suitable. Where the feeder lines are in phase the series- or parallel-resonant circuits of Fig. B-28*b* or *c* are applicable. In some cases the feed lines may be in quadrature phase, so the circuit of Fig. B-28*d* can be used. If the power input to the feeder lines is known, then L sections can be designed to give the proper division as shown in Fig. B-28*e*.

Small and Large Values of Variable Reactance

The design of a feeder system should be such that adjustments can be made with ease in the field. Some ideas are given here that may be of help in new designs or modifications of existing designs to make them easier to adjust.

If a very low value of capacitive reactance is required, it can be obtained easily by placing an inductor in series with a capacitor as shown in Fig. B-29*a*. This arrangement makes it easy to obtain equivalent capacity values up to infinity when the circuit becomes series-resonant. Thus, it is possible to obtain values of inductive or capacitive reactance near zero values. This arrangement is often used in the shunt or series arms of a T or π section, so the correct value can be easily obtained. It is usually more satisfactory than providing a variable capacitor. In this arrangement care must be taken not to exceed the current rating of the capacitor. This discussion neglects the resistance component, which is usually very small.

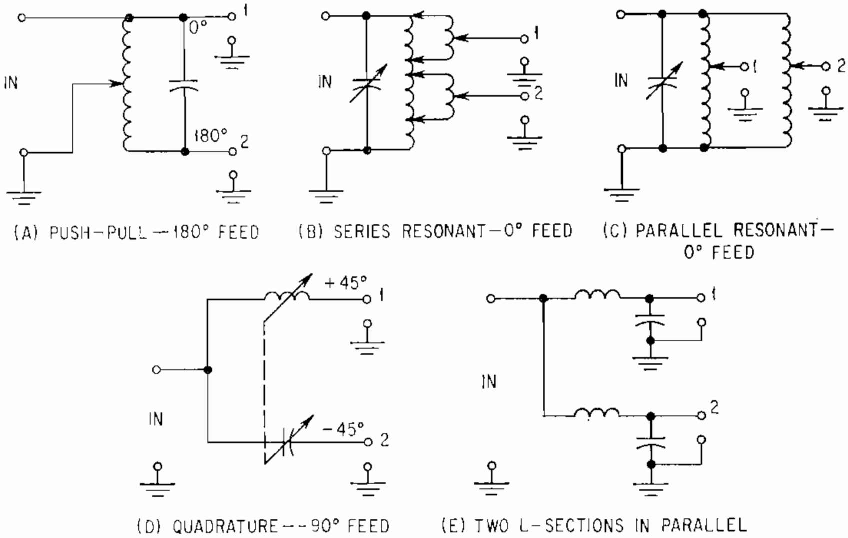


FIG. B-28. Typical power-dividing networks.

Sometimes it is necessary to obtain an inductive reactance larger than the reactance of available inductors. In such cases it is possible to parallel the coil with a very small capacitor. If the capacitor tap on the coil is moved as shown in Fig. B-29*b*, the desired value of inductive reactance can be achieved.

Adjustments

Theoretical Mesh Circuit Equation

In order to understand the operation of a directional-antenna system, it is desirable to understand how the circuit performs theoretically. With this understanding, it is easier to make the necessary adjustments. For a two-tower array the input terminals of the two towers can be considered to be a mesh circuit; hence the following simultaneous equations apply:

$$V_1 = I_1Z_{11} + I_2Z_{12} \qquad \text{(B-39)}$$

$$V_2 = I_1Z_{21} + I_2Z_{22} \qquad \text{(B-40)}$$

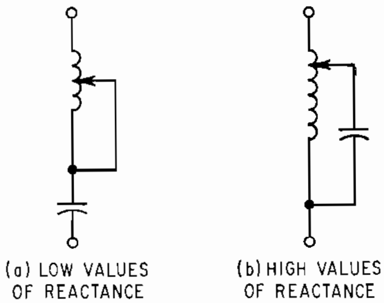


FIG. B-29. Methods of varying reactance.

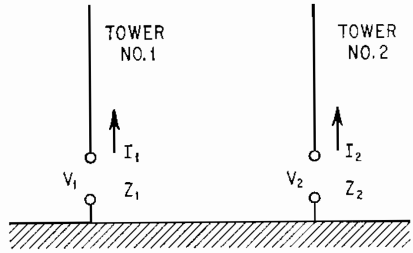


FIG. B-30. Two-tower input terminals.

where V_1 and V_2 = vector effective voltage at input terminals of towers 1 and 2 respectively, volts

I_1 and I_2 = vector effective current at input terminals of towers 1 and 2 respectively, amp

Z_{11} and Z_{22} = self-impedance of towers 1 and 2 respectively, ohms

$Z_{12} = Z_{21}$ = mutual impedance between towers 1 and 2, ohms

All the terms in the above mesh equations are complex quantities.

From this set of simultaneous equations it is possible to define the driving point impedance of each tower, thus

$$Z_1 = \frac{V_1}{I_1} = Z_{11} + \frac{I_2}{I_1} Z_{12} \tag{B-41}$$

$$Z_2 = \frac{V_2}{I_2} = \frac{I_1}{I_2} Z_{12} + Z_{22} \tag{B-42}$$

where Z_1 = driving-point impedance of tower 1 while array is in operation, ohms

Z_2 = driving-point impedance of tower 2 while array is in operation, ohms

The resistance component R_1 of Z_1 and R_2 of Z_2 is pure radiation resistance if there is no loss in the system. The directional-antenna system can be designed using this theoretical basis, and then from a knowledge of the system losses the driving-point impedances can be estimated with fair accuracy. (See Fig. B-30.)

Measured Base Self-impedance

If the towers are approximately 90° high or less and the spacing is not very close, then the self-impedance can be measured by leaving the terminals of tower 2 open while measuring the impedance of tower 1 with an RF bridge at the operating frequency. This can be seen by inspecting Eq. (B-41), where $I_2 = 0$; hence only Z_{11} will be measured for this condition.

Similarly, Z_{22} can be measured by leaving the terminals of tower 1 open while measuring at the terminals of tower 2.

Measured Base Mutual Impedance

This can be done by inserting a variable reactance in series with the terminals of tower 2 when the terminals of tower 1 are open and adjusting it so that only a pure resistance R_{22} remains. This can be done with an RF bridge. Tower 2 is now tuned to resonance at the operating frequency.

The next step is to drive tower 1 with a suitable voltage at the operating frequency and note the currents in towers 1 and 2 when tower 2 is tuned to resonance.

From these measurements the magnitude of the mutual impedance to a first approximation is

$$|Z_{12}| = -\frac{|I_2|}{|I_1|} R_{22} \tag{B-43}$$

The angle of the mutual impedance can best be approximated by using theoretical information. If the loop mutual-impedance phases are used, they must be delayed by the effective electrical distance of the loop above the tower base. If base mutual-impedance phases are used, they also must be delayed by the same effective electrical distance because they do not provide for time delay of the current to reach the loop position.

If the phase-monitoring system has been installed and is calibrated to read properly, it can be used to measure the phase of I_2 with respect to I_1 and thus provide the necessary phase angle of Z_{12}. This is a good way to check the theoretical values. It may be even a better check on the phase-monitor calibration.

The theoretical value of the magnitude of Z_{12} written $|Z_{12}|$ can be used in lieu of the above measured value. If the towers are near 180° in height, it is advisable to measure the mutual impedance. Also, if the spacing is less than 90°, the mutual-impedance values should be measured. In other words if the mutual impedance is large, it should be measured for best results.

Estimated Base Driving-point Impedance

The driving-point impedance Z_1 can now be estimated by using the above values of Z_{11} and Z_{12} along with the current ratio:

$$M_{21} = \frac{I_2}{I_1} \tag{B-44}$$

as specified in the directional-antenna design. When these values are substituted in Eq. (B-41), the driving-point impedance for tower 1 while the array is in operation results.

Similarly it is possible to obtain the driving-point impedance for tower 2.

Estimated Base Driving-point Current

Assuming no loss in the tower, insulators, or ground system, the authorized power input must be

$$P = |I_1|^2 R_1 + |I_2|^2 R_2 \tag{B-45}$$

Since the ratio of current is known, we can write

$$|I_1| = \frac{P}{R_1 + |M_{21}|^2 R_2} \tag{B-46}$$

and then,

$$|I_2| = |I_1|\,|M_{21}| \tag{B-47}$$

The above authorized power does not include the power allowed by FCC for feeder-system losses.

Feeder-system Adjustment

A good way to set up the feeder system is to make up dummy driving-point impedance loads with the aid of an RF bridge. If small components are available, only RF bridge measurements can be used. If larger resistors are used which will not change value when heated up with power, then the whole feeder system can be set up and adjusted for the correct power division using dummy driving-point impedance loads.

It is possible to adjust each transmission line to the tower input network using the dummy load, since the tower input impedance will not have the correct value until the whole directional-antenna system is operating properly. After these matching networks are adjusted with the RF bridge, it should not be necessary to make any further adjustments at this point. The networks at the towers can then be connected, and the completion of the feeder-system adjustments can usually be made at the common point where the power division and phasing controls are located.

Tower with Negative Resistance

In some directional-antenna systems a tower will have a negative resistance at the driving point. This means that power must be removed from the tower terminals. While the initial adjustments are made, this power can be dissipated, but for the final

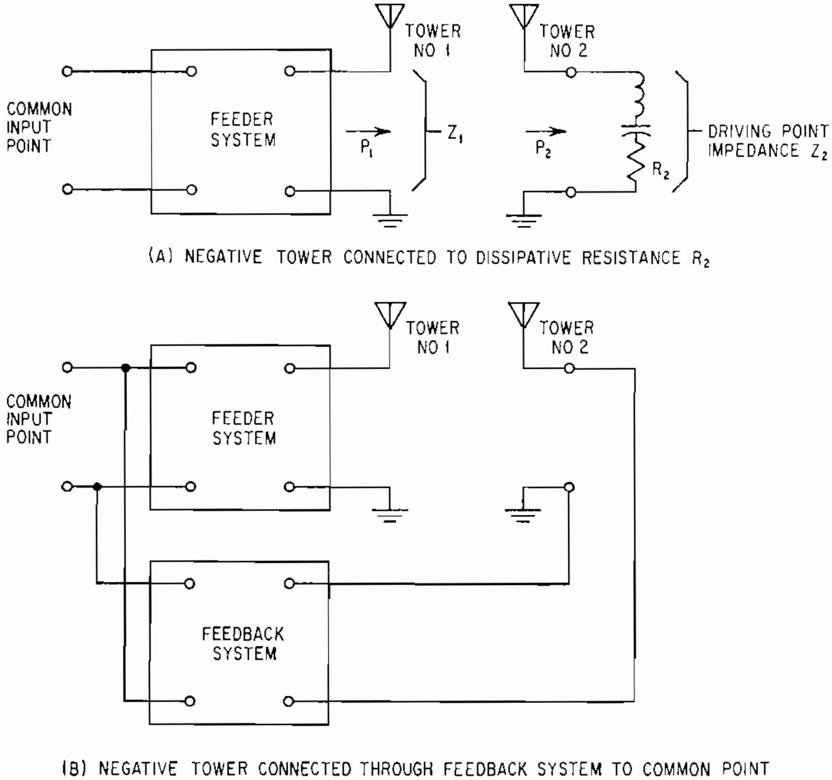


FIG. B-31. Addition of power from tower with negative resistance.

operation it is usually desirable to feed this power back into the system in order to maintain high efficiency.

In Fig. B-31*a* the antenna system is properly adjusted to give the required pattern shape but the power from tower 2 is being dissipated into a driving-point impedance with a negative resistance component. If the driving-point impedance of the negative tower is matched into a transmission line, this power can be fed back to the common-point input point as shown in Fig. B-31*b*. It is necessary to adjust the phase and magnitude of the feedback voltage properly so it will equal the magnitude and phase of the voltage where the feedback system is connected at the common point. Then the two circuits can be connected in parallel. The feedback system is used to control the phase and magnitude of the feedback voltage. When the feedback voltage is connected across the common-point input terminals, the input resistance will increase because the negative resistance in parallel with a positive resistance will have a resistance value larger than the positive resistance value alone.

In the design of the feeder system it is usually possible simply to tap on to the power-dividing network in the usual manner with the circuit to the tower having a negative resistance. In this case the phase shifts must be figured in the reverse direction owing to the reverse direction of power flow.

Table B-1. Minimum-depth Term *

F	$\frac{1}{F}$	F^2	$\frac{1+F^2}{2F}$	F	$\frac{1}{F}$	F^2	$\frac{1+F^2}{2F}$
0.995	1.0050	0.99002	1.00001	0.745	1.3422	0.55502	1.0436
0.990	1.0101	0.98010	1.00005	0.740	1.3513	0.54760	1.0457
0.985	1.0152	0.97022	1.00011	0.735	1.3605	0.54022	1.0478
0.980	1.0204	0.96040	1.00020	0.730	1.3698	0.53290	1.0499
0.975	1.0256	0.95062	1.00032	0.725	1.3793	0.52562	1.0522
0.970	1.0309	0.94090	1.00046	0.720	1.3888	0.51840	1.0544
0.965	1.0363	0.93122	1.00063	0.715	1.3986	0.51122	1.0568
0.960	1.0417	0.92160	1.00083	0.710	1.4084	0.50410	1.0592
0.955	1.0471	0.91202	1.00106	0.705	1.4184	0.49702	1.0617
0.950	1.0526	0.90250	1.00132	0.700	1.4285	0.49000	1.0643
0.945	1.0582	0.89302	1.0016	0.695	1.4388	0.48302	1.0669
0.940	1.0638	0.88360	1.0019	0.690	1.4492	0.47610	1.0696
0.935	1.0695	0.87422	1.0023	0.685	1.4598	0.46922	1.0724
0.930	1.0752	0.86490	1.0026	0.680	1.4705	0.46240	1.0753
0.925	1.0810	0.85562	1.0030	0.675	1.4814	0.45562	1.0782
0.920	1.0869	0.84640	1.0035	0.670	1.4925	0.44890	1.0812
0.915	1.0929	0.83722	1.0039	0.665	1.5037	0.44222	1.0844
0.910	1.0989	0.82810	1.0045	0.660	1.5151	0.43560	1.0875
0.905	1.1049	0.81902	1.0050	0.655	1.5267	0.42902	1.0909
0.900	1.1111	0.81000	1.0056	0.650	1.5384	0.42250	1.0942
0.895	1.1173	0.80102	1.0062	0.645	1.5503	0.41602	1.0977
0.890	1.1236	0.79210	1.0068	0.640	1.5625	0.40960	1.1012
0.885	1.1299	0.78322	1.0075	0.635	1.5748	0.40322	1.1049
0.880	1.1363	0.77440	1.0082	0.630	1.5873	0.39690	1.1086
0.875	1.1428	0.76562	1.0089	0.625	1.6000	0.39062	1.1125
0.870	1.1494	0.75690	1.0097	0.620	1.6129	0.38440	1.1164
0.865	1.1560	0.74822	1.0105	0.615	1.6260	0.37822	1.1205
0.860	1.1627	0.73960	1.0114	0.610	1.6393	0.37210	1.1246
0.855	1.1695	0.73102	1.0123	0.605	1.6528	0.36602	1.1289
0.850	1.1764	0.72250	1.0132	0.600	1.6666	0.36000	1.1333
0.845	1.1834	0.71402	1.0142	0.595	1.6806	0.35402	1.1378
0.840	1.1904	0.70560	1.0152	0.590	1.6949	0.34810	1.1425
0.835	1.1976	0.69722	1.0163	0.585	1.7094	0.34222	1.1472
0.830	1.2048	0.68890	1.0174	0.580	1.7241	0.33640	1.1521
0.825	1.2121	0.68062	1.0186	0.575	1.7391	0.33062	1.1571
0.820	1.2195	0.67240	1.0197	0.570	1.7543	0.32490	1.1621
0.815	1.2269	0.66422	1.0210	0.565	1.7699	0.31922	1.1675
0.810	1.2345	0.65610	1.0223	0.560	1.7857	0.31360	1.1728
0.805	1.2422	0.64802	1.0236	0.555	1.8018	0.30802	1.1784
0.800	1.2500	0.64000	1.0250	0.550	1.8181	0.30250	1.1841
0.795	1.2578	0.63202	1.0264	0.545	1.8348	0.29702	1.1899
0.790	1.2658	0.62410	1.0279	0.540	1.8518	0.29160	1.1959
0.785	1.2738	0.61622	1.0294	0.535	1.8691	0.28622	1.2021
0.780	1.2820	0.60840	1.0310	0.530	1.8867	0.28090	1.2084
0.775	1.2903	0.60062	1.0327	0.525	1.9047	0.27562	1.2149
0.770	1.2987	0.59290	1.0343	0.520	1.9230	0.27040	1.2215
0.765	1.3071	0.58522	1.0361	0.515	1.9417	0.26522	1.2284
0.760	1.3157	0.57760	1.0379	0.510	1.9607	0.26010	1.2354
0.755	1.3245	0.57002	1.0397	0.505	1.9802	0.25502	1.2426
0.750	1.3333	0.56250	1.0417	0.500	2.0000	0.25000	1.2500

* $(1 + F^2)/2F$ where either F or $1/F$ is the ratio of the inverse field strengths.

Table B-1. Minimum-depth Term (*Continued*)

F	$\frac{1}{F}$	F^2	$\frac{1+F^2}{2F}$	F	$\frac{1}{F}$	F^2	$\frac{1+F^2}{2F}$
0.495	2.0202	0.24502	1.2576	0.345	2.8985	0.11902	1.6218
0.490	2.0408	0.24010	1.2654	0.340	2.9411	0.11560	1.6406
0.485	2.0618	0.23522	1.2734	0.335	2.9850	0.11222	1.6600
0.480	2.0833	0.23040	1.2817	0.330	3.0303	0.10890	1.6802
0.475	2.1052	0.22562	1.2901	0.325	3.0769	0.10562	1.7010
0.470	2.1276	0.22090	1.2988	0.320	3.1250	0.10240	1.7225
0.465	2.1505	0.21622	1.3078	0.315	3.1746	0.09922	1.7448
0.460	2.1739	0.21160	1.3170	0.310	3.2258	0.09610	1.7679
0.455	2.1978	0.20702	1.3264	0.305	3.2786	0.09302	1.7918
0.450	2.2222	0.20250	1.3361	0.300	3.3333	0.09000	1.8167
0.445	2.2471	0.19802	1.3461	0.295	3.3898	0.08702	1.8424
0.440	2.2727	0.19360	1.3564	0.290	3.4482	0.08410	1.8691
0.435	2.2988	0.18922	1.3669	0.285	3.5087	0.08122	1.8969
0.430	2.3255	0.18490	1.3778	0.280	3.5714	0.07840	1.9257
0.425	2.3529	0.18062	1.3890	0.275	3.6363	0.07562	1.9557
0.420	2.3809	0.17640	1.4005	0.270	3.7037	0.07290	1.9869
0.415	2.4096	0.17222	1.4123	0.265	3.7735	0.07022	2.0193
0.410	2.4390	0.16810	1.4245	0.260	3.8461	0.06760	2.0531
0.405	2.4691	0.16402	1.4371	0.255	3.9215	0.06502	2.0883
0.400	2.5000	0.16000	1.4500	0.250	4.0000	0.06250	2.1250
0.395	2.5316	0.15602	1.4633	0.245	4.0816	0.06002	2.1633
0.390	2.5641	0.15210	1.4770	0.240	4.1666	0.05760	2.2033
0.385	2.5974	0.14822	1.4912	0.235	4.2553	0.05522	2.2451
0.380	2.6315	0.14440	1.5058	0.230	4.3478	0.05290	2.2889
0.375	2.6666	0.14062	1.5208	0.225	4.4444	0.05062	2.3347
0.370	2.7027	0.13690	1.5364	0.220	4.5454	0.04840	2.3827
0.365	2.7397	0.13322	1.5524	0.215	4.6511	0.04622	2.4331
0.360	2.7777	0.12960	1.5689	0.210	4.7619	0.04410	2.4860
0.355	2.8169	0.12602	1.5859	0.205	4.8780	0.04202	2.5415
0.350	2.8571	0.12250	1.6035	0.200	5.0000	0.04000	2.6000

Table B-2. Bessel Function, J_0 (S cos θ)

$S°$	Elevation angle, $\theta°$								
	0°	10°	20°	30°	40°	50°	60°	70°	80°
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3	0.999	0.999	0.999	0.999	1.000	1.000	1.000	1.000	1.000
4	0.999	0.999	0.999	0.999	0.999	0.999	1.000	1.000	1.000
5	0.998	0.998	0.998	0.999	0.999	0.999	1.000	1.000	1.000
6	0.997	0.997	0.998	0.998	0.998	0.999	0.999	1.000	1.000
7	0.996	0.996	0.997	0.997	0.998	0.998	0.999	1.000	1.000
8	0.995	0.995	0.996	0.996	0.997	0.998	0.999	0.999	1.000
9	0.994	0.994	0.995	0.995	0.996	0.997	0.998	0.999	1.000
10	0.992	0.993	0.993	0.994	0.996	0.997	0.998	0.999	1.000
11	0.991	0.991	0.992	0.993	0.995	0.996	0.998	0.999	1.000
12	0.989	0.989	0.990	0.992	0.994	0.996	0.997	0.999	1.000
13	0.987	0.988	0.989	0.990	0.992	0.995	0.997	0.998	1.000
14	0.985	0.986	0.987	0.989	0.991	0.994	0.996	0.998	1.000
15	0.983	0.983	0.985	0.987	0.990	0.993	0.996	0.998	0.999
16	0.981	0.981	0.983	0.985	0.985	0.992	0.995	0.998	0.999
17	0.978	0.979	0.981	0.984	0.987	0.991	0.994	0.997	0.999
18	0.976	0.976	0.978	0.982	0.985	0.990	0.994	0.997	0.999
19	0.973	0.974	0.976	0.980	0.986	0.989	0.993	0.997	0.999
20	0.970	0.971	0.973	0.977	0.982	0.987	0.992	0.996	0.999
21	0.967	0.968	0.971	0.975	0.980	0.986	0.992	0.996	0.999
22	0.964	0.965	0.968	0.973	0.973	0.985	0.991	0.996	0.999
23	0.960	0.961	0.965	0.970	0.977	0.983	0.970	0.975	0.999
24	0.957	0.958	0.962	0.967	0.974	0.982	0.985	0.995	0.999
25	0.953	0.954	0.958	0.965	0.972	0.980	0.988	0.994	0.999
26	0.949	0.951	0.955	0.962	0.970	0.979	0.987	0.994	0.998
27	0.945	0.947	0.953	0.959	0.968	0.977	0.986	0.994	0.998
28	0.941	0.943	0.948	0.956	0.965	0.976	0.985	0.993	0.998
29	0.937	0.939	0.944	0.953	0.963	0.974	0.984	0.993	0.998
30	0.933	0.935	0.940	0.949	0.960	0.972	0.983	0.992	0.998
31	0.928	0.930	0.936	0.946	0.958	0.970	0.982	0.992	0.998
32	0.924	0.926	0.932	0.942	0.955	0.968	0.981	0.991	0.998
33	0.919	0.921	0.928	0.939	0.952	0.966	0.979	0.990	0.998
34	0.914	0.916	0.924	0.935	0.945	0.964	0.978	0.990	0.997
35	0.905	0.912	0.919	0.931	0.941	0.962	0.977	0.985	0.997
36	0.904	0.907	0.915	0.927	0.943	0.960	0.976	0.989	0.997
37	0.899	0.901	0.910	0.923	0.940	0.957	0.974	0.986	0.997
38	0.893	0.896	0.905	0.919	0.937	0.955	0.973	0.987	0.997
39	0.888	0.891	0.900	0.915	0.933	0.953	0.971	0.987	0.997
40	0.882	0.885	0.895	0.911	0.930	0.950	0.970	0.986	0.996
41	0.876	0.880	0.890	0.906	0.926	0.948	0.968	0.985	0.996
42	0.870	0.874	0.885	0.902	0.923	0.945	0.967	0.984	0.996
43	0.864	0.868	0.880	0.897	0.919	0.943	0.965	0.984	0.996
44	0.858	0.862	0.874	0.892	0.915	0.940	0.963	0.983	0.996
45	0.852	0.856	0.868	0.888	0.913	0.937	0.962	0.982	0.995
46	0.845	0.850	0.862	0.883	0.908	0.935	0.960	0.981	0.995
47	0.839	0.843	0.857	0.878	0.904	0.932	0.958	0.980	0.995
48	0.832	0.837	0.851	0.873	0.900	0.929	0.957	0.980	0.995
49	0.825	0.830	0.845	0.868	0.896	0.926	0.955	0.979	0.994
50	0.818	0.823	0.838	0.862	0.891	0.923	0.953	0.978	0.994
51	0.812	0.817	0.832	0.857	0.887	0.920	0.951	0.977	0.994
52	0.804	0.810	0.826	0.851	0.883	0.917	0.949	0.976	0.994
53	0.797	0.803	0.820	0.846	0.878	0.913	0.947	0.975	0.994
54	0.790	0.796	0.813	0.840	0.874	0.910	0.945	0.974	0.993
55	0.783	0.789	0.807	0.835	0.869	0.907	0.943	0.973	0.993

Table B-2. Bessel Function, J_0 (S cos θ) (*Continued*)

$S°$	Elevation angle, $\theta°$								
	0°	10°	20°	30°	40°	50°	60°	70°	80°
56	0.775	0.782	0.800	0.829	0.865	0.904	0.941	0.972	0.993
57	0.767	0.774	0.793	0.823	0.860	0.900	0.939	0.971	0.993
58	0.760	0.767	0.786	0.817	0.855	0.897	0.937	0.970	0.992
59	0.752	0.759	0.779	0.811	0.850	0.893	0.935	0.969	0.992
60	0.744	0.751	0.772	0.805	0.845	0.890	0.933	0.968	0.992
61	0.736	0.743	0.765	0.799	0.840	0.886	0.930	0.967	0.991
62	0.728	0.735	0.758	0.792	0.835	0.883	0.928	0.966	0.991
63	0.720	0.728	0.750	0.786	0.830	0.879	0.926	0.965	0.991
64	0.712	0.720	0.743	0.780	0.825	0.875	0.923	0.964	0.991
65	0.703	0.712	0.735	0.773	0.820	0.871	0.921	0.963	0.990
66	0.695	0.703	0.728	0.766	0.815	0.867	0.919	0.962	0.990
67	0.686	0.695	0.720	0.760	0.810	0.863	0.916	0.960	0.990
68	0.678	0.686	0.712	0.753	0.804	0.860	0.914	0.959	0.989
69	0.669	0.678	0.704	0.746	0.798	0.856	0.911	0.958	0.989
70	0.660	0.669	0.696	0.739	0.792	0.851	0.909	0.957	0.989
71	0.652	0.661	0.688	0.732	0.787	0.847	0.906	0.956	0.988
72	0.642	0.652	0.680	0.725	0.781	0.843	0.904	0.954	0.988
73	0.634	0.643	0.672	0.718	0.776	0.839	0.901	0.953	0.988
74	0.625	0.635	0.664	0.711	0.770	0.835	0.898	0.952	0.987
75	0.615	0.626	0.656	0.703	0.764	0.830	0.896	0.950	0.987
76	0.606	0.617	0.648	0.697	0.758	0.826	0.893	0.949	0.987
77	0.597	0.607	0.639	0.689	0.752	0.822	0.890	0.948	0.986
78	0.588	0.599	0.631	0.682	0.746	0.818	0.887	0.947	0.986
79	0.578	0.589	0.622	0.674	0.740	0.813	0.884	0.945	0.986
80	0.569	0.580	0.613	0.667	0.734	0.808	0.882	0.944	0.985
81	0.559	0.571	0.605	0.659	0.728	0.804	0.879	0.943	0.985
82	0.550	0.561	0.596	0.652	0.722	0.799	0.876	0.941	0.985
83	0.540	0.552	0.587	0.644	0.715	0.794	0.873	0.939	0.984
84	0.531	0.543	0.579	0.636	0.709	0.790	0.870	0.938	0.984
85	0.521	0.535	0.570	0.628	0.702	0.785	0.867	0.937	0.983
86	0.511	0.524	0.561	0.620	0.696	0.780	0.864	0.935	0.983
87	0.502	0.515	0.552	0.612	0.689	0.775	0.861	0.934	0.983
88	0.492	0.505	0.543	0.604	0.683	0.770	0.858	0.933	0.982
89	0.482	0.495	0.534	0.596	0.678	0.766	0.854	0.931	0.982
90	0.472	0.486	0.525	0.588	0.670	0.761	0.851	0.929	0.981
91	0.462	0.476	0.516	0.580	0.663	0.756	0.848	0.928	0.981
92	0.452	0.466	0.506	0.572	0.656	0.751	0.845	0.926	0.981
93	0.442	0.456	0.497	0.564	0.649	0.746	0.842	0.924	0.980
94	0.432	0.447	0.488	0.556	0.643	0.741	0.839	0.923	0.980
95	0.422	0.437	0.479	0.547	0.636	0.735	0.835	0.921	0.979
96	0.412	0.427	0.470	0.539	0.629	0.730	0.832	0.920	0.979
97	0.402	0.417	0.461	0.531	0.622	0.725	0.829	0.918	0.978
98	0.392	0.407	0.451	0.522	0.615	0.720	0.825	0.916	0.978
99	0.382	0.397	0.442	0.514	0.608	0.714	0.822	0.915	0.977
100	0.372	0.387	0.432	0.506	0.601	0.709	0.818	0.913	0.977
101	0.361	0.377	0.423	0.497	0.594	0.703	0.815	0.911	0.977
102	0.352	0.367	0.414	0.489	0.587	0.698	0.812	0.909	0.976
103	0.341	0.357	0.404	0.480	0.579	0.693	0.808	0.908	0.976
104	0.331	0.347	0.395	0.471	0.572	0.687	0.804	0.906	0.975
105	0.321	0.337	0.385	0.463	0.565	0.682	0.801	0.904	0.975
106	0.311	0.327	0.375	0.454	0.558	0.676	0.797	0.902	0.974
107	0.301	0.317	0.366	0.446	0.551	0.671	0.793	0.900	0.974
108	0.290	0.307	0.356	0.437	0.543	0.665	0.790	0.899	0.973
109	0.281	0.297	0.347	0.428	0.536	0.660	0.786	0.897	0.973
110	0.270	0.287	0.337	0.419	0.528	0.654	0.783	0.895	0.972

Table B-2. Bessel Function, J_0 ($S \cos \theta$) (*Continued*)

$S°$	Elevation angle, $\theta°$								
	0°	10°	20°	30°	40°	50°	60°	70°	80°
111	0.260	0.277	0.328	0.411	0.521	0.648	0.779	0.893	0.972
112	0.250	0.267	0.318	0.402	0.513	0.642	0.775	0.891	0.971
113	0.240	0.257	0.309	0.393	0.506	0.636	0.771	0.890	0.971
114	0.230	0.247	0.299	0.385	0.498	0.630	0.767	0.888	0.970
115	0.220	0.237	0.290	0.376	0.491	0.625	0.763	0.886	0.970
116	0.210	0.227	0.280	0.367	0.484	0.619	0.760	0.884	0.969
117	0.200	0.217	0.271	0.359	0.476	0.613	0.756	0.882	0.969
118	0.190	0.208	0.261	0.350	0.468	0.607	0.752	0.880	0.968
119	0.180	0.198	0.252	0.341	0.461	0.601	0.748	0.878	0.968
120	0.170	0.188	0.242	0.332	0.453	0.596	0.744	0.876	0.967
121	0.160	0.178	0.233	0.323	0.445	0.590	0.740	0.874	0.967
122	0.150	0.168	0.223	0.314	0.438	0.584	0.736	0.872	0.966
123	0.140	0.158	0.214	0.306	0.430	0.578	0.732	0.870	0.965
124	0.130	0.148	0.204	0.297	0.422	0.572	0.728	0.868	0.965
125	0.120	0.139	0.195	0.288	0.415	0.565	0.724	0.866	0.964
126	0.111	0.129	0.185	0.279	0.407	0.559	0.720	0.864	0.964
127	0.101	0.120	0.176	0.270	0.400	0.553	0.716	0.861	0.963
128	0.092	0.110	0.167	0.261	0.392	0.547	0.712	0.859	0.963
129	0.082	0.101	0.158	0.253	0.384	0.541	0.707	0.857	0.962
130	0.072	0.091	0.148	0.244	0.376	0.535	0.703	0.855	0.961
131	0.063	0.082	0.139	0.235	0.368	0.529	0.699	0.853	0.961
132	0.053	0.072	0.129	0.227	0.360	0.522	0.695	0.851	0.960
133	0.044	0.063	0.120	0.218	0.353	0.516	0.690	0.848	0.960
134	0.035	0.053	0.111	0.209	0.345	0.510	0.686	0.846	0.958
135	0.026	0.044	0.102	0.201	0.337	0.503	0.682	0.844	0.958
136	0.017	0.035	0.093	0.192	0.329	0.497	0.678	0.842	0.958
137	0.007	0.026	0.094	0.183	0.321	0.491	0.673	0.840	0.957
138	−0.002	0.017	0.075	0.175	0.314	0.485	0.669	0.837	0.957
139	−0.011	0.008	0.066	0.166	0.308	0.478	0.665	0.835	0.956
140	−0.020	−0.001	0.058	0.158	0.299	0.472	0.660	0.833	0.955
141	−0.029	−0.010	0.049	0.149	0.291	0.466	0.656	0.830	0.955
142	−0.037	−0.019	0.040	0.141	0.283	0.459	0.652	0.828	0.954
143	−0.046	−0.028	0.031	0.132	0.275	0.453	0.647	0.826	0.954
144	−0.055	−0.036	0.022	0.124	0.267	0.446	0.642	0.823	0.953
145	−0.064	−0.045	0.013	0.115	0.259	0.440	0.638	0.821	0.952
146	−0.072	−0.053	0.005	0.107	0.252	0.434	0.634	0.819	0.952
147	−0.080	−0.062	−0.003	0.099	0.244	0.427	0.629	0.817	0.951
148	−0.088	−0.070	−0.012	0.090	0.236	0.420	0.625	0.814	0.950
149	−0.097	−0.078	−0.020	0.082	0.229	0.414	0.620	0.812	0.950
150	−0.105	−0.087	−0.029	0.073	0.221	0.408	0.615	0.809	0.949
151	−0.113	−0.095	−0.037	0.065	0.213	0.401	0.611	0.807	0.948
152	−0.121	−0.103	−0.045	0.057	0.205	0.395	0.606	0.805	0.947
153	−0.129	−0.111	−0.053	0.049	0.198	0.388	0.602	0.802	0.947
154	−0.137	−0.119	−0.062	0.040	0.190	0.382	0.597	0.800	0.946
155	−0.145	−0.126	−0.070	0.032	0.183	0.375	0.592	0.797	0.945
156	−0.153	−0.134	−0.078	0.024	0.175	0.368	0.587	0.795	0.945
157	−0.160	−0.142	−0.085	0.017	0.167	0.362	0.583	0.792	0.944
158	−0.167	−0.149	−0.093	0.009	0.160	0.356	0.578	0.790	0.943
159	−0.175	−0.157	−0.101	0.001	0.152	0.349	0.573	0.787	0.943
160	−0.182	−0.164	−0.108	−0.007	0.145	0.343	0.569	0.785	0.942
161	−0.189	−0.172	−0.116	−0.015	0.137	0.336	0.564	0.782	0.941
162	−0.196	−0.179	−0.123	−0.023	0.130	0.330	0.559	0.780	0.940
163	−0.203	−0.186	−0.131	−0.030	0.122	0.323	0.555	0.777	0.940
164	−0.210	−0.193	−0.138	−0.037	0.114	0.317	0.550	0.774	0.939
165	−0.217	−0.200	−0.146	−0.045	0.107	0.310	0.545	0.772	0.938

Table B-2. Bessel Function, J_0 (S cos θ) (*Continued*)

$S°$	Elevation angle, $\theta°$								
	0°	10°	20°	30°	40°	50°	60°	70°	80°
166	−0.223	−0.207	−0.153	−0.053	0.100	0.303	0.541	0.769	0.937
167	−0.230	−0.213	−0.159	−0.060	0.093	0.297	0.536	0.767	0.937
168	−0.236	−0.220	−0.167	−0.068	0.085	0.290	0.531	0.764	0.936
169	−0.242	−0.226	−0.173	−0.075	0.078	0.284	0.526	0.761	0.935
170	−0.249	−0.232	−0.180	−0.082	0.070	0.277	0.521	0.759	0.935
171	−0.255	−0.239	−0.187	−0.089	0.063	0.271	0.516	0.756	0.934
172	−0.261	−0.245	−0.194	−0.097	0.056	0.264	0.511	0.753	0.933
173	−0.266	−0.251	−0.200	−0.104	0.049	0.258	0.506	0.751	0.932
174	−0.272	−0.257	−0.207	−0.111	0.042	0.251	0.502	0.748	0.932
175	−0.278	−0.263	−0.213	−0.118	0.035	0.245	0.497	0.746	0.931
176	−0.283	−0.269	−0.220	−0.125	0.027	0.238	0.492	0.743	0.930
177	−0.289	−0.274	−0.226	−0.131	0.020	0.232	0.487	0.740	0.929
178	−0.294	−0.279	−0.232	−0.138	0.013	0.226	0.482	0.737	0.928
179	−0.299	−0.285	−0.238	−0.145	0.006	0.219	0.477	0.735	0.927
180	−0.304	−0.290	−0.244	−0.151	−0.001	0.212	0.472	0.732	0.927
181	−0.309	−0.295	−0.249	−0.158	−0.008	0.206	0.467	0.729	0.926
182	−0.314	−0.300	−0.255	−0.164	−0.015	0.200	0.462	0.726	0.925
183	−0.319	−0.305	−0.261	−0.171	−0.022	0.193	0.457	0.723	0.924
184	−0.323	−0.310	−0.266	−0.177	−0.028	0.187	0.452	0.721	0.923
185	−0.328	−0.315	−0.272	−0.183	−0.035	0.180	0.447	0.718	0.923
186	−0.332	−0.319	−0.277	−0.190	−0.041	0.174	0.442	0.715	0.922
187	−0.336	−0.324	−0.282	−0.196	−0.048	0.167	0.437	0.712	0.921
188	−0.340	−0.328	−0.287	−0.202	−0.055	0.161	0.432	0.709	0.920
189	−0.344	−0.332	−0.292	−0.208	−0.061	0.155	0.427	0.706	0.919
190	−0.348	−0.336	−0.297	−0.214	−0.068	0.148	0.422	0.704	0.918
191	−0.351	−0.340	−0.302	−0.219	−0.074	0.142	0.417	0.701	0.918
192	−0.355	−0.344	−0.307	−0.225	−0.081	0.136	0.412	0.698	0.917
193	−0.358	−0.348	−0.311	−0.231	−0.087	0.129	0.407	0.695	0.916
194	−0.362	−0.352	−0.316	−0.236	−0.094	0.123	0.402	0.692	0.915
195	−0.365	−0.355	−0.320	−0.242	−0.100	0.117	0.397	0.689	0.914
196	−0.368	−0.359	−0.324	−0.247	−0.106	0.110	0.392	0.686	0.913
197	−0.371	−0.362	−0.328	−0.252	−0.113	0.104	0.387	0.683	0.913
198	−0.374	−0.365	−0.332	−0.257	−0.119	0.098	0.382	0.680	0.912
199	−0.376	−0.368	−0.336	−0.262	−0.125	0.092	0.377	0.677	0.911
200	−0.379	−0.371	−0.340	−0.267	−0.131	0.086	0.372	0.674	0.910
201	−0.381	−0.374	−0.344	−0.272	−0.137	0.079	0.367	0.671	0.909
202	−0.383	−0.376	−0.347	−0.277	−0.143	0.073	0.361	0.668	0.908
203	−0.386	−0.379	−0.351	−0.282	−0.149	0.067	0.356	0.665	0.907
204	−0.388	−0.381	−0.354	−0.287	−0.154	0.061	0.351	0.662	0.906
205	−0.390	−0.383	−0.357	−0.292	−0.160	0.055	0.346	0.659	0.905
206	−0.391	−0.385	−0.360	−0.296	−0.166	0.049	0.341	0.656	0.904
207	−0.393	−0.387	−0.363	−0.301	−0.172	0.043	0.336	0.653	0.904
208	−0.394	−0.389	−0.366	−0.305	−0.177	0.037	0.331	0.650	0.903
209	−0.396	−0.391	−0.369	−0.309	−0.183	0.031	0.326	0.647	0.902
210	−0.397	−0.393	−0.372	−0.313	−0.188	0.025	0.321	0.644	0.901
211	−0.398	−0.394	−0.374	−0.317	−0.193	0.019	0.316	0.641	0.900
212	−0.399	−0.396	−0.377	−0.321	−0.199	0.013	0.311	0.638	0.899
213	−0.400	−0.397	−0.379	−0.325	−0.204	0.007	0.306	0.635	0.898
214	−0.401	−0.398	−0.382	−0.329	−0.209	0.001	0.301	0.632	0.897
215	−0.401	−0.399	−0.384	−0.333	−0.214	−0.004	0.296	0.629	0.896
216	−0.402	−0.400	−0.386	−0.336	−0.220	−0.010	0.291	0.626	0.895
217	−0.402	−0.401	−0.388	−0.340	−0.225	−0.016	0.285	0.623	0.894
218	−0.403	−0.401	−0.389	−0.343	−0.230	−0.022	0.280	0.620	0.893
219	−0.403	−0.402	−0.391	−0.346	−0.235	−0.027	0.275	0.616	0.892
220	−0.403	−0.402	−0.393	−0.350	−0.239	−0.032	0.270	0.613	0.892

Table B-2. Bessel Function, J_0 ($S \cos \theta$) (*Continued*)

$S°$	Elevation angle, $\theta°$								
	0°	10°	20°	30°	40°	50°	60°	70°	80°
221	−0.403	−0.403	−0.394	−0.353	−0.244	−0.038	0.265	0.610	0.891
222	−0.402	−0.403	−0.395	−0.356	−0.249	−0.044	0.260	0.607	0.890
223	−0.402	−0.403	−0.397	−0.359	−0.254	−0.049	0.255	0.604	0.889
224	−0.402	−0.403	−0.398	−0.362	−0.258	−0.055	0.250	0.601	0.888
225	−0.401	−0.403	−0.399	−0.364	−0.263	−0.061	0.245	0.597	0.887
226	−0.400	−0.402	−0.400	−0.367	−0.267	−0.066	0.240	0.594	0.886
227	−0.399	−0.402	−0.400	−0.370	−0.272	−0.072	0.235	0.591	0.885
228	−0.398	−0.401	−0.401	−0.372	−0.276	−0.077	0.230	0.588	0.884
229	−0.397	−0.401	−0.402	−0.374	−0.280	−0.083	0.225	0.585	0.883
230	−0.396	−0.400	−0.402	−0.377	−0.284	−0.088	0.220	0.581	0.882
231	−0.395	−0.399	−0.402	−0.379	−0.288	−0.093	0.215	0.578	0.881
232	−0.393	−0.398	−0.403	−0.381	−0.292	−0.099	0.210	0.575	0.880
233	−0.392	−0.397	−0.403	−0.383	−0.296	−0.104	0.205	0.572	0.879
234	−0.390	−0.396	−0.403	−0.385	−0.300	−0.109	0.200	0.568	0.878
235	−0.389	−0.395	−0.403	−0.387	−0.304	−0.114	0.195	0.565	0.877
236	−0.387	−0.393	−0.402	−0.388	−0.308	−0.119	0.190	0.562	0.876
237	−0.385	−0.391	−0.402	−0.390	−0.312	−0.124	0.185	0.559	0.875
238	−0.383	−0.389	−0.402	−0.391	−0.315	−0.129	0.180	0.555	0.874
239	−0.380	−0.388	−0.401	−0.393	−0.319	−0.134	0.175	0.552	0.873
240	−0.378	−0.386	−0.401	−0.394	−0.322	−0.139	0.170	0.549	0.871
241	−0.376	−0.384	−0.400	−0.395	−0.326	−0.144	0.165	0.546	0.870
242	−0.373	−0.382	−0.399	−0.397	−0.329	−0.149	0.160	0.543	0.869
243	−0.371	−0.380	−0.398	−0.398	−0.333	−0.154	0.155	0.540	0.868
244	−0.368	−0.377	−0.397	−0.399	−0.336	−0.159	0.150	0.536	0.867
245	−0.365	−0.375	−0.396	−0.399	−0.339	−0.164	0.145	0.533	0.866
246	−0.363	−0.372	−0.395	−0.400	−0.342	−0.168	0.140	0.530	0.865
247	−0.359	−0.370	−0.393	−0.401	−0.345	−0.173	0.135	0.526	0.864
248	−0.356	−0.367	−0.392	−0.401	−0.348	−0.178	0.130	0.523	0.863
249	−0.353	−0.364	−0.390	−0.402	−0.351	−0.183	0.125	0.520	0.862
250	−0.350	−0.361	−0.389	−0.402	−0.353	−0.187	0.120	0.516	0.861
251	−0.346	−0.358	−0.387	−0.402	−0.356	−0.192	0.116	0.513	0.860
252	−0.343	−0.355	−0.385	−0.403	−0.359	−0.196	0.111	0.510	0.859
253	−0.339	−0.352	−0.383	−0.403	−0.361	−0.201	0.106	0.506	0.858
254	−0.335	−0.349	−0.381	−0.403	−0.364	−0.205	0.101	0.503	0.857
255	−0.332	−0.346	−0.379	−0.403	−0.366	−0.209	0.097	0.500	0.856
256	−0.328	−0.342	−0.377	−0.402	−0.368	−0.214	0.092	0.496	0.855
257	−0.324	−0.339	−0.374	−0.402	−0.371	−0.218	0.087	0.493	0.854
258	−0.320	−0.335	−0.372	−0.402	−0.373	−0.222	0.082	0.489	0.852
259	−0.316	−0.331	−0.369	−0.401	−0.375	−0.226	0.077	0.486	0.851
260	−0.312	−0.327	−0.367	−0.401	−0.377	−0.231	0.072	0.483	0.850
261	−0.307	−0.324	−0.364	−0.400	−0.379	−0.235	0.067	0.479	0.849
262	−0.303	−0.320	−0.361	−0.400	−0.380	−0.239	0.063	0.476	0.848
263	−0.299	−0.316	−0.358	−0.399	−0.382	−0.243	0.058	0.472	0.847
264	−0.294	−0.312	−0.356	−0.398	−0.384	−0.247	0.053	0.469	0.846
265	−0.290	−0.307	−0.353	−0.397	−0.386	−0.251	0.049	0.466	0.844
266	−0.285	−0.303	−0.350	−0.396	−0.387	−0.255	0.044	0.462	0.843
267	−0.280	−0.299	−0.346	−0.395	−0.389	−0.259	0.039	0.459	0.842
268	−0.276	−0.294	−0.343	−0.393	−0.390	−0.262	0.035	0.455	0.841
269	−0.271	−0.290	−0.340	−0.392	−0.391	−0.266	0.030	0.452	0.840
270	−0.266	−0.285	−0.336	−0.391	−0.393	−0.270	0.026	0.449	0.839
271	−0.261	−0.281	−0.333	−0.389	−0.394	−0.274	0.021	0.446	0.838
272	−0.256	−0.276	−0.330	−0.387	−0.395	−0.277	0.017	0.442	0.837
273	−0.251	−0.271	−0.326	−0.385	−0.396	−0.281	0.012	0.439	0.835
274	−0.246	−0.267	−0.322	−0.384	−0.397	−0.284	0.007	0.435	0.834
275	−0.241	−0.262	−0.318	−0.382	−0.398	−0.288	0.003	0.432	0.833

Table B-2. Bessel Function, J_0 (S cos θ) (*Continued*)

$S°$	Elevation angle, $\theta°$								
	0°	10°	20°	30°	40°	50°	60°	70°	80°
276	−0.235	−0.257	−0.314	−0.380	−0.399	−0.291	−0.002	0.429	0.832
277	−0.230	−0.252	−0.310	−0.378	−0.399	−0.294	−0.006	0.425	0.831
278	−0.225	−0.247	−0.306	−0.376	−0.400	−0.298	−0.011	0.422	0.830
279	−0.219	−0.242	−0.302	−0.374	−0.401	−0.301	−0.015	0.418	0.829
280	−0.214	−0.236	−0.298	−0.372	−0.401	−0.304	−0.020	0.415	0.827
281	−0.208	−0.231	−0.294	−0.370	−0.402	−0.307	−0.024	0.411	0.826
282	−0.203	−0.226	−0.289	−0.367	−0.402	−0.311	−0.028	0.408	0.825
283	−0.197	−0.221	−0.285	−0.365	−0.402	−0.314	−0.033	0.404	0.824
284	−0.192	−0.215	−0.281	−0.362	−0.402	−0.317	−0.037	0.401	0.823
285	−0.186	−0.210	−0.276	−0.360	−0.403	−0.320	−0.042	0.397	0.822
286	−0.181	−0.205	−0.272	−0.357	−0.403	−0.323	−0.046	0.394	0.820
287	−0.175	−0.199	−0.267	−0.354	−0.403	−0.326	−0.050	0.390	0.819
288	−0.169	−0.194	−0.263	−0.351	−0.403	−0.328	−0.055	0.387	0.818
289	−0.163	−0.188	−0.258	−0.349	−0.403	−0.331	−0.059	0.384	0.817
290	−0.157	−0.182	−0.253	−0.346	−0.402	−0.334	−0.063	0.380	0.816
291	−0.151	−0.177	−0.248	−0.343	−0.402	−0.337	−0.068	0.377	0.814
292	−0.146	−0.171	−0.243	−0.340	−0.402	−0.339	−0.072	0.373	0.813
293	−0.140	−0.166	−0.238	−0.336	−0.401	−0.342	−0.076	0.370	0.812
294	−0.134	−0.160	−0.233	−0.333	−0.401	−0.344	−0.080	0.366	0.810
295	−0.128	−0.154	−0.228	−0.330	−0.400	−0.346	−0.084	0.363	0.809
296	−0.122	−0.148	−0.223	−0.326	−0.400	−0.349	−0.089	0.359	0.808
297	−0.116	−0.143	−0.218	−0.323	−0.399	−0.351	−0.093	0.356	0.807
298	−0.110	−0.137	−0.213	−0.320	−0.398	−0.354	−0.097	0.352	0.805
299	−0.104	−0.131	−0.208	−0.316	−0.397	−0.356	−0.101	0.349	0.804
300	−0.098	−0.125	−0.203	−0.313	−0.396	−0.358	−0.105	0.345	0.803
301	−0.092	−0.119	−0.198	−0.309	−0.395	−0.360	−0.109	0.342	0.802
302	−0.086	−0.113	−0.192	−0.305	−0.394	−0.362	−0.113	0.338	0.801
303	−0.080	−0.107	−0.187	−0.301	−0.393	−0.364	−0.117	0.335	0.799
304	−0.076	−0.101	−0.182	−0.298	−0.392	−0.366	−0.121	0.332	0.798
305	−0.068	−0.095	−0.176	−0.294	−0.391	−0.368	−0.125	0.328	0.797
306	−0.062	−0.090	−0.171	−0.290	−0.390	−0.370	−0.129	0.325	0.796
307	−0.056	−0.084	−0.165	−0.286	−0.388	−0.372	−0.133	0.321	0.794
308	−0.050	−0.078	−0.160	−0.282	−0.387	−0.374	−0.137	0.318	0.793
309	−0.044	−0.072	−0.155	−0.278	−0.385	−0.376	−0.141	0.314	0.792
310	−0.038	−0.066	−0.149	−0.273	−0.384	−0.377	−0.145	0.311	0.791
311	−0.032	−0.060	−0.144	−0.269	−0.382	−0.379	−0.149	0.307	0.789
312	−0.026	−0.054	−0.138	−0.265	−0.380	−0.380	−0.152	0.304	0.788
313	−0.020	−0.048	−0.133	−0.261	−0.379	−0.382	−0.156	0.300	0.787
314	−0.014	−0.042	−0.127	−0.256	−0.377	−0.383	−0.160	0.297	0.786
315	−0.008	−0.036	−0.122	−0.252	−0.375	−0.385	−0.163	0.293	0.784
316	−0.002	−0.030	−0.116	−0.248	−0.373	−0.386	−0.167	0.290	0.783
317	0.004	−0.024	−0.110	−0.243	−0.371	−0.387	−0.171	0.286	0.781
318	0.010	−0.018	−0.104	−0.239	−0.369	−0.389	−0.175	0.283	0.780
319	0.016	−0.013	−0.099	−0.234	−0.367	−0.390	−0.178	0.279	0.779
320	0.022	−0.007	−0.093	−0.229	−0.365	−0.391	−0.182	0.276	0.777
321	0.028	−0.001	−0.088	−0.225	−0.363	−0.392	−0.185	0.273	0.776
322	0.034	0.005	−0.082	−0.220	−0.360	−0.393	−0.189	0.269	0.775
323	0.039	0.011	−0.076	−0.215	−0.358	−0.394	−0.192	0.266	0.773
324	0.045	0.017	−0.071	−0.211	−0.356	−0.395	−0.196	0.262	0.772
325	0.051	0.023	−0.065	−0.206	−0.353	−0.396	−0.200	0.259	0.771
326	0.056	0.028	−0.059	−0.201	−0.351	−0.397	−0.203	0.255	0.770
327	0.062	0.034	−0.053	−0.196	−0.348	−0.397	−0.206	0.252	0.768
328	0.068	0.040	−0.048	−0.191	−0.345	−0.398	−0.210	0.248	0.767
329	0.073	0.046	−0.042	−0.186	−0.343	−0.399	−0.213	0.245	0.766
330	0.079	0.051	−0.037	−0.182	−0.340	−0.399	−0.217	0.241	0.764

Table B-2. Bessel Function, J_0 (S cos θ) (*Continued*)

$S°$	Elevation angle, $\theta°$								
	0°	10°	20°	30°	40°	50°	60°	70°	80°
331	0.085	0.057	−0.031	−0.177	−0.337	−0.400	−0.220	0.238	0.763
332	0.090	0.062	−0.025	−0.172	−0.334	−0.400	−0.223	0.234	0.762
333	0.095	0.068	−0.020	−0.167	−0.331	−0.401	−0.227	0.231	0.760
334	0.101	0.073	−0.014	−0.162	−0.328	−0.401	−0.230	0.227	0.759
335	0.106	0.079	−0.009	−0.157	−0.325	−0.402	−0.233	0.224	0.758
336	0.111	0.084	−0.003	−0.152	−0.322	−0.402	−0.236	0.221	0.756
337	0.116	0.090	0.003	−0.147	−0.319	−0.402	−0.239	0.218	0.755
338	0.122	0.095	0.008	−0.141	−0.316	−0.402	−0.242	0.214	0.754
339	0.127	0.100	0.014	−0.136	−0.313	−0.403	−0.245	0.211	0.752
340	0.132	0.106	0.020	−0.131	−0.310	−0.403	−0.249	0.207	0.750
341	0.137	0.111	0.025	−0.126	−0.307	−0.403	−0.252	0.204	0.749
342	0.142	0.116	0.031	−0.121	−0.303	−0.403	−0.255	0.200	0.748
343	0.147	0.121	0.036	−0.116	−0.300	−0.403	−0.258	0.197	0.746
344	0.151	0.126	0.042	−0.111	−0.297	−0.403	−0.261	0.193	0.745
345	0.156	0.131	0.047	−0.105	−0.293	−0.402	−0.263	0.190	0.744
346	0.161	0.136	0.052	−0.100	−0.290	−0.402	−0.266	0.187	0.742
347	0.166	0.141	0.058	−0.095	−0.286	−0.402	−0.269	0.183	0.741
348	0.170	0.146	0.063	−0.090	−0.282	−0.402	−0.272	0.180	0.740
349	0.175	0.151	0.068	−0.084	−0.279	−0.401	−0.275	0.176	0.738
350	0.170	0.155	0.073	−0.079	−0.275	−0.401	−0.278	0.173	0.737
351	0.184	0.160	0.079	−0.074	−0.271	−0.400	−0.281	0.169	0.735
352	0.188	0.164	0.084	−0.069	−0.268	−0.400	−0.283	0.166	0.734
353	0.192	0.169	0.089	−0.064	−0.264	−0.399	−0.286	0.163	0.732
354	0.197	0.173	0.094	−0.058	−0.260	−0.399	−0.289	0.159	0.731
355	0.201	0.178	0.099	−0.053	−0.257	−0.398	−0.291	0.156	0.730
356	0.205	0.182	0.104	−0.048	−0.253	−0.397	−0.294	0.152	0.729
357	0.209	0.187	0.109	−0.043	−0.249	−0.397	−0.297	0.149	0.727
358	0.213	0.191	0.114	−0.038	−0.245	−0.396	−0.299	0.146	0.726
359	0.216	0.194	0.119	−0.033	−0.241	−0.395	−0.302	0.142	0.724
360	0.220	0.199	0.124	−0.027	−0.237	−0.394	−0.304	0.139	0.723
361	0.224	0.203	0.128	−0.022	−0.233	−0.393	−0.307	0.136	0.722
362	0.228	0.207	0.133	−0.017	−0.228	−0.392	−0.309	0.132	0.720
363	0.231	0.211	0.138	−0.012	−0.224	−0.391	−0.312	0.129	0.719
364	0.234	0.215	0.143	−0.006	−0.220	−0.390	−0.314	0.125	0.717
365	0.238	0.218	0.147	−0.001	−0.216	−0.389	−0.316	0.122	0.716
366	0.241	0.222	0.152	0.004	−0.212	−0.388	−0.319	0.119	0.714
367	0.244	0.226	0.156	0.009	−0.208	−0.387	−0.321	0.116	0.713
368	0.247	0.229	0.161	0.014	−0.204	−0.386	−0.323	0.113	0.712
369	0.250	0.233	0.165	0.019	−0.199	−0.384	−0.325	0.109	0.710
370	0.253	0.236	0.170	0.024	−0.195	−0.383	−0.327	0.106	0.708
371	0.256	0.239	0.174	0.029	−0.191	−0.381	−0.330	0.103	0.707
372	0.259	0.242	0.178	0.034	−0.186	−0.380	−0.332	0.099	0.705
373	0.262	0.245	0.182	0.039	−0.182	−0.378	−0.334	0.096	0.704
374	0.264	0.248	0.186	0.044	−0.178	−0.377	−0.336	0.093	0.702
375	0.267	0.251	0.190	0.049	−0.173	−0.375	−0.338	0.089	0.701
376	0.269	0.254	0.194	0.054	−0.169	−0.374	−0.340	0.086	0.700
377	0.271	0.257	0.198	0.059	−0.164	−0.372	−0.342	0.083	0.698
378	0.274	0.260	0.202	0.064	−0.160	−0.370	−0.344	0.079	0.697
379	0.276	0.262	0.206	0.069	−0.156	−0.369	−0.346	0.076	0.695
380	0.278	0.265	0.210	0.074	−0.151	−0.367	−0.348	0.073	0.694
381	0.280	0.267	0.213	0.079	−0.147	−0.365	−0.349	0.070	0.692
382	0.282	0.270	0.217	0.084	−0.142	−0.363	−0.351	0.066	0.691
383	0.283	0.272	0.220	0.088	−0.138	−0.361	−0.353	0.063	0.689
384	0.285	0.274	0.224	0.093	−0.133	−0.359	−0.355	0.060	0.688
385	0.287	0.276	0.227	0.097	−0.128	−0.357	−0.357	0.057	0.686

Table B-2. Bessel Function, J_0 $(S \cos \theta)$ (*Continued*)

$S°$	Elevation angle, $\theta°$								
	0°	10°	20°	30°	40°	50°	60°	70°	80°
386	0.288	0.278	0.230	0.102	−0.124	−0.355	−0.358	0.053	0.685
387	0.290	0.280	0.233	0.107	−0.119	−0.353	−0.360	0.050	0.684
388	0.291	0.282	0.237	0.111	−0.115	−0.351	−0.362	0.047	0.682
389	0.292	0.284	0.240	0.116	−0.110	−0.349	−0.363	0.044	0.681
390	0.293	0.285	0.243	0.120	−0.106	−0.347	−0.365	0.040	0.679
391	0.295	0.287	0.246	0.125	−0.101	−0.345	−0.366	0.037	0.678
392	0.296	0.288	0.249	0.129	−0.097	−0.342	−0.368	0.034	0.676
393	0.296	0.290	0.251	0.134	−0.092	−0.340	−0.369	0.031	0.675
394	0.297	0.291	0.254	0.138	−0.087	−0.338	−0.371	0.028	0.673
395	0.298	0.292	0.257	0.142	−0.082	−0.335	−0.372	0.025	0.671
396	0.298	0.294	0.259	0.146	−0.078	−0.333	−0.374	0.021	0.670
397	0.299	0.295	0.262	0.151	−0.073	−0.331	−0.375	0.018	0.668
398	0.299	0.296	0.264	0.155	−0.069	−0.328	−0.376	0.015	0.667
399	0.300	0.297	0.267	0.159	−0.064	−0.326	−0.378	0.012	0.665
400	0.300	0.297	0.269	0.163	−0.060	−0.323	−0.379	0.009	0.664
401	0.300	0.298	0.271	0.167	−0.055	−0.321	−0.380	0.006	0.662
402	0.300	0.298	0.273	0.171	−0.050	−0.318	−0.381	0.003	0.661
403	0.300	0.299	0.275	0.175	−0.046	−0.315	−0.382	0.000(−)	0.659
404	0.300	0.299	0.277	0.179	−0.041	−0.313	−0.383	−0.003	0.658
405	0.300	0.300	0.279	0.183	−0.036	−0.310	−0.385	−0.006	0.656
406	0.299	0.300	0.281	0.186	−0.032	−0.307	−0.386	−0.009	0.655
407	0.299	0.300	0.283	0.190	−0.027	−0.304	−0.387	−0.012	0.653
408	0.298	0.300	0.284	0.194	−0.023	−0.302	−0.388	−0.016	0.652
409	0.298	0.300	0.286	0.198	−0.018	−0.299	−0.389	−0.019	0.650
410	0.297	0.300	0.287	0.201	−0.013	−0.296	−0.390	−0.022	0.648
411	0.296	0.300	0.289	0.204	−0.009	−0.293	−0.390	−0.025	0.647
412	0.296	0.299	0.290	0.208	−0.004	−0.290	−0.391	−0.028	0.645
413	0.295	0.299	0.291	0.211	0.000(+)	−0.287	−0.392	−0.031	0.644
414	0.294	0.298	0.293	0.215	0.005	−0.284	−0.393	−0.034	0.642
415	0.292	0.298	0.294	0.218	0.009	−0.281	−0.394	−0.037	0.641
416	0.291	0.297	0.295	0.221	0.014	−0.278	−0.394	−0.040	0.639
417	0.290	0.297	0.295	0.224	0.018	−0.275	−0.395	−0.043	0.638
418	0.289	0.296	0.296	0.227	0.023	−0.272	−0.396	−0.046	0.636
419	0.287	0.295	0.297	0.230	0.027	−0.269	−0.396	−0.049	0.635
420	0.286	0.294	0.298	0.233	0.032	−0.266	−0.397	−0.052	0.633

APPENDIX C. DIRECTIONAL ANTENNAS HAVING MORE THAN TWO TOWERS

A Three-tower-in-line-array Pattern Shape

Three towers in line spaced an equal distance between adjacent towers and with the end towers having equal inverse fields and phasings that are equal but opposite in sign are shown in Fig. C-1*a*. The resultant inverse field strength at 1 mile in the direction of any point P in the horizontal plane is shown in the vector diagram of Fig. C-1*b*. The resultant vector E always lies along the vector reference axis. This simplifics the pattern computations.

The resultant inverse field strength E at 1 mile in the direction of point P in the horizontal plane is given by

$$E = E_1\underline{|0} + E_2\underline{|\beta_2} + E_3\underline{|\beta_3} \tag{C-1}$$

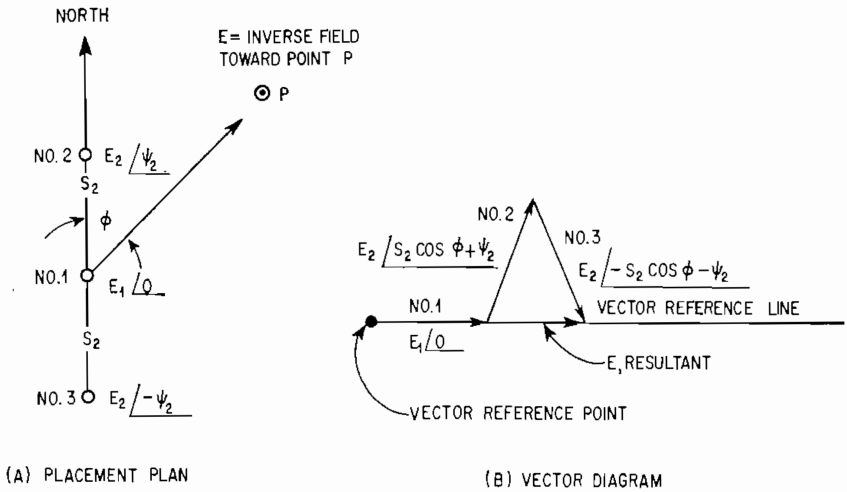


FIG. C-1. Three-tower-in-line array.

where E = resultant inverse field strength at 1 mile, mv/m
E_1 = inverse field strength from tower 1 at 1 mile while array is in operation, mv/m
E_2 = inverse field strength from towers 2 and 3 at 1 mile while array is in operation, mv/m

$$\beta_2 = -\beta_3 = S_2 \cos \phi + \Psi_2 \tag{C-2}$$

where S_2 = spacing from tower 1 to 2 and 3, deg
ϕ = azimuth angle to observation point P, deg
Ψ_2 = phase of tower 2 with respect to tower 1, deg

The magnitude of E in the above equation can be written

$$E = E_1(1 + 2F_2 \cos \beta_2) \tag{C-3}$$

where $F_2 = E_2/E_1$. This equation is in convenient form for computing the horizontal pattern. It can also be used to determine the effect of any change in the design parameters. For example, for a given spacing $S_2 = 90°$ and direction $\phi = 60°$, the equation can be written

$$E = E_1[1 + 2F_2 \cos (45 + \Psi_2)] \tag{C-4}$$

If $F_2 = 0.5$, then the equation becomes

$$E = E_1[1 + \cos (45 + \Psi_2)] \tag{C-5}$$

Now when Ψ_2 is selected properly, E can be made to have any value from 0 to $2E_1$. If E is to be zero at 60 and 300°, since the pattern is symmetrical, then $\cos (45 + \Psi_2) = -1$ or $\Psi_2 = 135°$. For this condition the horizontal-pattern equation is written:

$$E = E_1[1 + \cos (90 \cos \phi + 135)] \tag{C-6}$$

When ϕ is varied from 0 to 180°, the complete pattern can be determined because it is symmetrical around the line of towers.

In general a three-tower-in-line array will produce a pattern with four nulls. Actually the pattern of Eq. (C-6) has four nulls, but two occur at $\phi = 60°$, and two occur at $\phi = 300°$. This results in wider angles of low field strength at these two bearings than would be the case with single nulls.

The multiplication form for three towers in line is a more useful form and in the horizontal plane is written

$$E = 2E_1\sqrt{F_2F_3}\left[\left(\frac{1 + F_2^2}{2F_2} + \cos\beta_2\right)\left(\frac{1 + F_3^2}{2F_3} + \cos\beta_3\right)\right]^{1/2} \tag{C-7}$$

where $F_2 = E_2/E_1$
$F_3 = E_3/E_1$
$\beta_2 = S_2 \cos\phi + \Psi_2$
$\beta_3 = -S_3 \cos\phi - \Psi_3$

and the other values are defined above. Each parenthesis term in Eq. (C-7) gives the pattern shape for two towers. The resulting pattern is produced by multiplying these terms together and taking the square root. With this design the direction of the nulls can be controlled for each pair of towers, the center tower in this case acting like two towers. If F_2 and F_3 are other than unity, a minimum rather than a null will result. Thus it is possible to fill in one pair of nulls independently of the other set.

Attention is directed to the minimum-depth terms

$$\frac{1 + F_2^2}{2F_2} \quad \text{and} \quad \frac{1 + F_3^2}{2F_3}$$

which can be determined from Table B-1. The actual values of F_2 and F_3 or their reciprocal values can be used to obtain the same result. If the actual reciprocal values are used to make adjustments in the field, this fact should be made clear in the report to FCC and there should be no objection on their part.

Four-tower Parallelogram-array Pattern Shape

General Case

The plan configuration of a four-tower parallelogram array is shown in Fig. C-2 along with the related vector diagram. The general equation for the pattern can be written

$$E = E_1 f_1(\theta)[1 + F_2^2 + F_3^2 + F_4^2 + 2F_2\cos\beta_2 + 2F_3\cos\beta_3 + 2F_4\cos\beta_4 + 2F_2F_4\cos(\beta_2 - \beta_4) + 2F_2F_3\cos(\beta_2 - \beta_3) + 2F_3F_4\cos(\beta_3 - \beta_4)]^{1/2} \tag{C-8}$$

where E = inverse field strength at 1 mile in direction of point P, mv/m

$\beta_2 = S_2\cos(\phi_2 - \phi)\cos\theta + \Psi_2$

$\beta_3 = S_3\cos(\phi_3 - \phi)\cos\theta + \Psi_2$

$\beta_4 = S_4\cos(\phi_4 - \phi)\cos\theta + \Psi_2$

$F_2 = \dfrac{E_2 f_2(\theta)}{E_1 f_1(\theta)}$

$F_3 = \dfrac{E_3 f_3(\theta)}{E_1 f_1(\theta)}$

$F_4 = \dfrac{E_4 f_4(\theta)}{E_1 f_1(\theta)}$

E_1, E_2, E_3, and E_4 = inverse field strength at 1 mile produced by towers 1 to 4, respectively when, the array is in operation, mv/m

$f_1(\theta)$, $f_2(\theta)$, $f_3(\theta)$, and $f_4(\theta)$ = vertical radiation characteristic of towers 1 to 4, respectively

This equation is valid for towers of unequal height but is of a form seldom used. If the restriction $\beta_4 = \beta_2 + \beta_3$ and $F_4 = F_2F_3$ is applied, Eq. (C-8) can be written

$$E = 2E_1 f_1(\theta)\sqrt{F_2F_3}\left[\left(\frac{1 + F_2^2}{2F_2} + \cos\beta_2\right)\left(\frac{1 + F_3^2}{2F_3} + \cos\beta_3\right)\right]^{1/2} \tag{C-9}$$

where the terms are defined above.

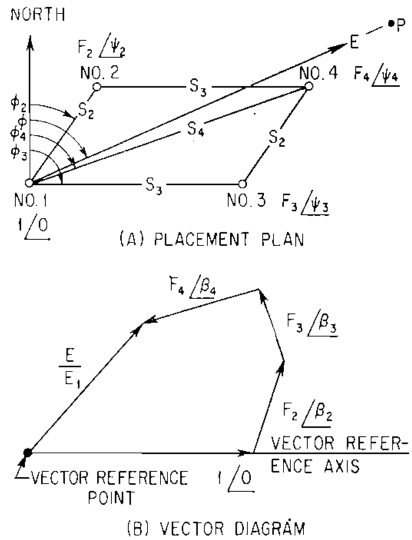


Fig. C-2. General parallelogram array.

It is noted that tower 4 must have the following field ratio:

$$F_4 = F_2F_3 = \frac{E_2f_2(\theta)E_3f_3(\theta)}{E_1^2f_1^2(\theta)} \tag{C-10}$$

If $E_1 = E_2 = E_3$, then the vertical-radiation characteristics of tower 4 must be

$$f_4(\theta) = \frac{f_2(\theta)f_3(\theta)}{f_1^2(\theta)} \tag{C-11}$$

Since all $f(\theta)$ values are unity along the ground, this condition cannot be detected in the horizontal plane. However, if the parallelogram array is operated at night when high angle radiation is involved, it is necessary to compute the radiation at various elevation angles and the above equation must be considered.

The greatest practical value of Eq. (C-9) is that it gives information concerning the exact location of the four minima, two for each of the two-tower patterns unless spacings greater than 180° are used, and in such cases there may be four minima per two-tower pattern. This information is useful in the design and adjustment of the parallelogram array. It comes from the condition when $\beta = 180°$.

Then the minimum-depth terms give useful information concerning the value of field strength to be expected in these directions. They are helpful in shaping the pattern to meet the design requirements.

The expression inside the brackets completely defines the pattern shape. The factor $2E_1f_1(\theta)\sqrt{F_2F_3}$ outside the bracket defines the pattern size, especially the term E_1, which will be evaluated in a later section of this appendix.

Special Three-tower-in-line Case

If tower 2 is placed on top of tower 3, a three-tower-in-line array will result as shown in Fig. C-2. This arrangement is redrawn in Fig. C-3.

Special Three Towers Not in Line

If in Eq. (C-8) the condition that $F_4 = 0$ is imposed, the equation reduces to

$$E = E_1f_1(\theta)\left[2F_2\left(\frac{1+F_2^2}{2F_2} + \cos\beta_2\right) + 2F_3\left(\frac{1+F_3^2}{2F_3} + \cos\beta_3\right) - 1 + 2F_2F_3\cos(\beta_2-\beta_3)\right]^{1/2} \tag{C-12}$$

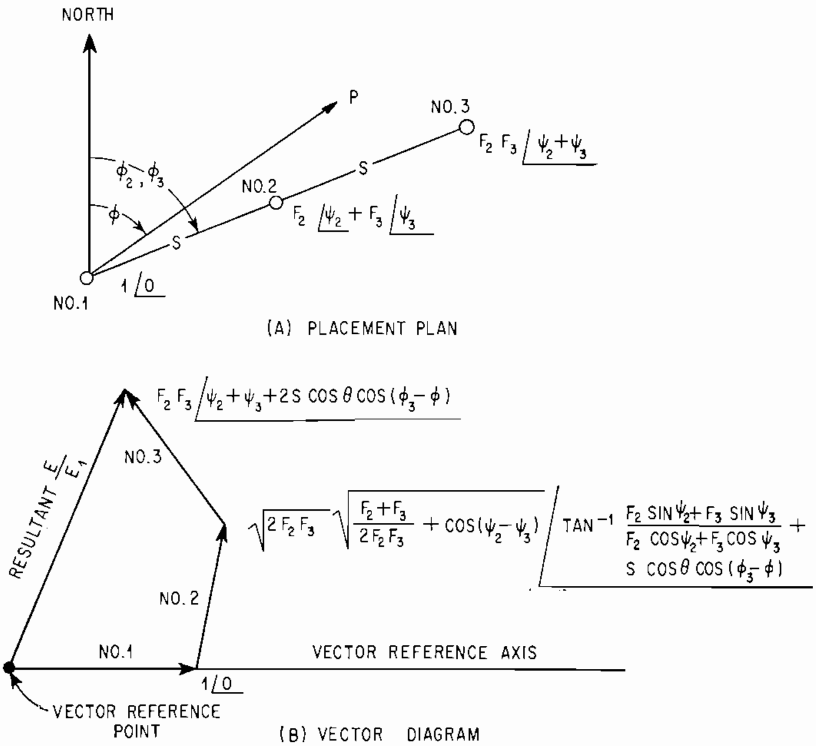


FIG. C-3. Special three-tower-in-line array.

This equation is essentially an addition formula for a three-tower-not-in-line array as shown in Fig. C-4 plus the variable term $2F_2F_3 \cos(\beta_2 - \beta_3) - 1$. The -1 merely translates the sum of the other three terms to the left one unit. Hence it remains only to find how the pattern changes with the addition of the two patterns plus the term $2F_2F_3 \cos(\beta_2 - \beta_3)$. The effect of change in parameter values can be noted in the computations. The information can be very useful in making adjustments on this type of array.

Pattern-size Determination

Four-tower Array

The equation to determine the field strength from the reference tower 1 is

$$E_1 = E_{1s}\sqrt{\frac{R_{11}}{R_1 + M_{21}{}^2R_2 + M_{31}{}^2R_3 + M_{41}{}^2R_4}} \tag{C-13}$$

where E_1 = inverse field strength at 1 mile in horizontal plane from tower 1 while operating in the array, mv/m

E_{1s} = inverse field strength at 1 mile in horizontal plane from tower 1 operating alone, mv/m

R_1, R_2, R_3, and R_4 = driving-point resistance values at input terminals of towers 1 to 4 respectively, ohms

M_{21}, M_{31}, and M_{41} = loop-current ratios of towers 2, 3 and 4 to tower 1, respectively

Only magnitude values are used in the above equation. The driving-point resistances, as in Eq. (B-5), are made up of self-, mutual-, and loss-resistance terms.

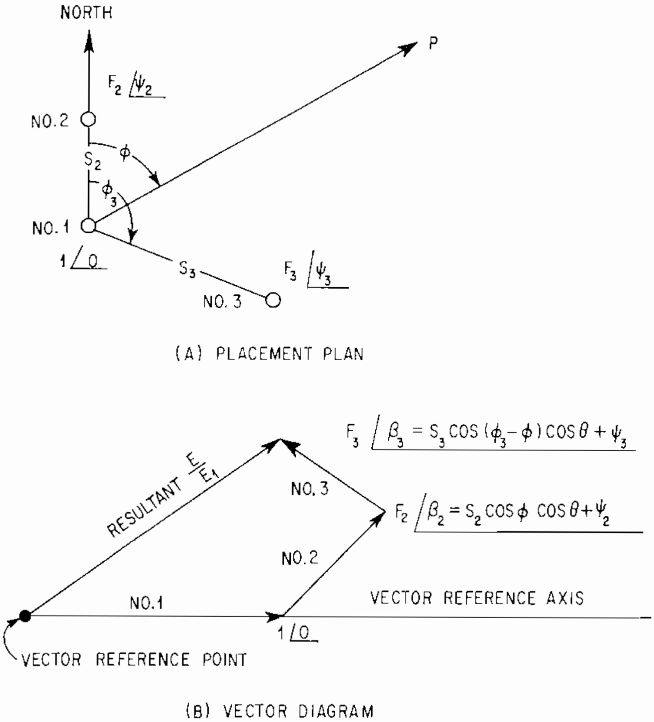


FIG. C-4. Special three-tower-not-in-line case.

They can be written

$$R_1 = R_{11} + R_{L1} + R_{C1} \tag{C-14}$$

$$R_2 = R_{22} + R_{L2} + R_{C2} \tag{C-15}$$

$$R_3 = R_{33} + R_{L3} + R_{C3} \tag{C-16}$$

$$R_4 = R_{44} + R_{L4} + R_{C4} \tag{C-17}$$

where R_{11}, R_{22}, R_{33}, and R_{44} = self-loop radiation resistance of towers 1 to 4, respectively, ohms

R_{L1}, R_{L2}, R_{L3}, and R_{L4} = loop-loss resistance of towers 1 to 4, respectively, ohms

R_{C1}, R_{C2}, R_{C3}, and R_{C4} = loop-coupled resistance of towers 1 to 4, respectively, ohms

In Eq. (C-13) the value of E_{1s}, R_{11}, R_{22}, R_{33}, and R_{44} can be obtained from Fig. A-5. R_{L1}, R_{L2}, R_{L3}, and R_{L4} are usually assumed to be 2 ohms for towers 90° high or taller. The values of coupled resistance can be obtained from the mutual-impedance terms in mesh circuit equations, which can be written

$$R_{C1} = M_{21}Z_{12}\cos(\Psi_{12} + \gamma_{12}) + M_{31}Z_{13}\cos(\Psi_{13} + \gamma_{13}) + M_{41}Z_{14}\cos(\Psi_{14} + \gamma_{14}) \tag{C-18}$$

$$R_{C2} = M_{12}Z_{21}\cos(\Psi_{21} + \gamma_{21}) + M_{33}Z_{23}\cos(\Psi_{23} + \gamma_{23}) + M_{42}Z_{24}\cos(\Psi_{24} + \gamma_{24}) \tag{C-19}$$

$$R_{C3} = M_{13}Z_{31}\cos(\Psi_{31} + \gamma_{31}) + M_{23}Z_{32}\cos(\Psi_{32} + \gamma_{32}) + M_{43}Z_{34}\cos(\Psi_{34} + \gamma_{34}) \tag{C-20}$$

$$R_{C4} = M_{14}Z_{41}\cos(\Psi_{41} + \gamma_{41}) + M_{24}Z_{42}\cos(\Psi_{42} + \gamma_{42}) + M_{34}Z_{43}\cos(\Psi_{43} + \gamma_{43}) \tag{C-21}$$

where $Z_{pq} = Z_{qp}$ = magnitude of loop mutual impedance between tower p and tower q, ohms

$\gamma_{pq} = \gamma_{qp}$ = angle of loop mutual impedance between tower p and tower q, deg

$\Psi_{pq} = -\Psi_{qp}$ = electrical phasing of tower q with respect to tower p, deg

The loop coupled reactance X_{c1}, X_{c2}, X_{c3}, and X_{c4} of towers 1 to 4, respectively can be calculated from Eqs. (C-18) to (C-21) by replacing cos by sin throughout. The coupled reactance values are not needed for the determination of the size of E_1. However, they are useful when it comes to determining the driving-point impedances and setting up the matching networks at the towers.

The mutual-impedance terms required above for ordinary equal-height towers are shown in Fig. B-14. The mutual impedance between top-loaded towers may be assumed equal to the mutual impedance between the same towers not top-loaded in most cases.

The above equations can also be applied to top-loaded sectionalized towers but with major problems. The radiation E_{1s} and self-resistance values are not readily available in general. Also, the mutual impedances must be calculated except for special cases which are available.

When E_1 is determined by Eq. (C-13), the pattern can be plotted to its exact size.

Three-tower Array

The equation to determine the field strength for a three-tower array can be written

$$E_1 = E_{1s}\sqrt{\frac{R_{11}}{R_1 + M_{21}{}^2R_2 + M_{31}{}^2R_3}} \qquad \text{(C-22)}$$

where the values are defined following Eq. (C-13). The terms involving tower 4 in Eqs. (C-18), (C-19), and (C-20) will vanish.

Horizontal-plane RMS Field Strength of Four-tower Array

The equation for the rms field strength in the horizontal plane of a four-tower array is

$$\begin{aligned} E_0 = E_1[1 &+ F_2{}^2 + F_3{}^2 + F_4{}^2 \\ &+2F_2 \cos \Psi_{12}J_0(S_{12}) \\ &+2F_3 \cos \Psi_{13}J_0(S_{13}) \\ &+2F_4 \cos \Psi_{14}J_0(S_{14}) \\ &+2F_2F_3 \cos \Psi_{23}J_0(S_{23}) \\ &+2F_2F_4 \cos \Psi_{24}J_0(S_{24}) \\ &+2F_3F_4 \cos \Psi_{34}J_0(S_{34})]^{1/2} \end{aligned} \qquad \text{(C-23)}$$

where E_0 = rms inverse field strength in horizontal plane, mv/m

E_1 = inverse field strength at 1 mile produced by tower 1 while operating in array, mv/m

F_2, F_3, and F_4 = inverse field-strength ratios of towers 2, 3 and 4 to tower 1, respectively.

Ψ_{pq} = electrical phasing of tower q with respect to tower p as designated by the subscript numbers, deg

S_{pq} = spacing of tower q to tower p as designated by the subscript numbers, deg

$J_0(S_{pq})$ = Bessel function of first kind and zero order of the spacing as designated by the subscripts and given in Table B-2

A good check on the arithmetic is to measure the pattern area with a planimeter.

For a four-tower parallelogram array Eq. (C-23) reduces to

$$
\begin{aligned}
E_0 = E_1[1 &+ F_2^2 + F_3^2 + F_4^2 \\
&+2(F_2 + F_3F_4) \cos \Psi_{12}J_0(S_{12}) \\
&+2F_4 \cos \Psi_{14}J_0(S_{14}) \\
&+2F_2F_3 \cos \Psi_{23}J_0(S_{23}) \\
&+2(F_3 + F_2F_4) \cos \Psi_{13}J_0(S_{13})]^{1/2}
\end{aligned}
\qquad \text{(C-24)}
$$

where the terms are defined following Eq. (C-23).

Horizontal-plane RMS Field Strength of Three-tower Array

The equation for the rms field strength in the horizontal plane of a three-tower array is

$$
\begin{aligned}
E_0 = E_1[1 &+ F_2^2 + F_3^2 \\
&+2F_2 \cos \Psi_{12}J_0(S_{12}) \\
&+2F_3 \cos \Psi_{13}J_0(S_{13}) \\
&+2F_2F_3 \cos \Psi_{23}J_0(S_{23})]^{1/2}
\end{aligned}
\qquad \text{(C-25)}
$$

where the terms are defined following Eq. (C-23).

For the special three-tower-in-line array of Fig. C-1 the above equation reduces to

$$
\begin{aligned}
E_0 = E_1[1 &+ 2F_2^2 \\
&+4F_2 \cos \Psi_{12}J_0(S_{12}) \\
&+2F_2^2 \cos (2\Psi_{12})J_0(2S_{12})]^{1/2}
\end{aligned}
\qquad \text{(C-26)}
$$

where the terms are defined following Eq. (C-23).

Part 4

MAINTENANCE OF DIRECTIONAL ANTENNAS *

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INTRODUCTION

Except for the development of precise frequency control, it is probable that no other technical development has contributed so much to the efficient utilization of the standard broadcast band as the directional antenna. As of Sept. 1, 1959, there were authorized in the United States some 3,500 standard broadcast stations. Of these, about 1,000, or roughly 30 per cent, use directional antennas in either daytime or nighttime or both. Because some stations use more than one pattern, a total of over 1,200 different directional-antenna patterns are involved.

Before authorization is granted for construction of a directional antenna in the United States, the Federal Communications Commission requires that a complete engineering showing be made. Before a license is granted for the regular operation of a directional antenna, a complete and thorough proof of performance must be made and submitted by the permittee and approved by the FCC.

We can thus assume that each directional antenna is operating properly at the time that it commences regular operation. But what of the problems of maintenance of the antenna in day-to-day operation of the system? Let us examine the factors affecting the maintenance of directional-antenna systems.

Factors Affecting the Maintenance of Directional Antenna Systems

To begin with, the design of the antenna system will affect the maintenance problems. In his design, the engineer must determine whether the array will operate with reasonable stability and efficiency. Generally speaking, the design must be such as to avoid low values of base operating resistance, either negative or positive. Such a condition could lead to excessive losses in the system and possibly to a "flip-flop" operating condition where a small change in tuning results in a drastic change in operating parameters.

In so far as the design engineer can do so, he must avoid deep minima in the pattern, since this results in a condition where a relatively small change in phase or current can cause a relatively large change in field intensity radiated in the directions of the minima.

Further factors affecting the stability of a directional antenna and the problem of its maintenance arise in the design of the phasing and coupling equipment. A design

* Supplemented by material prepared by Dixie B. McKey from the "NAB Engineering Handbook," 4th ed.

which incorporates a minimum of resonant circuits will, in general, exhibit greater stability than one which has a number of such circuits.

In the physical location of phasing and coupling equipment, one method frequently used is to have the power-division and phasing equipment distributed through the system and placed in tuning houses at the antenna bases. While this has the advantage of requiring a minimum length of transmission line and furnishes some protection against unauthorized tinkering by operating personnel, it has the disadvantage of making the initial tune-up and any necessary subsequent readjustment more difficult and lengthy than would be the case with a more convenient arrangement. The alternative and probably better arrangement is to concentrate the phasing and power-dividing equipment in the transmitter building. Here the effect of adjustments can be observed at once with the monitoring system, and the tuning of the array can be completed more easily and quickly. Under this concentrated arrangement, the equipment is usually better housed, thus making for better and easier maintenance.

Transmission Lines

Still more factors affecting maintenance of the directional-antenna system arise in the course of construction of the system. The choice of transmission and sampling lines, for instance, is important. Open-wire lines are unsuited for use with directional-antenna systems. The characteristics of such lines change with the accumulation of water, ice, or snow on the wires and insulators, and this alters the operating parameters of the array.

The solid-dielectric transmission lines having an outer conductor of copper braid, such as RG17U and RG19U, are also unsuitable for a directional-antenna system unless special precautions are taken. The somewhat lower efficiency of these lines must be taken into account in the design of the system. Because the outer conductor of such lines "leaks" RF energy and because of the difficulty of adequately grounding the lines along each run, the most satisfactory way in which to handle this type of line is to install it in well-grounded metal conduit. The expense of doing this, however, increases the cost of the installation so greatly as to nullify the advantage of the lower first cost of the line itself.

No more satisfactory transmission line or sampling line can be found than air-dielectric line having an outer conductor of copper tubing and grounded adequately along each run. When properly installed and maintained, such lines provide many, many years of satisfactory service. The June, 1957, issue of *Broadcast News* contains an excellent article by one of the IRE Professional Group members, Joseph Novik, on Installing Antenna Systems for AM Operations.

In any installation of pressurized lines, particular attention must be given to the arrangement for pressurizing the lines. Maintenance of pressure in the lines is an important part of the over-all maintenance of the system; therefore, the arrangement for pressurizing must be convenient and readily accessible.

It goes without saying that the tuning equipment must be adequately housed, that all ground connections must be well made, and that good workmanship must be used in all details of the installation if maintenance problems are to be kept to a minimum.

Phase Monitor

One of the most important aids in maintaining a directional-antenna system, if not the most important, is an adequate sampling system and a reliable current and phase monitor. A sampling loop mounted on the tower is to be preferred to a resonant pickup circuit coupled to the antenna lead. If the resonant circuit is used, it will be found that the relative phase and current indications of the phase monitor will change as the circuit drifts or is jarred out of resonance. If such a sampling pickup is used, the maintenance procedure at the station should provide for frequent checking of resonance of each such circuit.

The phase monitor at the station should be maintained according to the directions of the manufacturer.

GENERAL MAINTENANCE PROCEDURES

Mention was made earlier of the desirability of avoiding deep minima in the design of the directional-antenna pattern. It follows that in the adjustment of the antenna, the field radiated in the direction of each minimum must not be reduced substantially below the theoretical value, since, if carried too far, such a reduction will result in a low value of field strength difficult to maintain in regular operation.

After an array has been properly adjusted in the initial operation, useful and valuable information can and should be obtained by measuring the reactance of the component branches of all tuning networks. Then if it should be necessary to replace a defective component at a later date, the value of reactance originally established can be quickly achieved. Also, the data obtained from such measurements can be used in later checking the condition of a suspected component.

After a directional antenna has been properly adjusted, a record should be made of all dial settings of variable tuning elements and the position of any clips on tapped inductors should be marked. Such marking can be done quickly and effectively by painting a strip of fingernail polish across the clip and the turn of the coil on which it is located. Where a coil has two or more clips, a different color should be used for each clip. Then, if a clip should accidentally be dislodged, it is a simple matter to replace it in the proper location.

In the maintenance of a directional-antenna system, as in the maintenance of other equipment, one rule is important: Keep it clean! Components should be wiped and blown clean each week. The tuning houses should be kept rodent and reptileproof. It adds nothing to the operation of the system to have a scorched mouse, a dead snake, or a large dirt-dauber's nest scattered among the tuning components.

Vegetation should be kept down in the vicinity of each tower base. Cut vegetation should be raked away from the tower base and burned under supervision to minimize reseeding and to prevent a fire hazard. Chemicals can be used to inhibit growth of vegetation.

Pressure in the transmission and sampling lines should be maintained at 10 to 15 lb, using dry air or dry gas, to prevent the entry of moisture. If a leak develops, it should be located and repaired promptly. Periodic checks should be made of the pressure gauges so as to be certain that no gauge has become stuck and is giving false indications.

It is helpful to apply a very light coating of silicone compound to exposed insulators and end seals to prevent formation of a moisture film during wet weather. It goes without saying that all insulators should be kept free of paint.

Inspection of Components

An important part of the maintenance procedure is to make a weekly visual inspection of all elements of the antenna system. Broken insulators or other damaged elements shonld be replaced at once. Where necessary, lightning gaps should be respaced, using a piece of flat insulation of the proper thickness as a feeler gauge.

The tightness of all connections in the antenna tuning equipment should be checked at quarterly intervals. At yearly intervals and also after every violent windstorm, a transit should be used to determine whether each tower remains plumb. It is advisable at the same time to check all tower bolts and nuts for tightness and to check for bent members. During these checks, a visual inspection should be made of the guy wires and insulators for any signs of damage or deterioration. If a tower is found to be out of plumb or other difficulties are found, a competent tower erector shonld be employed to correct the situation.

Meter Readings

Meter readings having to do with the antenna system should be made carefully and logged accurately so that if difficulty arises, a complete and accurate record of what has transpired is available for reference. If an electrical storm occurs in the vicinity of the antenna, that fact should be entered in the log. Readings of the antenna base meters and the sampling loop meters should be made under conditions of no modulation. Usually, the cooperation of studio operating personnel can be obtained and a pause of 5 sec or so allowed between announcements or musical selections so that each reading can be obtained accurately. When reading antenna base meters, the operator should carry with him a monitor permitting him to discern when no modulation is present. A crystal diode rectifier wired across a telephone jack and equipped with a probe or pickup coil can be used with a pair of headphones to provide snch a monitor.

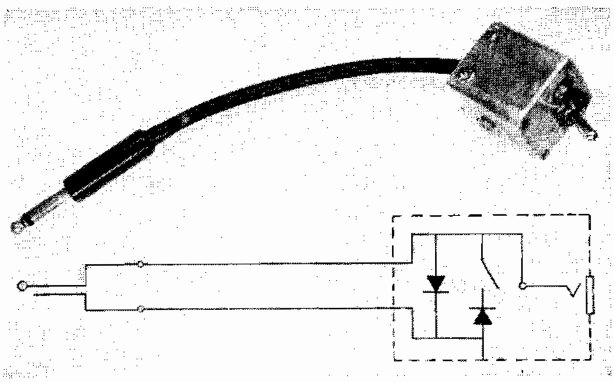

FIG. 4-1. Detector–noise limiter for use in antenna work.

A device which has proved useful in antenna work is shown in Fig. 4-1. With the switch open, this device is a useful monitor. Adequate pickup is obtained by holding the sleeve of the plug in one's hand while touching the tip to a metal panel, messenger cable, or the like. With the switch closed, the device becomes an effective noise limiter for use with a receiver in RF bridge work.

Maintenance Report

Components

A report or maintenance book can be set up as follows. The first section shown in Fig. 4-2 will consist essentially of a complete description of the individual component parts arranged in four subdivisions consisting of inductance coils, capacitors, resistors, and relays. The listing in each of the subdivisions should carry a description of the unit, its location or function in the circuit, its type number, replacement-ordering information, and circuit designation. The listing should also cover the number of turns in use of each inductance coil, the value of each of the capacitors, and the dial settings of the capacitors if variable.

Meters

The second subdivision (Fig. 4-3) should furnish complete information concerning all meters used in the operation of the array and should consist of a listing of these units showing the circuit designations, the location and function of the unit, its range, type and serial number, and the current reading for the required output. The required phase-monitor reading for normal operation should be listed in this subdivision.

Circuit Information

Circuit Designation	*Circuit Function*	*Adjustment Information*	*Replacement Information*
L1	Shunt input coil	20½ turns	Continuously variable coil—type 4224 MS4—26 μh
L2	Series input coil	9½ turns	Variable tap coil—type 322-4N4—26 μh
L3	No. 1 tank coil	8 turns	Variable tap coil—type 3208NT10—38 μh
L4	No. 2 tank coil	7 turns	Variable tap coil—type 3208NT10—38 μh
L5	No. 1 line feed coil	½ turn	Continuously variable coil—type 4103—HMS5—7 μh
L6	No. 2 line feed coil	7¾ turns	Continuously variable coil—type 4103—HMS5—7 μh
L7	No. 3 line feed coil	7 turns	Continuously variable coil—type 4103—HMS5—7 μh
L8	No. 4 line feed coil	5½ turns	Continuously variable coil—type 4103—HMS5—7 μh
L9	No. 1 line series phase coil	13¼ turns	Continuously variable coil—type 4224 MS4—26 μh
L12)	No. 2 line series phase coil	8¼ turns	Continuously variable coil—type 4224 MS4—26 μh
L13)			
L14	No. 2 line shunt phase coil	8½ turns	Variable tap coil—type 4164-N5—16 μh
L15)	No. 3 line series phase coil	11⅓ turns	Continuously variable coil—type 4224 MS4—26 μh
L16)			
L17	No. 3 line shunt phase coil	5¾ turns	Variable tap coil—type 4164-N5—16 μh
L18)	No. 4 line series phase coil	8¼ turns	Continuously variable coil—type 4224 MS4—26 μh
L19)			
L20	No. 4 line shunt phase coil	6 turns	Variable tap coil—type 4164-N5—16 μh
L21	No. 1 tower series input coil	11 turns	Variable tap coil—type 3164-N5—16 μh
L22	No. 1 tower series output coil (D)	7 turns	Variable tap coil—type 4165-N5—22 μh
L23	No. 1 tower shunt coil	D10 turns ND 3½ turns	Variable tap coil—type 3106-NT12—10 μh
L25	No. 2 tower series input coil	9 turns	Variable tap coil—type 4165-N5—22 μh
L26	No. 2 tower series output coil	4½ turns	Variable tap coil—type 4105-N5—12 μh
L27	No. 2 tower shunt coil	10 turns	Variable tap coil—type 4164-N5—16 μh
L29	No. 3 tower series input coil	1 turn	Variable tap coil—type 4143-N5—8 μh
L30	No. 3 tower series output coil	4 turns	Variable tap coil—type 4165-N5—22 μh
L31	No. 3 tower shunt coil	11 turns	Variable tap coil—type 4164-N5—16 μh
L33	No. 1 tower series output coil (ND)	10¾ turns	Variable tap coil—type 4165-N5—22 μh
L34	No. 4 tower series input coil	11¼ turns	Variable tap coil—type 3164-N5—16 μh
L35	No. 4 tower series output coil	5½ turns	Variable tap coil—type 3165-N5—22 μh
L36	No. 4 tower shunt coil	12 turns	Variable tap coil—type 3164-N5—16 μh
L24	No. 1 TC choke coil		RF choke
L28	No. 2 TC choke coil		RF choke
L32	No. 3 TC choke coil		RF choke
L37	No. 4 TC choke coil		RF choke
L38	No. 1 tower static drain		
L39	No. 2 tower static drain		
L40	No. 3 tower static drain		
L41	No. 4 tower static drain		

	Condensers	*Setting*	
C1	Shunt input capacity		Type 750FBA90—750 μμf
CA	Series input capacity		Type 1000 FBA90—1,000 μμf
C2	No. 1 tank tuning capacity	45	Type 750FVSP250—750 μμf
C3	No. 2 tank tuning capacity	85	Type 750FVSP250—750 μμf
C4	No. 1 line series phase capacity		Type 1500 FBA90—1,500 μμf
C5	No. 2 line shunt phase capacity		Type 1000 FBA90—1,000 μμf
C6	No. 3 line shunt phase capacity		Type 1000 FBA90—1,000 μμf
C7	No. 4 line shunt phase capacity		Type 1000 FBA90—1,000 μμf
C8	No. 1 tower series output capacity		Type 1000 FBA90—1,000 μμf
C9	No. 1 tower shunt capacity		Type 1250FD150—1,200 μμf
C11	No. 2 tower series output capacity		Type 1000 FBA90—1,000 μμf
C12	No. 2 tower shunt capacity		Type 1000 FBA90—1,000 μμf
C14	No. 3 tower shunt output capacity		Type 1000 FBA90—1,000 μμf
C16	No. 4 tower shunt capacity		Type 1000 FBA90—1,000 μμf
C17	No. 3 tower series output capacity		Type 1000 FBA90—1,000 μμf
C19	No. 4 tower series output capacity		Type 1000 FBA90—1,000 μμf
C20	No. 1 tower series output capacity (D)		Type 1000 FBA90—1,000 μμf
C10	No. 1 TC shunt capacity		Type CD 2-MFD
C13	No. 2 TC shunt capacity		Type CD 2-MFD
C15	No. 3 TC shunt capacity		Type CD 2-MFD
C17	No. 4 TC shunt capacity		Type CD 2-MFD

	Relays		
S1	Antenna array transfer relay		RF contactor
S4	No. 1 tower antenna ammeter switch		MBB switch
S5	No. 1 tower antenna transfer relay		RF contactor
S6	No. 2 tower antenna ammeter switch		MBB switch
S7	No. 2 tower antenna transfer relay		RF contactor
S8	No. 3 tower antenna ammeter switch		MBB switch
S9	No. 3 tower antenna transfer relay		RF contactor
S12	No. 4 tower antenna ammeter switch		MBB switch
S13	No. 4 tower antenna transfer relay		RF contactor

Fig. 4-2

METER INFORMATION

Current

Meter	*Range*	*Model*	*No.*	D	ND	*Unit*
M1	0 8	640	2845	4.58	—	Transmitter input to divider network
M2	0–15	640	2843	1.0	9.9	Transmission-line current—tower 1
M3	0–8	640	2835	3.9	—	Transmission-line current—tower 2
M4	0–8	640	2820	3.8	—	Transmission-line current—tower 3
M5	0–8	640	2830	2.5	—	Transmission-line current—tower 4
M6	0–15	640	2810	1.0	9.45	Transmission-line coupling unit—tower 1
M9	0–8	640	2815	2.6	—	Transmission-line coupling unit—tower 2
M12	0–8	640	2816	3.85	—	Transmission-line coupling unit—tower 3
M15	0–5	640	2819	2.5	—	Transmission-line coupling unit—tower 4
M8	0–15	640	2821	3.0	10.39	Antenna current—tower 1
M11	0–8	640	2822	5.4	—	Antenna current—tower 2
M14	0–8	640	2823	5.35	—	Antenna current—tower 3
M17	0–5	640	2924	3.11	—	Antenna current—tower 4
*M7	0–15	425	3130	3.0	10.39	Remote antenna current—tower 1
*M10	0–8	425	3131	5.4	—	Remote antenna current—tower 2
*M13	0–8	425	3133	5.35	—	Remote antenna current—tower 3
*M16	0–8	425	3134	3.11	—	Remote antenna current—tower 4
MP1	0–150%	743	3638	100%	100%	Phase monitor—tower 1
MP2	0–150%	743	3624	100%		Phase monitor—tower 2
MP3	0–150%	743	3636	100%		Phase monitor—tower 3
MP4	0–150%	743	3621	100%		Phase monitor—tower 4

Note: All meters Weston Electric Company.
* External heater type—see Fig. 4-5 for location in circuits.

Phase Monitor Readings for Directional Operation
Tower 1 Leads tower 2 by 230°
Tower 1 Leads tower 3 by 84°
Tower 1 Leads tower 4 by 302°

FIG. 4-3

Monitoring Points

The third subdivision (Fig. 4-4) should contain a listing of the monitoring points as designated by the Federal Communications Commission's license and should show the number of the monitoring points, a complete description for reaching these points, the bearing and distance, the specified unattenuated field value at 1 mile, the obtained unattenuated field value at 1 mile, together with the actual received field.

Diagrams and Measurements

The fourth and last subdivision (Fig. 4-5) should contain a schematic diagram and, if available, a wiring diagram of the complete antenna array equipment together with the series of curves from the Proof of Performance Report showing the dividing network or driving-point impedance of the array (Fig. 4-6) equipment and operating tower impedance (Fig. 4-7) if a single tower is used for nondirectional daytime operation. Additional pertinent information that would be of assistance to the maintenance engineer, such as transmission-line and capacitor gas pressures, should be included. While it may appear that some of this information will be a duplicate of the Proof of Performance Report, it is believed that by rearranging the data in this form and making them part of the maintenance routine, the constant reference to this information by the station engineering personnel will acquaint them with the equipment and its functions far better than a casual reference to the Proof of Performance Report.

MONITOR POINTS AND FIELD-STRENGTH INFORMATION

Point 4

Azimuth angle	Distance, miles	Mv/m 1 mile Specified	Mv/m 1 mile Obtained	Mv/m Measured
12°	1.89	30	20	3.95

Insert location of measuring point as described in proof of performance

Point 14

Azimuth angle	Distance, miles	Mv/m 1 mile Specified	Mv/m 1 mile Obtained	Mv/m Measured
40°	2.75	90	76	6.5

Insert location of measuring point as described in proof of performance

Point 25

Azimuth angle	Distance, miles	Mv/m mile Specified	Mv/m mile Obtained	Mv/m Measured
63°	1.33	70	25	8.55

Insert location of measuring point as described in proof of performance

Point 62

Azimuth angle	Distance, miles	Mv/m I mile Specified	Mv/m I mile Obtained	Mv/m Measured
181°	1.36	72	40	10.75

Insert location of measuring point as described in proof of performance

Point 82

Azimuth angle	Distance, miles	Mv/m 1 mile Specified	Mv/m 1 mile Obtained	Mv/m Measured
219°	2.18	52	40	5.6

Insert location of measuring point as described in proof of performance

Point 104

Azimuth angle	Distance, miles	Mv/m 1 mile Specified	Mv/m 1 mile Obtained	Mv/m Measured
302°	0.86	40	17	7.6

Insert location of measuring point as described in proof of performance

Point 118

Azimuth angle	Distance, miles	Mv/m 1 mile Specified	Mv/m 1 mile Obtained	Mv/m Measured
337°	1.15	61	40	13.4

Insert location of measuring point as described in proof of performance

FIG. 4-4

Daily Work Schedules

The second section of the maintenance report book should contain a complete list and schedules of the daily work to be done and, where necessary, complete instruction covering the methods and equipment to be used. A suggested list is shown in Table 4-1. In the case of the example used, the antenna maintenance work is divided into two main classifications. The first classification is designed to cover the daily routine inspection and work that is to be handled by the "late trick" station engineer after sign-off. This work has been arranged in such a manner that all parts and circuits

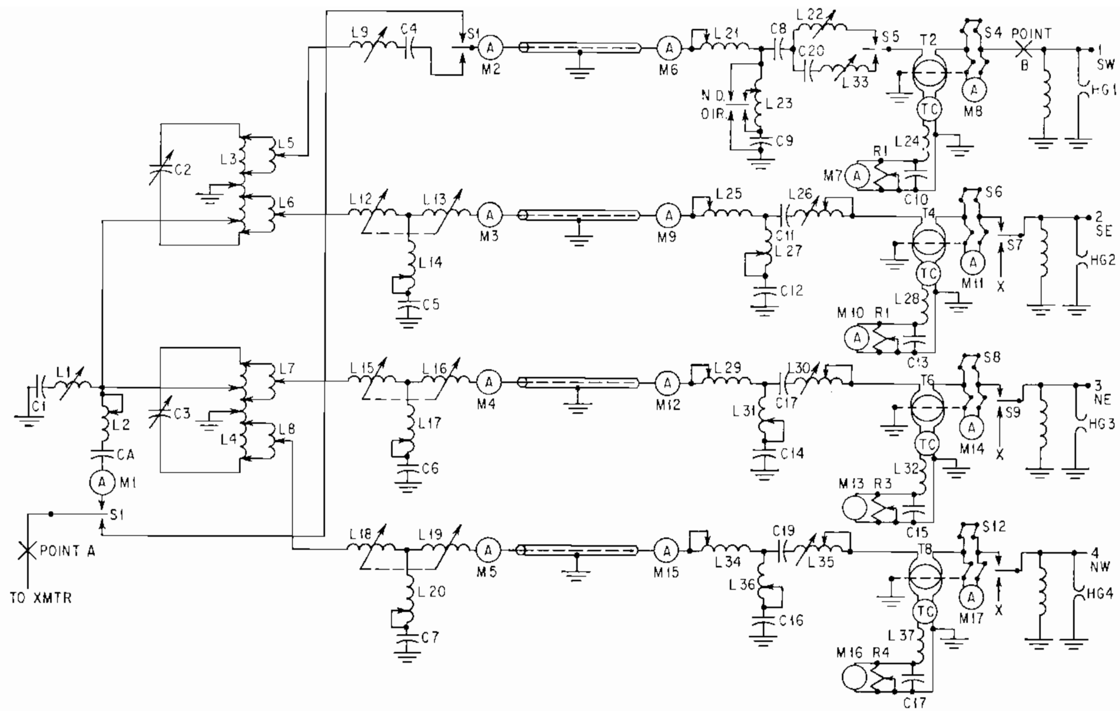

Fig. 4-5. Schematic diagram showing coupling and phasing networks.

will be cleaned and inspected at least once each week. The second classification already mentioned has been designed to cover a series of special maintenance routines for checking the array operation at regular specified intervals.

FREQ (KC)	R (OHMS)	X (OHMS)
1350	47	8.7
1355	58	4
1360	65	0
1365	68.5	-2.5
1370	68	-3
1375	62	-2
1380	51.5	0
1385	48	8.5
1390	54	25.4
1395	64	28
1400	80	23.2
1405	108	14
1410	153	0

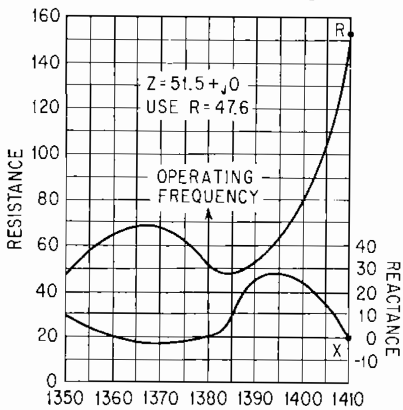

FIG. 4-6. Dividing network impedance.

FREQ (KC)	R (OHMS)	X (OHMS)
1350	41.5	36
1355	42	37.5
1360	43	39.2
1365	44	41.3
1370	45	43.5
1375	45.5	44.5
1380	46.5	46.4
1385	47.5	47.5
1390	48.25	47.8
1395	49	50
1400	50	51.1
1405	51	52.7
1410	52.1	54.1

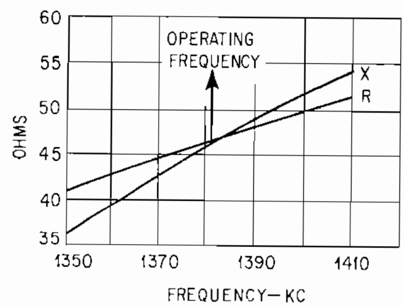

FIG. 4-7. Nondirectional tower 1 impedance.

Weekly Log

The third section of the maintenance report book contains the weekly station maintenance log. This portion of the routine is of extreme importance, as it will provide the station supervisor or chief engineer with a method for checking the work done as well as the data necessary to determine the operating conditions of the array and its equipment at all times. The log shown in Fig. 4-8 as set up for the example station is arranged to cover one week's complete maintenance information divided into daily sections.

Each daily section provides space for recording the temperature, weather, array meter readings, phase-monitor readings, transmission-line pressures, routine maintenance performed, routine tests results, other pertinent data, and the signature of the duty engineer.

The recorded data obtained from the daily and special maintenance tests after a period of six months can be plotted to show the actual operating conditions of the array. Variations from the normal conditions will undoubtedly appear in the graphs. By a careful analysis of the records, it will be possible to identify any variations due to seasonal or weather conditions. This accumulated information properly evaluated should provide the station engineer with a complete and thorough understanding of his directional-antenna-array operating and maintenance problems.

Month			Sun.		Mon.		Tues.		Wed.		Thur.		Fri.		Sat.		Remarks				Eng.			
Date																								
Weather																								
Temperature																								
M1-Dir.																								
M2-N on-Dir.																								
M7-Dir.																								
M7-Non-Dir.																								
M10																								
M13																								
M16																								
#1-#2 Phase																								
#1-#3 Phase																								
#1-#4 Phase																								
TX Line #1 Press.																								
TX Line #2 Press.																								
TX Line #3 Press.																								
TX Line #4 Press.																								
Phase Monitor																								
Prot. Circuits																								
EMC TX Lines																								
Main Phase Unit																								
Non-Dir. Imp.																								
Dir. Imp.																								
FS Mon. Pt. #4																								
FS Mon. Pt. #14																								
FS Mon. Pt. #25																								
FS Mon. Pt. #62																								
FS Mon. Pt. #82																								
FS Mon. Pt. #104																								
FS Mon. Pt. #118																								
Overall Dir. Test																								
#1 Coupling Unit																								
#2 Coupling Unit																								
#3 Coupling Unit																								
#4 Coupling Unit																								

FIG. 4-8. Weekly maintenance report.

It is, of course, realized that the suggestions and recommendations described above are not the total and complete answer to all directional antennas. However, it is believed that the need for establishing schedules similar to the suggested program is well demonstrated and can be fitted to the individual station requirements, and the results of this program will be of mutual benefit to both the engineering staff and management.

Usually, the station license requires that field-strength measurements be made periodically at each of the monitoring points. In the event that the license does not require such measurements, it is a good practice to make them at monthly intervals.* Such measurements should, of course, be made carefully, and an accurate record maintained, indicating the date and time of each measurement and the field strength observed at each monitoring point. If any unusual conditions are encountered, a record should be made of them. If a monitoring point becomes unusable, an informal application should be made to the FCC to change to a new monitoring point along that radial.

In dealing with tuning equipment for directional antennas, we must deal with the component parts which are commercially available, not the idealized components on which theoretical considerations are based. It will be found that as the components of the system age and undergo variations in temperature and vibration, their values will usually drift. Also, tower base impedances will frequently change, and the effective conductivity of the soil will vary with moisture content and temperature. In time, these changes may result in change of the operating parameters of the array to the extent that the field strengths at the monitoring points are no longer within the allowable values and it becomes necessary to readjust the array.

READJUSTMENT OF ARRAY

Any readjustment should be attempted only by personnel familiar with directional antenna theory. Unfortunately, in recent years qualified personnel seem to have left the field of standard broadcasting. This has happened for a number of reasons, primarily financial in nature. Since any adjustments of the tuning elements probably will alter the common-point impedance, it follows that the person making the adjustments must have an RF bridge and associated equipment and must be familiar with their operation.

In correcting for any drift in adjustment of the array, the initial goal should be to reestablish the operating conditions obtained in the original adjustment as indicated by phase-monitor, loop-current, and base-current readings. However, owing to what has been politely termed the perversity of the inanimate objects, it will on occasion be found that reestablishing the original current ratios and phase indications does not result in producing the desired field strengths at the monitoring points. Assuming that the monitoring system is in good working order, it then becomes necessary to readjust the array.

Readjustment Aids

In undertaking readjustment of the array, certain aids may be found useful in guiding the adjustments to be made. For a two-element directional-antenna system, it is helpful to have a copy of the theoretical pattern on which the directions of the minima are indicated, as well as the direction of each monitoring point. Figure 4-9 illustrates such a pattern. It is also helpful to indicate on this pattern the direction in which the minima will move for an increase in phase difference between the towers. It will be recognized, of course, that the depth of the minima will depend upon the current ratio. Theoretically the minima will become complete nulls if the fields radiated by the two towers are equal. This overlooks the effects of reradiation from nearby objects, but this concept does provide a point of departure for adjustment of the array.

* This is particularly important if the station contemplates applying to the FCC for remote control authorization.

A similar device may be found useful in readjusting an array with four towers arranged in the shape of a parallelogram. In this case, it is desirable to portray the basic patterns which go to make up the final pattern, preferably in contrasting colors. Figure 4-10 shows a pattern produced by such a four-tower array. In Fig. 4-11, one

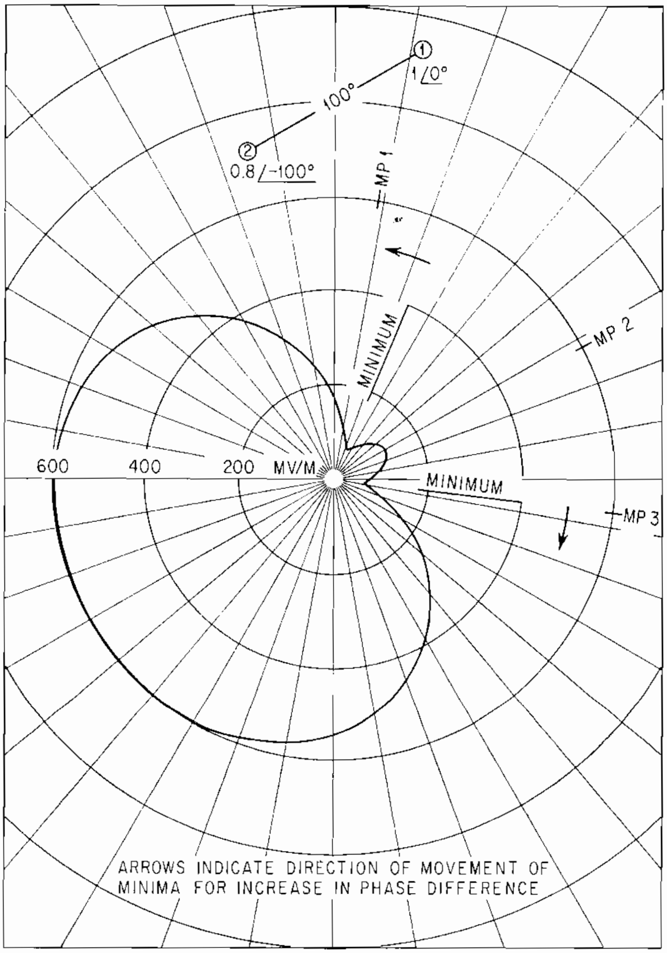

FIG. 4-9. Two-element directional-antenna pattern on which have been indicated directions of minima and directions of movement of minima for increase in phase difference.

of the basic patterns is shown as a solid line and the other as a dashed line. Here, too, arrows have been placed on the basic patterns to indicate the direction of movement of each minimum for an increase in phase difference between the sets of towers making up each basic pattern. The direction to each monitoring point is also given. Since the final pattern is the result of multiplying together the values of the basic patterns in any given direction, the effect of a change of parameters of a basic pattern on the final pattern can be readily visualized.

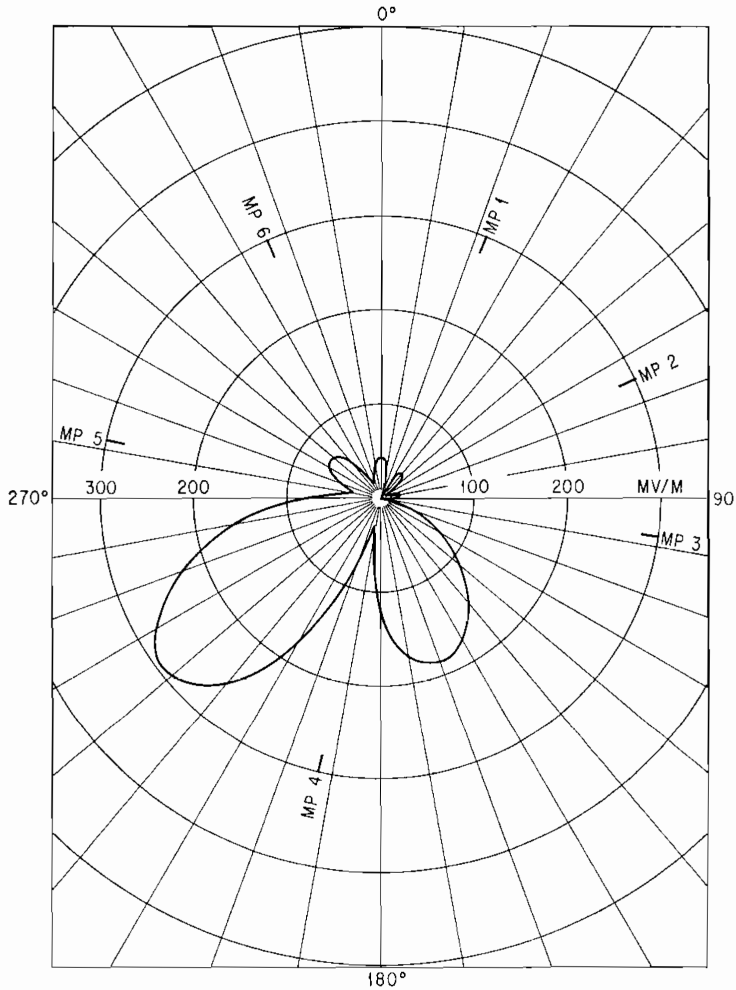

FIG. 4-10. Pattern produced by a directional antenna consisting of four elements arranged in a parallelogram.

Vector Calculator

Of possible use for a two-tower system is a calculator in the form of a circular slide rule, based on an article appearing in the December, 1944, issue of *Proceedings of the IRE.* Figure 4-12 illustrates such a calculator, which was quickly constructed from two sheets of graph paper and a piece of cardboard. In the operation of this calculator, the towers are numbered 1 and 2, and the phase of tower 2, read on the scale on the periphery of the rotary element, is set to the vertical zero degree line. The outer fixed scale on the base represents the bearing from the line of towers, measured from the tower 2 end. A separate outer scale is needed for each tower spacing. The group of figures on the runner represents field ratios. The resultant vector field is

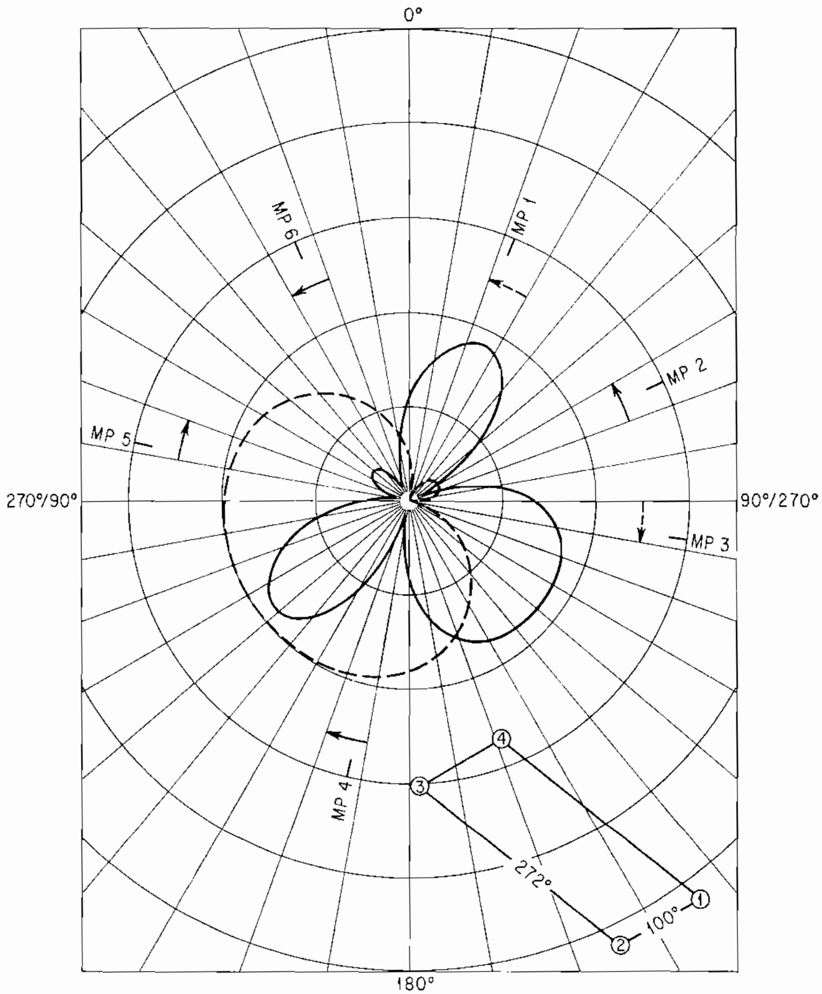

FIG. 4-11. Basic vector patterns which make up the pattern of Fig. 4-10. Arrows indicate the directions of movement of minima for increase in phase difference between pairs of elements.

read from the inner scale opposite the figure for the field ratio. It can be seen that the effect of a change in phase or field ratio on the field radiated in any given direction can be quickly determined.

A modified form of the calculator can be used with a three-element in-line array. The vector representation of the resultant field of such an array in a given direction is as shown in Fig. 4-13, where vector 2 represents the field from the center tower and vectors 1 and 3 represent the fields from the end towers. Considering the position of vector 2 as fixed, vectors 1 and 3 revolve in opposite directions as one's vantage point is moved around the array.

When redrawn, the vector relationship is as shown in the lower half of Fig. 4-13.

Here R is the resultant vector, drawn from the origin of vector 1 to the terminal point of vector 3. If we construct a mechanical device having scales depicting the position of vectors 1 and 3 for various bearings from the line of towers, we can then determine the effect of changes in operating parameters on the resultant field in any desired direction.

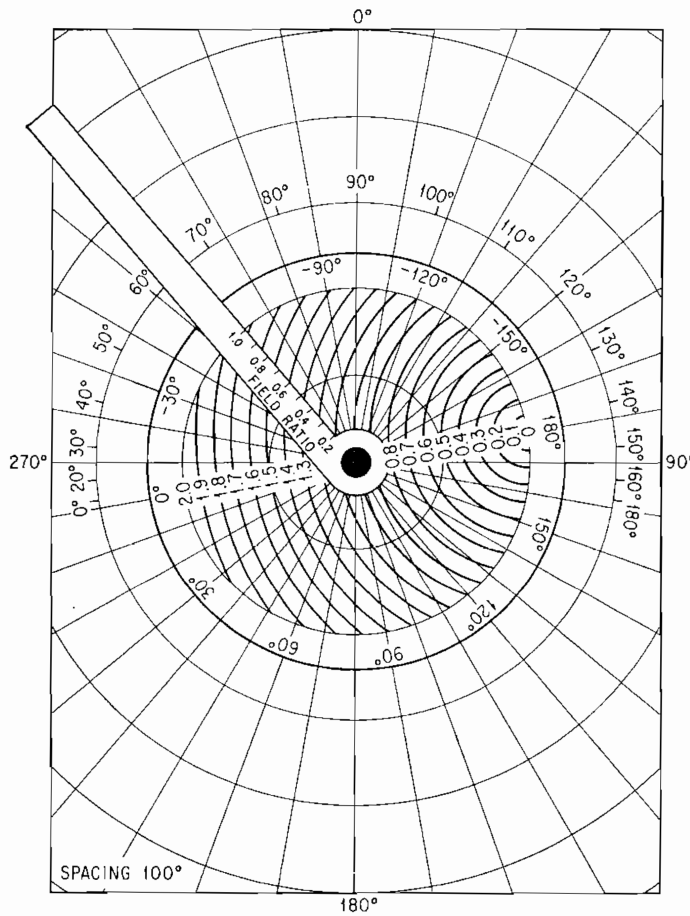

Fig. 4-12. Calculator for two-element directional antenna having spacing of 100° between elements.

Such a device is illustrated in Fig. 4-14. Here the distance between pivot points for the rotary elements has been scaled to represent the magnitude of vector 2. The radius of each of the rotary elements has been chosen to represent the magnitude of vectors 1 and 3. If desired, a scale could be marked on each of the rotary elements along the line from the center to the 0° mark on the periphery.

When this device is used, a pencil mark or a small tab of drafting tape is placed on the periphery of each rotary element at a point corresponding to the phase of the tower there represented.

To determine the relative field radiated in a given direction, the rotary elements

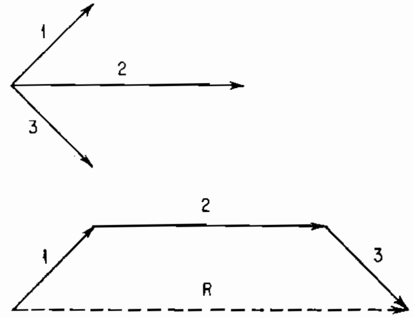

Fig. 4-13. Typical relationship of field vectors for three-element directional-antenna system.

are rotated so that the tab or mark lies at the desired bearing shown on each fixed scale. The distance between the 0° marks on the periphery of the rotary elements then corresponds to the resultant vector field. The effect of a change in phase of any of the towers or a change in field ratios can be readily visualized.

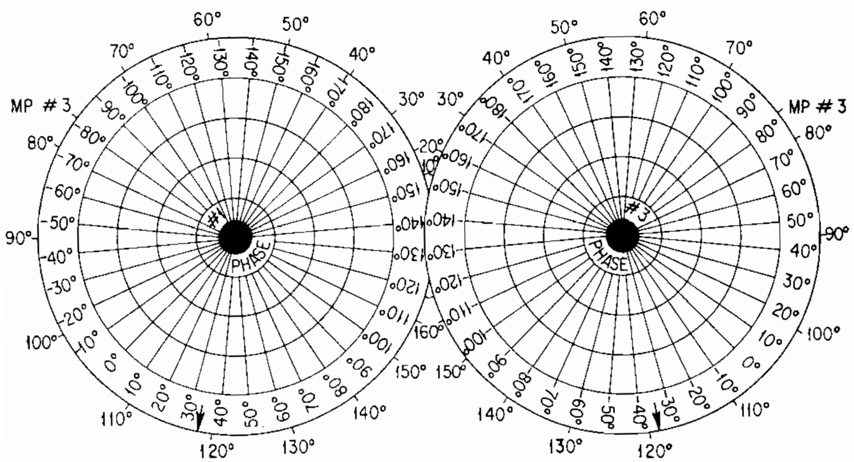

Fig. 4-14. Calculator for three-element in-line directional antenna.

Unfortunately, these relatively simple procedures cannot be so easily applied to arrays with more elements; however, if the basic patterns that go to make up the over-all pattern are known, these procedures can be applied to the basic patterns.

Table 4-1. Maintenance Schedules

Sunday

1. Transfer all towers and antenna phasing units to emergency transmission lines and operate at full power for 5 min.
2. Restore all equipment to regular transmission lines. Check operation under full power.
3. Clean and check all connections, remote meter, phase monitor, and meter panels.
4. Check all phase monitor tubes with tube checker. Check all transmission-line protective circuits.
5. Check and record all transmission-line gas pressures.

Table 4-1. Maintenance Schedules (*Continued*)

Monday

1. Check all condensers and other equipment in antenna phasing unit immediately after sign-off for overheating.
2. Clean and check all transmission-line end seals.
3. Clean interior of all sections of antenna phasing units.
4. Clean contacts and check alignment of antenna transfer relay.
5. Check and tighten all connections in antenna phasing unit.
6. Check gas-filled condensed pressures.

Tuesday

1. With array set for directional operation check drive-point impedance at X with radio-frequency bridge at operating frequency (first and third Tuesdays).
2. With array set for nondirectional operation check drive-point impedance at X with radio-frequency bridge at operating frequency (first and third Tuesdays).
3. Set up array for normal full-power directional operation. Compare readings of all antenna and remote antenna meters. Make any necessary adjustments.
4. Make complete set of field-strength readings at indicated monitor points (second and fourth Tuesdays).
5. Check and record all transmission-line gas pressures.

Wednesday

Antenna coupling unit 1:

1. Check all condensers and equipment in coupling house for overheating immediately after sign-off.
2. Check spacing and clean antenna and transmission-line horn gaps.
3. Check and clean all antenna lead-in insulators.
4. Check and clean all transmission-line end seals.
5. Clean contacts and check alignment of antenna relay.
6. Clean contacts and check alignment of antenna ammeter switch.
7. Check and tighten all connections of inductance coils and condensers.
8. Clean all meters.

Transmitter building:

Read and record all transmission-line gas pressures.

Thursday

Antenna coupling unit 2:

1. Check all condensers and equipment in coupling honse for overheating immediately after sign-off.
2. Check spacing and clean antenna and transmission-line horn gaps.
3. Check and clean all antenna lead-in insulators.
4. Check and clean all transmission-line end seals.
5. Clean contacts and check alignment of antenna relay.
6. Clean contacts and check alignment of antenna ammeter switch.
7. Check and tighten all connections of inductance coils and condensers.
8. Clean all meters.

Transmitter building:

Read and record all transmission-line gas pressures.

Friday

Antenna coupling unit 3:

1. Check all condensers and equipment in coupling house for overheating immediately after sign-off.
2. Check spacing and clean antenna and transmission-line horn gaps.
3. Check and clean all antenna lead-in insulators.
4. Check and clean all transmission-line end seals.
5. Clean contacts and check alignment of antenna relay.
6. Clean contacts and check alignment of antenna ammeter switch.
7. Check and tighten all connections of inductance coils and condensers.
8. Clean all meters.

Transmitter building:
Read and record all transmission-line gas pressures.

Saturday

Antenna coupling unit 4:
1. Check all condensers and equipment in coupling house for overheating immediately after sign-off.
2. Check spacing and clean antenna and transmission-line horn gaps.
3. Check and clean all antenna lead-in insulators.
4. Check and clean all transmission-line end seals.
5. Clean contacts and check alignment of antenna relay.
6. Clean contacts and check alignment of antenna ammeter switch.
7. Check and tighten all connections of inductance coils and condensers.
8. Clean all meters.

Transmitter building:
Read and record all transmission-line gas pressures.

Part 5

TRANSMISSION LINES FOR BROADCAST USE

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INTRODUCTION

Since the early days of broadcasting, transmission lines have been one of the vital elements of the broadcasting plant—the connecting link between transmitter and radiator. The choice of the proper line for adequate planning, construction, and maintenance procedures is an all-important ingredient of a satisfactory system. Transmission-line technology has changed radically along with the radical changes in broadcasting. Starting with open-wire lines in the early days of AM broadcasting, the art has progressed through a wide variety of coaxial-line types, both air and solid dielectric, rigid and flexible, and more recently into waveguides.

It is not the intent here to describe basic transmission-line theory or design methods. A wide variety of transmission lines are available to the broadcaster of today. His chief concern is the selection of the proper one for his application and an understanding of the proper methods of installation and maintenance. Factors to be considered in selecting a line for various broadcast services will be presented. A discussion of recommended installation procedures will allow the broadcaster to lay out and construct a system suited to his specific requirements.

A large number of different transmission lines have been used in the past, including lines of various characteristic impedances, sizes, and physical characteristics.

The coaxial lines and waveguides which will form the basis of this presentation and their flanges and connectors are those that have been standardized or are in the process of being standardized by the EIA (Electronic Industries Association). Most manufacturers of electronic products adhere to these existing and proposed standards so that interchangeability and interconnection between products of different companies can be accomplished. The measures proposed or adopted by the EIA allow for standardization of the transmission-line conductor diameters as well as line flanges and connectors. The standard lines described herein have a 50-ohm characteristic impedance. Other EIA standard lines, such as those having a 75-ohm impedance, are also used, but mostly for special applications. It is, of course, true that some special applications require transmission lines that are not covered by the standards; however, the selection and use of these lines are usually considerations of the equipment designer rather than the broadcaster. Such special lines will therefore not be included in this chapter.

DESCRIPTION AND APPLICATION

In general, a transmission line is selected on the basis of efficiency (degree of attenuation), power handling, and mechanical considerations. In AM, FM, and TV, power handling is one of the most important factors to be considered. After a transmission line has been selected which will satisfy the power-handling requirement, the attenuation rating of the line must then be examined. A long-transmission-line installation requires a lower per-unit attenuation. It is a question of economics, balancing line cost, installation cost, and maintenance, vs. the alternatives of antenna gain, tower height, and transmitter power. These economics usually favor a larger diameter transmission line (having less attenuation) and a better antenna rather than a larger transmitter.

Solid-dielectric Cable

The simplest and cheapest type of RF energy transfer is through the use of solid-dielectric cables such as RG-8/U and RG-17/U, as shown in Fig. 5-1. Solid-dielectric

FIG. 5-1. RG-8/U and RG-17/U solid-dielectric cables.

cables are comprised of a solid or stranded inner conductor, plastic insulating material, and a braided sheath which serves as the outer conductor. These highly flexible cables are used in many applications where the length is short or the frequency is low enough that attenuation is not an important factor. Since attenuation in this type of cable is high, it is not recommended for long runs. Because of its aging characteristics, it is not suited for permanent outdoor use.

In the broadcast field, its use is generally limited to sampling lines, jumper connections, and occasionally as the main feeder line. In FM and TV installations, it is rarely used except for the receiver systems. For microwave, it is used for interconnections between components and in jumper connections at the bottom and top of the air-dielectric run. Radio relay systems use solid-dielectric cables in the 450-Mc band when the transmission lines are quite short. Solid-dielectric cable is frequently used in translator service because of short-length requirements.

Semiflexible Air-dielectric Cable

Semiflexible cable consists of soft-temper copper inner and outer conductors. The inner conductor is concentrically spaced by means of Steatite insulators. Figure 5-2 shows ⅞-in.-diameter semiflexible cable. Bending of the cable assembly is generally limited to one or two bending cycles, and care must be taken, when bending, to avoid kinks.

Semiflexible cable is very popular for general-purpose VHF communications and AM broadcasting because it is economical, dependable, and easy to install. Semiflexible cable, of course, can be used for all the above applications. In addition, because of its lower loss, it can be used for more varied applications. It has a very high efficiency as compared with solid cables of similar size. For example, a 1-kw FM transmitter at 100 Mc will lose 425 watts in a 300-ft run of RG-17/U cable compared with only 250 watts loss in the same length of ⅞-in. semiflexible air-dielectric cable. This cable is widely used for directional AM broadcast arrays. It is a favored cable for moderate-power AM stations and probably the most commonly used for AM sampling lines. Semiflexible cable is occasionally used for FM feeders, TV translator service, and low-power TV.

Continuous Air-dielectric Cable

Continuous air-dielectric (flexible) cable is fast becoming the most popular cable for many installations, since it combines high efficiency with ease of handling and a very low VSWR. It can be used for all the applications listed for semiflexible cable. There are several types on the market today. Electrical and mechanical data can be obtained from the various manufacturers. A typical continuous air-dielectric cable is shown in Fig. 5-3. Cable of this type is comprised of a continuous inner and outer conductor. The inner insulation is also continuous throughout the entire length of the cable. Since the cable is produced by a continuous process, no joints are required even for very long lengths of several thousand feet. The continuous process thus eliminates electrical discontinuities, and a low VSWR is achieved.

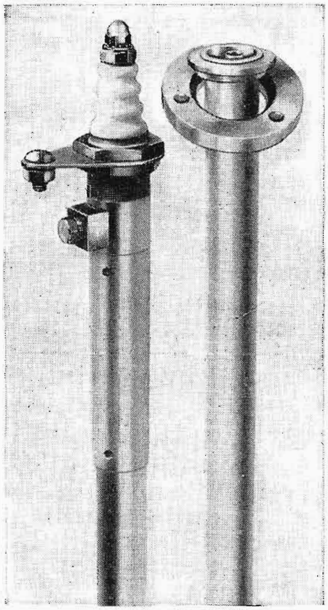

FIG. 5-2. ⅞-in. semiflexible cable.

FIG. 5-3. Continuous air dielectric cable.

Weatherproofing for most continuous cables is accomplished by a tough jacket covering the outer conductor. This enables the cable to be used in any environment such as salt air, direct ground burial, or under water.

Some continuous air-dielectric cables can withstand repeated bending, while others are limited to one or two bending cycles similar to the semiflexible cables mentioned previously. The manufacturer's flexing recommendations should be followed in all cases. Most continuous cables are shipped on reels and are uncoiled without difficulty. They can also be attached directly to a tower, thus eliminating the need for spring or sliding hangers.

Rigid Transmission Line

Rigid air-dielectric transmission line has very low attenuation and VSWR. It is manufactured from hard-temper copper tubing in standard 20-ft flanged lengths.

The rigid inner conductor is supported by Teflon pegs. In the past, ceramic discs were used for the inner-conductor support. The inner connector used with rigid lines has an insulator (also of Teflon) which anchors the inner conductor and supports it in vertical runs. Figure 5-4 shows 1⅝- and 9-in.-diameter rigid lines.

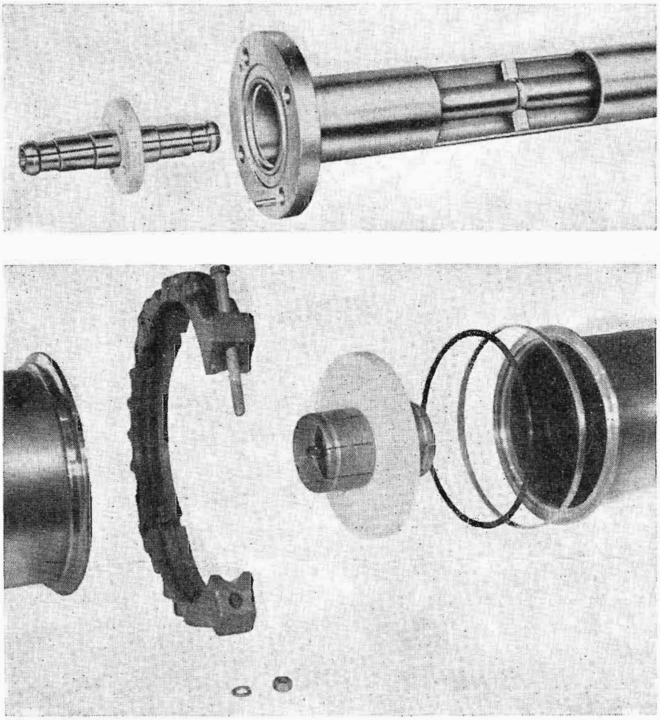

FIG. 5-4. 1⅝- and 9-in. rigid coaxial lines.

Rigid transmission line is used mainly for higher power levels. Its use in AM is generally limited to the main feeder lines on omnidirectional or directional AM arrays using 5 kw or more. In FM and VHF TV, rigid lines constitute 99 per cent of the feeders. In UHF TV, rigid line is used for the transmitter-room interconnections, for the final antenna connection, and usually as the main feeder along the tower. The ⅞- and 1⅝-in.-diameter rigid lines are ideal for inside runs in low- or medium-power communications or TV broadcasting installations. These rigid transmission lines are especially recommended for connections between transmitters, diplexers, receivers, dummy loads, switching systems, and other components.

For short transmission line runs in UHF-TV installations 3⅛-in.-diameter rigid line is particularly economical. It can be used for such applications when the transmitter power does not exceed the line rating (18 kw at Channel 14 and 13 kw at Channel 83). For high-power applications in VHF TV and low-channel UHF TV, 6⅛-in.-diameter transmission line is recommended. For the higher UHF TV frequencies up to 890 Mc (Channel 83) 75-ohm 6⅛-in. line is used. Nine-inch-diameter rigid transmission line has been designed for very high power systems and for low-channel UHF TV.

Waveguide

For the UHF TV broadcaster, the use of waveguide from the transmitter to the antenna provides a lower attenuation than any coaxial line. It is manufactured, using sheet-metal processes, from copper-clad steel or aluminum. Three common types,

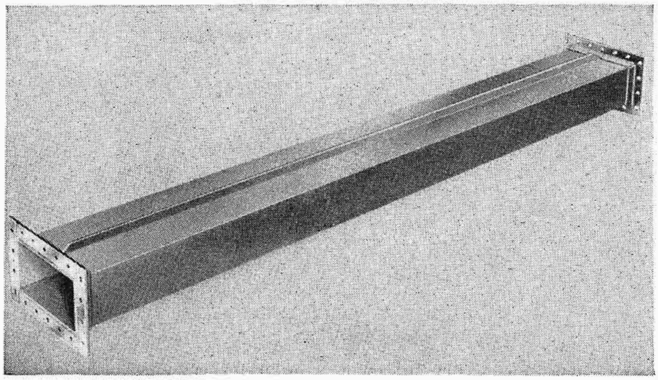

FIG. 5-5. WR-975 waveguide.

supplied in standard 10-ft flanged sections, are WR-1500, WR-1150, and WR-975 with inner dimensions of 15 by 7½, 11½ by 5¾, and 9¾ by 4⅞ in., respectively. A section of WR-975 waveguide is shown in Fig. 5-5.

The copper-clad steel waveguide has two advantages over aluminum waveguide. It has a lower attenuation, and its thermal coefficient is the same as that of the steel tower, eliminating the need for sliding and spring hangers for tower installations. Aluminum waveguide must be provided with a means to accommodate thermal expansion and contraction.

Waveguide is suited for medium and long runs in UHF TV high-power systems because of its power-handling ability, noise-free performance, and its high efficiency.

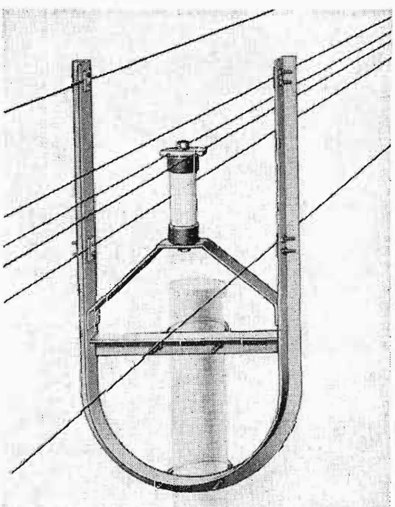

FIG. 5-6. Open-wire line.

Others

Another method of RF energy transfer is the open-wire line. This line is limited in use generally to AM broadcast and high-frequency antenna systems. It generally consists of six solid-copper wire lines acting as a coaxial line. The four outer wires are grounded, and the two center wires are "hot" and connected in parallel. Open-wire line has the advantage of high power ratings and very low loss but has the disadvantage of considerable line maintenance and interference-producing radiation. It is less costly than rigid line of the same power-handling ability; however, open-wire line has been largely supplanted by rigid air-dielectric coaxial line because of technical considerations. Open-wire line is shown in Fig. 5-6.

ELECTRICAL CHARACTERISTICS OF TRANSMISSION LINES

Attenuation

Attenuation in a transmission line is loss created by imperfect conductivity of the conductors and the imperfect insulating medium or dielectric. In open-wire lines, an additional loss is incurred in the form of radiation. In coaxial lines and waveguides, this loss is not incurred, since the RF field is totally enclosed within the cable. Attenuation for RF cables is generally expressed in decibels per 100 ft. In rectangular or round waveguides with air as the dielectric, the entire loss is conductor loss. In coaxial cable, the losses are conductor losses and the dielectric losses associated with material used as the inner-conductor support. In solid-dielectric cables, the dielectric loss is appreciable and at high frequencies may exceed the conductor losses in spite of high-quality dielectric materials. In so-called "air-dielectric coaxial cables," the insulating supports are limited to a very small portion of the total dielectric space, so that the dielectric is principally air; therefore, the total dielectric losses are generally negligible. At very high frequencies, they may become large enough to become a significant portion of the total loss.

Because of skin effect, the RF current penetrates less of the conductor as frequency increases. Attenuation due to conductor losses thus increases with frequency and is proportional to the square root of frequency. Attenuation due to dielectric loss is directly proportional to frequency. Attenuation can be calculated; however, actual measured values do not always agree with theoretical values. It has therefore become common practice to use measured attenuation values rather than calculated ones. The actual attenuation is generally quite close to calculated values but may vary owing to surface condition, connector alloy, and its actual conductivity. Measured attenuation curves for several line sizes are shown in Fig. 5-7.

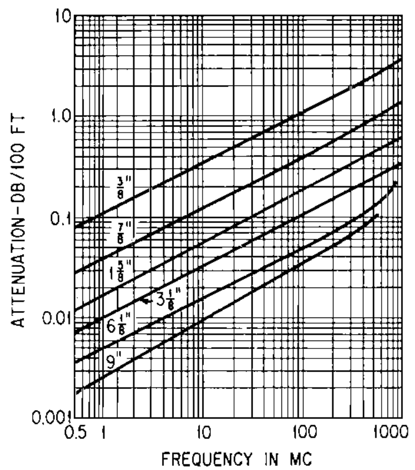

Fig. 5-7. Measured attenuation for several sizes of air-dielectric coaxial lines.

Actual attenuation experienced in operation may be further influenced by VSWR occurring on the line owing to an imperfect load. This is generally not a problem from the increased-loss standpoint, since a considerable VSWR is necessary to produce any significant loss increase. Loss is increased by VSWR by the factor $1 + (\mathrm{VSWR})^2/2\mathrm{VSWR}$. Figure 5-8 illustrates this effect.

Efficiency of a transmisison-line system can be easily calculated from the total attenuation.

$$\text{Efficiency} = \frac{1}{\text{antilog}\ (\alpha/10)} \text{ expressed as a decimal per cent}$$

where α is the total attenuation in decibels. Often line sizes larger than necessary from the power-handling standpoint alone are used in order to obtain better line efficiencies.

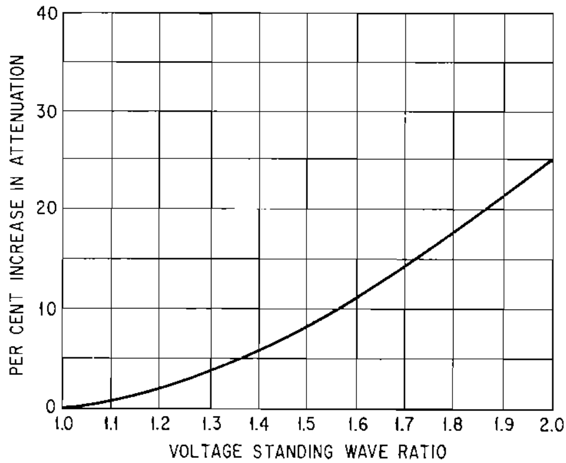

FIG. 5-8. Increase in attenuation in line due to VSWR on line.

Voltage Standing-wave Ratio (VSWR)

When a transmission line is terminated in an impedance different from the characteristic impedance of the line, a portion of the energy traveling down the line is reflected. The amount of reflection depends on the degere of mismatch. The incident and reflected traveling waves combine to produce an uneven voltage distribution along the line, and voltage and current maxima and minima occur. VSWR has been defined as the ratio of the maximum to minimum voltage; that is, VSWR $= E_{max}/E_{min}$. This effect is measurable with various types of instruments such as slotted lines, bridges, and reflectometers.

As stated previously, the electronics industry has standardized on 50 ohms for characteristic impedance of coaxial cables. There are other impedance cables available for special purposes, as mentioned; however, most antennas, loads, or other coaxial devices are almost exclusively designed for 50-ohm operation. Although the nominal value of terminating devices can be described as 50 ohms (or other impedance level), their actual impedance characteristic may be different when a band of frequencies is considered; thus, an antenna or other load can be described as 50-ohm impedance with a VSWR indicated over a particular band. This means that the impedance of the device is approximately 50 ohms and, over the band considered, would create a VSWR on a 50-ohm transmission line no greater than that indicated.

The effects of VSWR may or may not be a problem, depending on the type of service, power levels involved, etc. As VSWR increases, the maximum voltage points increase, and breakdown problems might occur if the power level and VSWR were high enough and the cable choice was small. Irregular heating along the cable due to current maxima may cause problems also, especially in solid-dielectric cables, where the plastic dielectric material may soften. These possibilities would require large VSWR values to cause problems. Other effects of VSWR, where the cable is not impaired but the service may be, are ghosts in a TV picture, intermodulation in multiplex FM, an undesirable impedance at the transmitter end of the line, etc. As already described in the preceding section on attenuation, VSWR also causes some increase in the actual attenuation of a transmission line.

In many services, a moderate VSWR is of no consequence as long as the line ratings are not exceeded. In AM broadcast applications, VSWR may be as much as 3 or more with perfectly satisfactory operation. In FM broadcasting, system VSWR is generally less than 1.75. In TV, an industry standard of system VSWR of less than 1.1 has been rather arbitrarily arrived at as desirable, but many stations are operating very satisfactorily with greater values.[1] In general, discontinuities contributing to VSWR that are located close to the transmitter will have little or no effect on picture quality. The transmission line itself, the line fittings, or both may produce some VSWR. This is usually very small and is of little consequence for most services. For TV or certain microwave applications, it is sometimes large enough to influence performance.

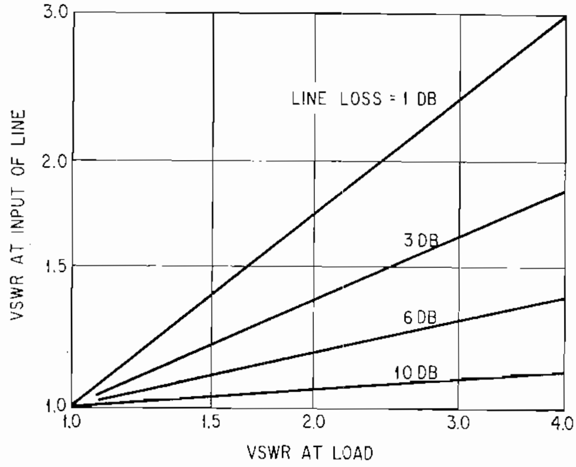

FIG. 5-9. VSWR improvement due to line attenuation.

In cases where the line has considerable attenuation, VSWR at the input end is lower than that of the antenna or load itself. The curves in Fig. 5-9 illustrate the extent of this effect.

Power Ratings

There are two basic types of power ratings for transmission lines. One is based on the maximum heating the cable construction might safely withstand. It is generally referred to as the "average power rating." The other is based on voltage-breakdown considerations and is generally described as the "peak-power rating." Consideration of both ratings is necessary for most services.

Average power is the power in the signal capable of creating heat. Peak power is that maximum rms power which can be reached in any interval (such as during a modulation cycle) and should not be misinterpreted as any relation between peak and rms voltages such as $\sqrt{2}$ in sine waves. In a continuous CW carrier (including FM), peak power equals average power. In 100 per cent AM, the power rises to four times the carrier power, so in this case, the peak power is four times the carrier power. Since average-power rating is limited by heating which is created by line losses, this rating decreases with increasing frequency. Peak-power rating is dependent on voltage considerations which are not significantly frequency sensitive; thus this rating is constant with frequency. Transmission-line ratings can be arrived at by various experimental and calculated procedures. The over-all picture is complicated by the effects of environment, such as ambient temperature, cable pressure, and others. Whatever basis for rating is used, it must be stated with the rating or

[1] Not recommended for other reasons than power losses, etc.

it is meaningless. Once a rating is determined for the conditions stipulated, the rating can be adjusted for other conditions. As was mentioned, ratings can be arrived at by various means. The following procedure is one way which has been used for many years and has been found to be very satisfactory. Curves illustrating these ratings for several popular line sizes are shown in Fig. 5-10.

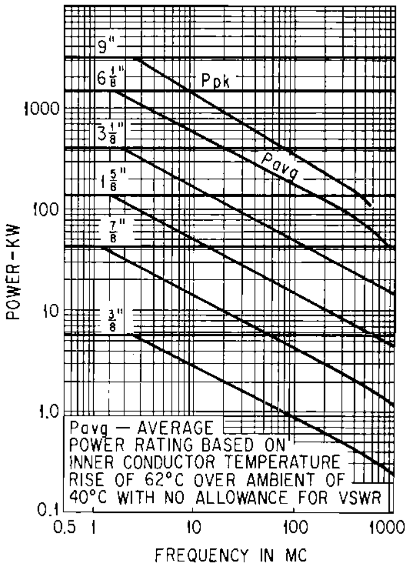

FIG. 5-10. Curves illustrating peak-power and average-power ratings. (P_{pk}—peak-power rating based on dry air at 1 atmosphere absolute pressure at sea level with no allowance for modulation or VSWR.)

Rigid Air-dielectric Coaxial Line

Peak-power Rating. The procedure here is to establish a peak voltage the line will withstand every time if it is manufactured properly. The maximum voltage gradient occurs at the inner-conductor surface in a coaxial line.

A theoretical breakdown gradient cannot be used, since breakdown is a highly variable phenomenon occurring at widely different values depending on small effects such as scratches, dust particles, and insulator condition. Derating theoretical breakdown to 35 per cent of theoretical has been found to be a practical value for a d-c test voltage (or 60-cycle peak test voltage). The equation below is derived from the maximum voltage gradient in a coaxial line and includes factors considering pressure, temperature, and inner conductor curvature. It also includes the derating of 35 per cent described above and results in a very reliable production test voltage. This test voltage is then further derated and used for power rating purposes.

$$E_p = 3.17(10)^4 a\delta \left(\log_{10}\frac{b}{a}\right)\left(1 + \frac{0.273}{\sqrt{a\delta}}\right)$$

where E_p = production test voltage, volts
a = inner-conductor OD, in.
b = outer-conductor ID, in.
δ = air-density factor = $3.92B/T$
where B = absolute pressure, cm of mercury
T = temperature, °K

$$(\delta = 1 \text{ for } B = 76 \text{ cm and } T = 23°\text{C} = 296°\text{K})$$

The values are generally rounded off as follows for the common 50-ohm line sizes:

Nominal Cable OD, In.	*Production Test Voltage, DC Volts or 60-cycle Peak Volts*
⅜	2,200
⅞	6,000
1⅝	11,000
3⅛	19,000
6⅛	35,000
9	50,000

The next step is to derate this production test voltage to a realistic RF rms operating voltage. The voltage is derated to 0.7 of its above value to go to RF conditions, by $1/\sqrt{2}$ to go to rms value, and by a suitable safety factor which is usually 2.

$$E_{rf} = \frac{0.7E_p}{\sqrt{2}\,(\mathrm{SF})} = 0.247E_p \qquad \text{volts}$$

where E_{rf} = maximum RF rms operating voltage with no allowance for VSWR or modulation, but including safety factor

SF = safety factor on voltage of 2

This voltage, E_{rf}, determines peak power rating.

$$P_{pk} = \frac{(E_{rf})^2}{z_0} \qquad \text{watts}$$

This rating must be derated further for VSWR and amplitude modulation, although these vary with the application and are not a part of the basic rating. This would be done as follows:

$$P_{\max} = \frac{P_{pk}}{(1 + M)^2 \mathrm{VSWR}} \qquad \text{watts}$$

where M is the modulation index and 1 is for 100 per cent. This would derate P_{pk} by 4 for 100 per cent AM due to modulation (as mentioned earlier) to obtain the rating in terms of carrier power or transmitter nameplate rating. Notice that peak-power rating must be reduced directly by VSWR.

A very significant point should be noticed in the equation for E_p, in that the breakdown voltage, in the range of pressures normally used, is approximately proportional to absolute pressure; thus, the peak-power rating is proportional to the absolute pressure squared, and doubling the absolute pressure in any line will multiply the peak-power rating by 4. This is often a valuable tool in achieving high-peak-power operation. Certain high-dielectric-strength gasses other than air, such as sulfur hexafluoride, have also been used to increase peak-power rating. This gas, as compared with air at equivalent pressures, will effect approximately a 2-to-1 voltage- or 4-to-1 peak-power-rating improvement. Combining the effects of using special gaseous dielectrics and pressurizing to several atmospheres pressure are also possible, compounding the improvement.

Average-power Rating (Air-dielectric Coaxial Line). Average-power rating is limited by heating due to line losses. Owing to the character of coaxial-line construction, the loss and temperature rise of the inner conductor are greater than those of the outer conductor. The ultimate temperature that the inner conductor might be safely allowed to reach determines the rating. This temperature is determined by such considerations as inner-conductor expansion and oxidation, dielectric mechanical strength at elevated temperature, etc. The most common standard method in use for many years limits the outer-conductor temperature to 23°C rise over 40°C ambient. The corresponding inner-conductor rise is 62°C rise; therefore, the ultimate inner-conductor temperature for normal conditions is limited to 102°C (216°F). Temperature rise of outer- vs. inner-conductor rise for a 50-ohm air-dielectric coaxial line is illustrated in Fig. 5-11.

The average-power rating can be calculated from the following:

$$P_{\mathrm{avg}} = \frac{16{,}380\sigma D}{db_1} \qquad \text{watts}$$

where P_{avg} = average-power rating for 23°C temperature rise of the outer conductor (62°C rise of inner), watts

D = outside diameter of line, in.

db_1 = 1.085α where α is measured attenuation, db/100 ft (1.085 is increase in α at elevated temperature)

σ = heat-emissivity coefficient of outer conductor, watts/sq in.

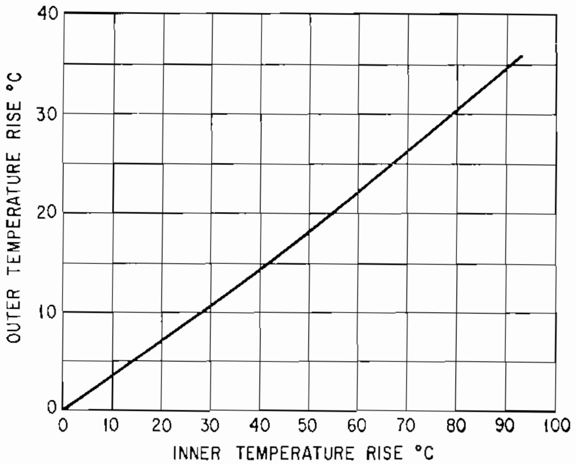

FIG. 5-11. Inner- and outer-conductor temperature rise for a coaxial line with $Z_0 = 50$ ohms.

The values of σ for common line sizes are as follows:

Line OD, In.	*σ, W/Sq In.*
⅜	0.166
⅞	0.134
1⅝	0.120
3⅛	0.111
6⅛	0.10
9	0.095

The resulting average-power rating must be further derated directly with VSWR; however, this is variable, depending on type of service, and is not a part of the basic rating.

The heat emissivity of a conductor varies with surface conditions, and it depends on whether the surface is shiny, oxidized, painted, etc. The values shown above are for copper outer conductors between slightly and normally oxidized. A curve illustrating how σ varies with temperature rise and tube size is illustrated in Fig. 5-12. The values of σ as given are taken from this set of curves.

The curves of Figs. 5-11 and 5-12 are shown to illustrate how an average-power rating can be rerated for other conditions. A study of these two figures will show that it is possible to adjust a rating for different ambient temperatures and predict temperature rises for powers other than the full-power rating. A curve indicating rating change for other ambient temperatures, as generated from these curves, is illustrated in Fig. 5-13. These curves are valuable for quickly predicting performance at conditions other than those specified for the standard ratings.

The heat exchange above is assumed to be in still air with no direct solar radiation. Moving air will improve the situation, while sunshine will increase heating.

Semiflexible Coaxial Lines

These are essentially air-dielectric lines, and power rating is handled the same as in the previous section. The difference in rating procedure occurs only in the average-power rating, which is limited by an ultimate inner-conductor temperature dependent on the temperature characteristics of the dielectric material used. Peak-power rating would be influenced by pressure and VSWR as described in the previous section on rigid air-dielectric coaxial line.

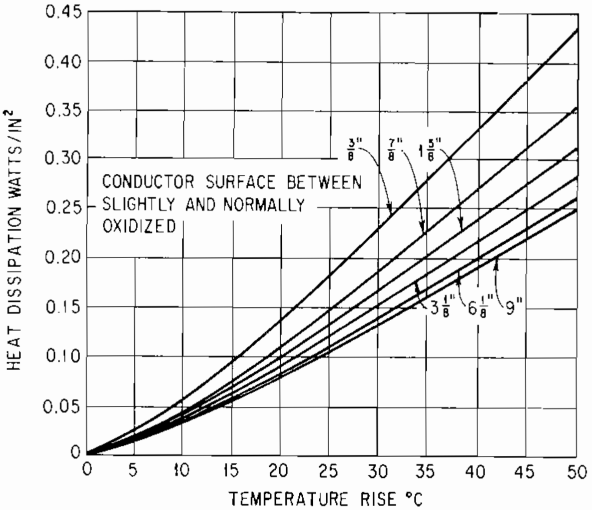

FIG. 5-12. Heat dissipation by radiation and convection vs. temperature rise for various outer-conductor diameters.

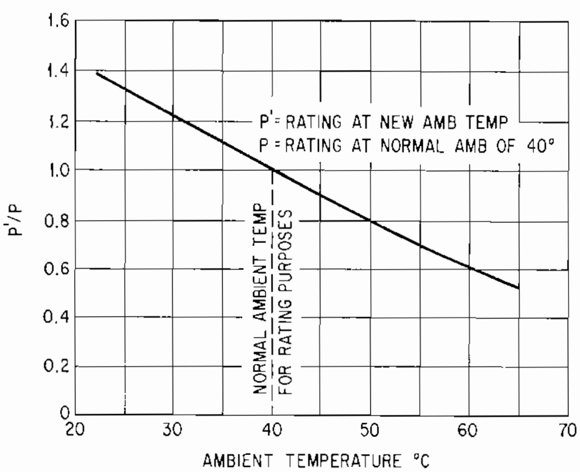

FIG. 5-13. Average-power-rating variation in transmission line for variation in ambient temperatures.

Solid-dielectric Coaxial Lines

Power ratings for solid-dielectric coaxial lines are controlled to some extent by agencies such as ASESA and EIA. Manufacturers' ratings are sometimes different, but the differences are generally small. The rating limitations are based on considerations similar to those described in detail above; however, the average-power rating for polyethylene-insulated cables is limited by an ultimate inner-conductor temperature of 80°C. Most ratings for these cables, such as those given by EIA in Standard RS-199, are for this 80°C maximum inner-conductor temperature at an ambient of 40°C. RS-199 gives conservative power-rating curves and attenuation curves for many of the popular solid-dielectric cables. RS-199 also gives a table for rerating average-power rating of these cables for other ambient temperatures. It is partially tabulated below.

Ambient Temp, °C	*Rerating Factor*
40	1.00
50	0.72
60	0.46
70	0.20
80	0

Rectangular Waveguides

Waveguides have power ratings considerably in excess of the transmitter powers presently available to broadcasters; thus, power rating is not a factor in the selection of a waveguide.

Power Ratings for Various Services

Power ratings are often published already derated for various types of service depending on expected VSWR, modulation, and peculiarities in transmitter ratings (such as in TV).

In derating for VSWR, it is common to consider system VSWR as follows: broadcast and HF: AM, 3.0; FM, 1.75; TV, 1.1.

In derating for AM services, the peak-power rating is often derated by 4.5 to allow for modulation with some overmodulation, resulting in a rating for AM in terms of carrier power or transmitter nameplate rating.

For TV, black level video power plus aural power is actually 10 per cent greater than the transmitter nameplate rating (for cases where aural power is 50 per cent of peak video synchronizing power); thus, TV ratings are often given already derated by 1.1 for this reason and an additional 1.1 for system VSWR.

Some of these deratings may seem of minor effect but are given to provide consistent ratings for the initial conditions of temperature rise or voltage governing the ratings. The VSWR deratings given above are assumed as typical maxima, and for a particular circumstance where the actual VSWR is known, it would be better to derate accordingly.

INSTALLATION

Mechanical considerations of a radio or TV station involve not only the installation of the transmission line but also line maintenance. Broadcast installations are usually planned for long-term operation. A very carefully planned and executed original installation will assure long and trouble-free operation. Since air time is expensive, it is worthwhile to go to considerable effort to insure continuous uninterrupted operation.

The transmission-line system (in the case of FM and TV) consists of a vertical run which connects to the antenna and a horizontal run which connects to the transmitter or diplexer. A variety of hangers is required for supporting and anchoring the line. Connections between various units of transmitter equipment inside the building are made by unpressurized line, which may incorporate a switching system for switching between units.

Expansion and contraction, due to changes in temperature of the line, are accommodated by use of spring hangers on the tower and swinging hangers for the horizontal run. The line is anchored at the antenna by a rigid hanger and at the transmitter building by a wall anchor, so that movement of the line is away from the equipment. Over a temperature range of −25 to +125°F, expansion of the line is about 1½ in. per 100 ft. This amount of movement must be allowed for in the horizontal run. The steel tower expands or contracts with temperature change at a different rate from that of copper, and copper conductors of a transmission line will change length relative to the tower, approximately ½ in. per 100 ft over the above temperature range. The spring and swinging hangers support the weight of the line but permit free axial movement during changes in temperature. This expansion or contraction of the system accumulates at the base of the tower; therefore, 15 or 20 ft of line on each side of the elbow at the base of the tower must be free to flex and accommodate the change in length. A lateral brace, which is used at the base of the tower, prevents lateral line motion which would be caused by wind forces but does not interfere with movement caused by change in line length.

The importance of the effects of expansion and contraction cannot be overemphasized. The thermal force occurring in rigid transmission lines during a temperature change is sufficient (when causing contraction) to tear hangers from the structure and pull the line from the transmitter building bulkhead fitting. When the line expands, severe buckling can occur and cause tower strain which could eventually end in failure of the transmission line or tower.

Rigid-transmission-line Installation

1. Since rigid-line installations are the most common in use today, the following pages present a step-by-step approach to the installation of a 3⅛-in. rigid-transmission-line system beginning with the Bill of Materials table which gives the approximate items and quantities required for a single-line television installation on a 300-ft tower.

Bill of Materials

Item	*Quantity*	*Use*
1. 90° mitered elbow, flanged	3	For changing line direction
2. Special lengths of line, unflanged	7	For custom applications
3. Soft soldered flange kit	7	For field flanging lines and elbows
4. Rigid hanger	1	For anchoring top of line to tower
5. Mounting adapter	28	For use if tower members do not have holes
6. Combination spring and sliding hanger	27	For hanging transmission line
7. 20-ft section of line	17	For main run
8. 15-ft section of line	2	For main run
9. Lateral brace	1	For prevention of lateral line movement
10. Horizontal hanger	4	For free-swing support of horizontal line
11. Horizontal anchor	1	For anchoring line at building wall
12. Gas barrier	1	For pressure termination of line
13. Automatic dehydrator	1	For automatically pressurizing line
14. Straight coupling	7	For joining unflanged line
15. 90° elbow, flanged one end	3	For changing line direction
16. 90° elbow, unflanged	2	For changing line direction

The antenna input may be a solid-dielectric connection, a flanged connection for a pressurized antenna, or a flanged connection for an unpressurized antenna. To mate the transmission line with the solid-dielectric connection, an adapter for connecting between air- and solid-dielectric cables must be used (see Fig. 5-14). The adapter also functions as a gas barrier. For a flange connection, where the diameter of the antenna input flange is smaller than the diameter of the transmission-line flange, a reducer is used. A reducer is shown in Fig. 5-15.

When the antenna harness is of air dielectric, gas from the transmission line should be permitted to enter the antenna. A gas-inlet fitting (Fig. 5-16) should be inserted at the point of connection for possible use in purging the line. The fitting can be omitted if the antenna harness has a gas port.

If, for any reason, an antenna with an air-dielectric harness is not to be pressurized, a gas barrier, as shown in Fig. 5-17, must be provided at the point of connection. In this case, the unpressurized line above the gas barrier may collect moisture, so drain holes should be drilled immediately above the gas-barrier insulator. Various antenna connections are shown in Fig. 5-18.

2. Transmission-line assembly normally starts at the antenna and proceeds to the transmitter. Since the connection at the top of the tower depends on the type of tower, type of antenna, and the position of the antenna, a custom connection must be made at the antenna with two mitered elbows and two special lengths of line. Mitered elbows, like the one shown in Fig. 5-19, are used much more than the older sweep-type 90° bends, which are now obsolete, since they are more versatile mechanically and are of higher quality electrically. The special lengths are field-cut to the exact dimension required and are flanged with soft-soldered flange kits (see Fig. 5-20). A rigid hanger (Fig. 5-21) must be used at the top of the transmission-line run so that thermal expansion and contraction of the line do not affect the antenna. A typical installation at the top of the tower is shown in Fig. 5-22. For new installations using towers having angle-type members, the tower manufacturer, in most cases, will punch the members with holes for mounting the hangers. For towers that are already erected and for new towers with round members, mounting adapters that attach the hangers to the towers without drilling must be used. Tower members should not be drilled without consent of the manufacturer because of possible weakening of the structure.

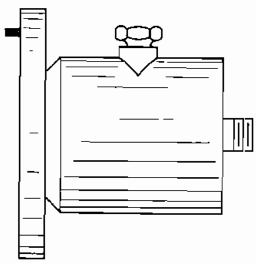

Fig. 5-14. Adapter.

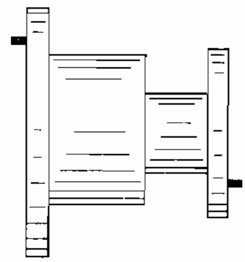

Fig. 5-15. Reducer.

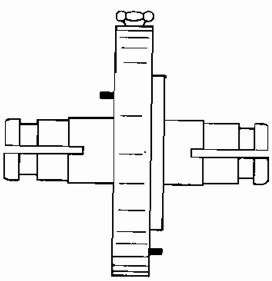

Fig. 5-16. Gas inlet.

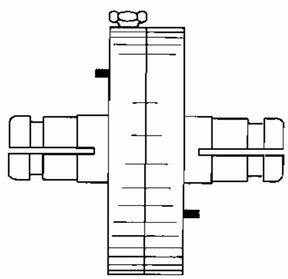

Fig. 5-17. Gas barrier.

3. The second phase of the installation is along the tower where the spring hangers aud sliding hangers are used. The slidiug hangers are merely guides placed at 10-ft intervals along the vertical run to keep the transmission line from any lateral motion. The spring hangers are used to support the weight of the line and to accommodate differential expansion between line and tower. Sliding and spring hangers are made by some manufacturers as a combination hanger, as shown in Fig. 5-23. As the assembly proceeds, make certain to use a combination spring and sliding hanger at 10-ft intervals, placing a hanger 5 ft from each end of the standard 20-ft section (see Fig. 5-24). The most convenient location to hang the transmission line is near the tower ladder, where it is easily accessible for periodic inspection.

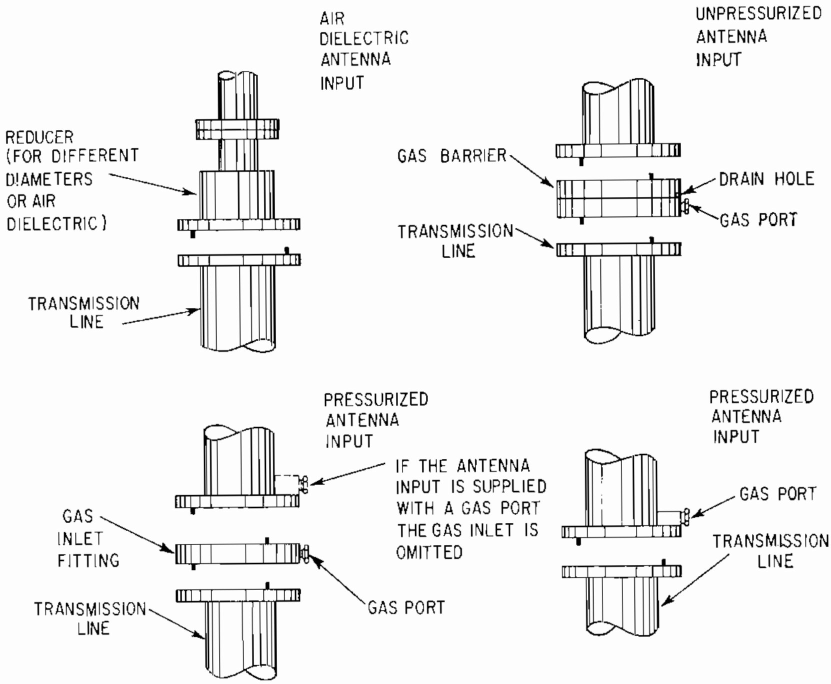

FIG. 5-18. Various antenna connections.

Alternatively, the line can be attached to a tower leg inside the tower. Do not support more than one section of line on a flange joint without using hangers. It is much safer to leave the hoist line tied to the line section until after the hangers are attached. Tapered towers involve changes in the line direction that are different from the 45 and 90° permitted by the standard elbows. In such cases, it is possible to bend a section of transmission line to make a change of up to 5° for 3⅛-in. line or smaller and up to 1° for 6⅛-in. line. For greater changes, special angle elbows must

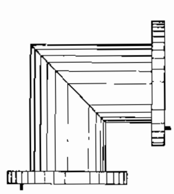

FIG. 5-19. 90° mitered elbow.

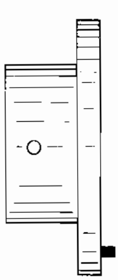

FIG. 5-20. Soft-soldered field flange.

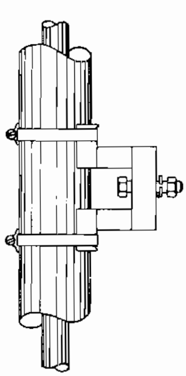

FIG. 5-21. Rigid hanger.

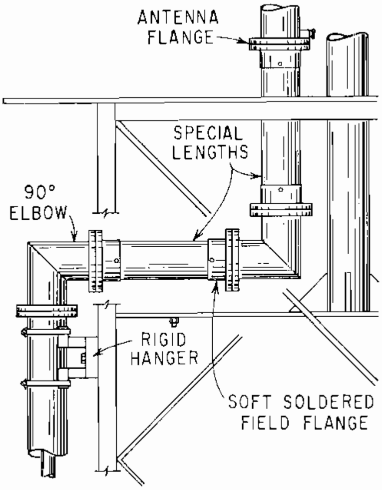

FIG. 5-22. Installation at top of tower.

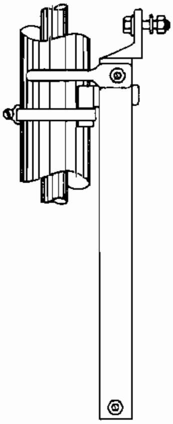

FIG. 5-23. Combination spring and sliding hanger.

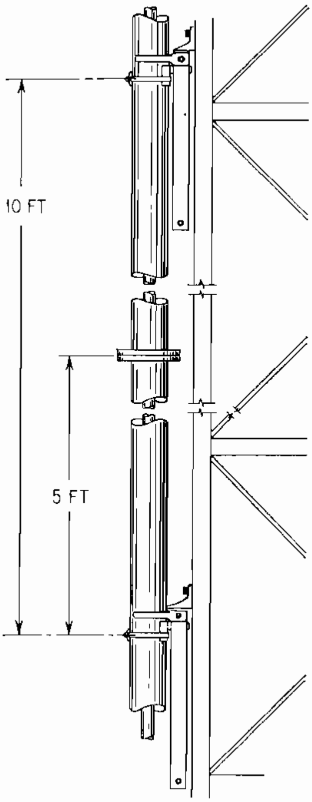

FIG. 5-24. Installation on tower.

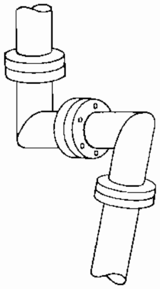

FIG. 5-25. Two 90° elbows in tandem.

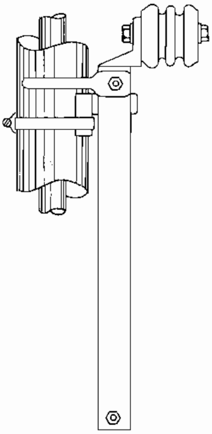

FIG. 5-26. Insulated spring and sliding hanger.

be obtained or two 90° mitered elbows can be connected in tandem, as shown in Fig. 5-25, to produce the desired angle.

If the supporting tower is also used as an AM broadcast radiator, some method must be used to prevent the AM energy from being grounded by the transmission line that feeds the TV or FM antenna. A popular method is to isolate the line up the tower for a distance of a quarter wavelength (at the AM broadcast frequency) from the base, using insulated line hangers. A typical insulated spring hanger is illustrated in Fig. 5-26. Extension spacers must be used with the noninsulated

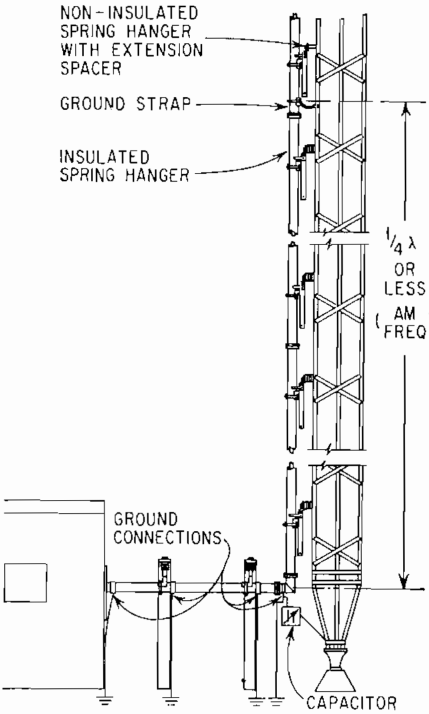

Fig. 5-27. Installation on AM tower.

hangers above the quarter-wave point to space them the same distance from the tower as the insulated spring hangers. This must be done to keep the transmission line in vertical alignment. Because of the quarter-wave isolation at the base of the tower, a very high impedance between the tower and the line is presented to the AM energy. Common practice is to make the isolated section approximately 0.22 wavelength long and to use a variable capacitor at the base of the tower to tune to quarter-wave resonance. Figure 5-27 shows an installation on an AM tower. *Caution:* Since a high RF potential exists between the line and the tower, the line should be mounted where it will not be accidentally touched by anyone on the tower ladder.

4. The third phase of the installation is at the base of the tower. The 15-ft sections of line (Item 12 in the Bill of Materials) are installed here, one length vertically and one starting the horizontal run. These lengths are not supported by hangers but are left free to flex and accommodate the changes in length caused by line expansion and contraction (see Fig. 5-28). If the bend from the vertical run to the horizontal run is 90°, a standard 90° mitered elbow is used; however, if the bend is

of some other angle as in the case of a tapered tower, two 90° elbows can be used in tandem to produce any angle form 0 to 180°. The bottom of the line (near the elbow) is supported with a lateral brace, as shown in Fig. 5-29. The brace prevents lateral motion of the line but permits line expansion and contraction.

The horizontal run, like the vertical run, is also affected by thermal forces, so provisions must be made to provide horizontal support while permitting the line to change length. To accomplish this, the line is supported by horizontal swinging hangers which bolt to support post arms. A horizontal swinging hanger is shown in Fig. 5-30. Some installations use maple rollers for the support, allowing complete freedom for the transmission line. As on vertical runs, the hangers should be placed at 10-ft intervals.

Horizontal runs in icing country should have ice shields installed above them. Effective ice shields are made from ¼-in. steel plate installed like a tent over the full length of the horizontal run. The angle generally used is 45° for each of the sides. A 3- by 3-in. steel angle is placed at the top, and a 2- by 2-in. angle is attached to the bottom of each side, making a rigid installation (see Fig. 5-31). In places where icing conditions are severe, this scheme is frequently reinforced by additional angles along the top of the plates. In mountain country, it is not uncommon to have huge chunks of ice break off the tower.

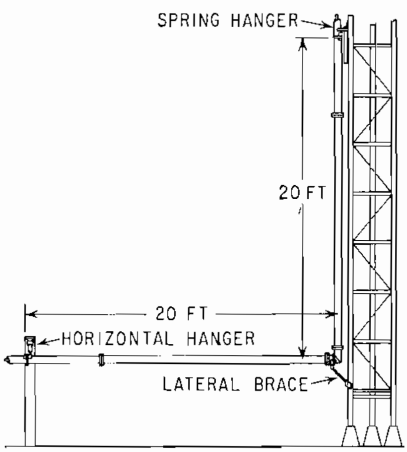

Fig. 5-28. Installation at base of tower.

Heating effects of direct solar radiation on a transmission line may lower its power rating substantially. In cases where this is a limiting factor, the problem can be solved by providing a sun shield that protects the line from direct radiation. The shield must be so designed that it permits circulation of air around the line.

The line is anchored at the building wall with a horizontal anchor which is like the rigid anchor on top of the vertical run. A horizontal anchor is shown in Fig. 5-32. Its purpose is to keep line movement away from the equipment, permitting expansion and contraction to build up at the tower end of the horizontal run.

Long horizontal runs of transmission line are quite common, particularly in directional installations. Frequently towers are spaced at a considerable distance and roads and walkways must be crossed, so occasionally lines are buried in the ground. It must be pointed out, however, that generally speaking, rigid lines are not recommended for burial. The EIA (formerly RETMA) Standard RS-158, par. 6, states, "Lines buried or run underground shall be protected and shall have provision for minimizing the effects of galvanic and corrosive action." To avoid corrosion problems, lines are not buried directly in the soil but are laid in a trench made of wood or concrete which is provided with a cover. Ducts made of tile or other suitable material are also used. When lines must be buried directly in soil, the soil conditions should be carefully checked. If the soil is alkaline, the transmission line will not deteriorate. Vinyl- or polyethylene-covered lines are more suitable for buried installations than bare copper or aluminum lines and should be used if possible. Stray ground currents may attack the line. This condition should be investigated periodically. When lines are buried, markers are placed at convenient intervals, usually at splices in the line.

5. Inside the building, the transmission line connects to the gas barrier immediately upon entering the building. The barrier has a gas port to which the automatic dehydrator is attached. The automatic dehydrator keeps the entire length of line from the building to the antenna pressurized. The transmission line inside the build-

ing (on the other side of the gas barrier) is unpressurized. Connections between line sections inside the building are made with straight ungassed couplings. A coupling is shown in Fig. 5-33. These couplings make it convenient to get at connections for maintenance purposes. Connections from the transmitter to the diplexer and the

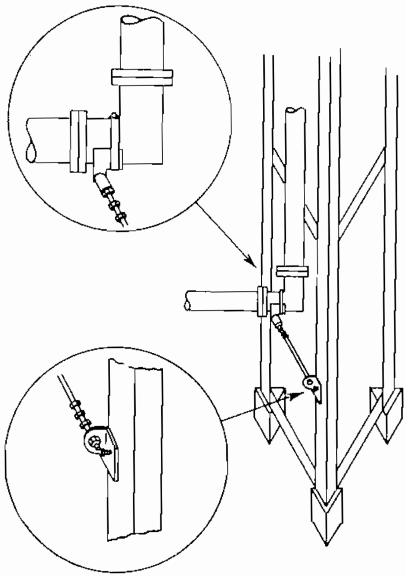

Fig. 5-29. Lateral brace.

line are shown in Fig. 5-34. This is a simple station arrangement. Since all stations are different, the inside connections are never quite alike; therefore, no set installation rules exist.

6. After all outside flange connections are completed and the gas barrier is attached to the transmission line inside the building, the line should be pressurized.

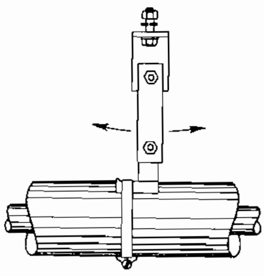

Fig. 5-30. Horizontal hanger.

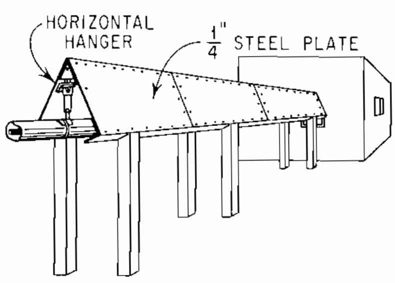

Fig. 5-31. Protected horizontal run.

If moist air has entered the system during installation, it should be purged by pressurizing three or four times, releasing all air between pressure cycles. Proper purging is done by removing the gas port plug located at the antenna end of the transmission line. After purging, replace the plug and pressurize the line. Changes in temperature can cause moisture from any outside air that enters the line to condense and very seriously impair the efficiency of the line. For this reason, the line should be operated under pressure at all times. A gauge pressure of 5 to 10 psi is adequate for most installations. Dry air is recommended for this purpose. Dry nitrogen can also be used, in which case be certain to use oil-pumped nitrogen.

Uupressurized installations are not recommended. If, because of unusual circumstances, the line is to be operated without pressure, a hole must be provided at the

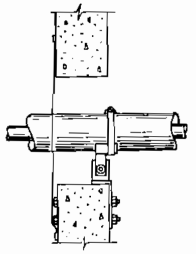

Fig. 5-32. Horizontal anchor.

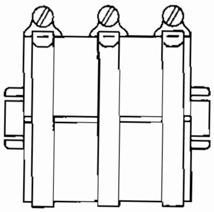

Fig. 5-33. Straight coupling.

lowest point in the system to allow the condensate to drain. This should be done by filing a notch through the outer conductor at the underside of the line, using a triangular file. Do not drill or punch a hole in the line, as this will leave undesirable burrs inside the outer conductor.

7. Coaxial switching systems are recommended for all television installations. Such a system greatly reduces transmitter tune-up and testing time and also reduces off-the-air time caused by equipment failure. Motor-driven coaxial switches are ideal for this application. Manual coaxial switches and coaxial patch panels are also frequently used. Use of switches eliminates time-consuming manual changes of transmission-line connections during emergencies. Standby equipment can be quickly and easily checked under actual operating conditions. Many stations usually are equipped with such standby equipment as an auxiliary diplexer, standby antenna, and a dummy load for tuning. The chart of Fig. 5-35 shows three frequently used switching systems.

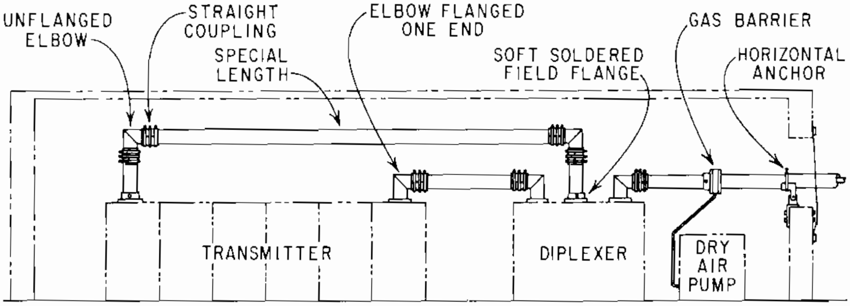

Fig. 5-34. Installation inside transmitter building.

8. There are numerous other accessories used with transmission lines to make broadcast operation more reliable, convenient, and versatile. Some items are breakaway sections, flexible sections, slug tuners, and stub tuners.

a. Prior to the advent of the breakaway section, it was necessary to install four elbows in the shape of a U in order to break into a transmission line installed on a tower in order to measure antenna characteristics or trouble-shoot the line (see Fig.

5-36). Now, with a breakaway section (Fig. 5-37) these four elbows can be eliminated, and it is a simple matter to service the antenna or transmission line. To break a long run before breakaway sections were available, it was necessary to start at the

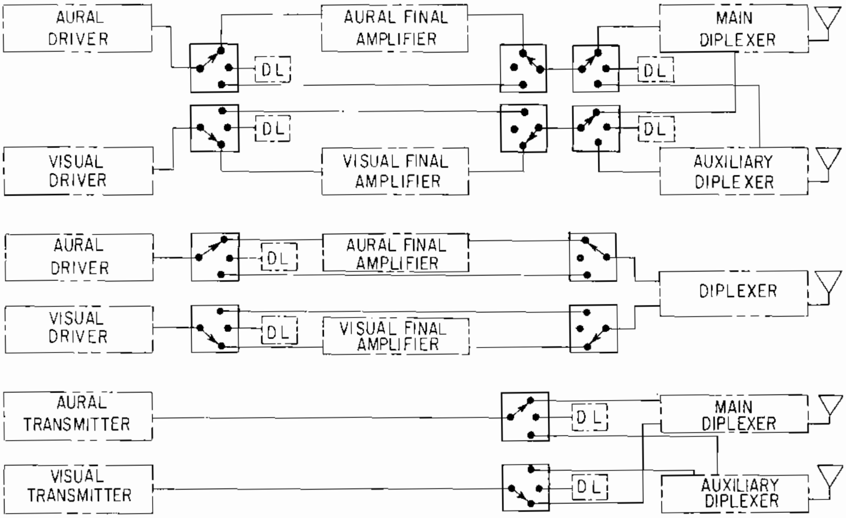

FIG. 5-35. Typical switching arrangements.

bottom and take the line apart all the way up or, alternatively, to push the line down against the pressure of all the spring hangers.

b. Flexible sections (Fig. 5-38) are ideal for correcting slight errors in transmission-line alignment and for providing a slight change iu direction as may be necessary.

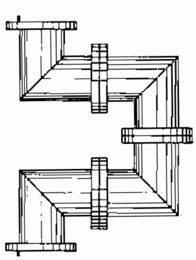

FIG. 5-36. Break in arrangement.

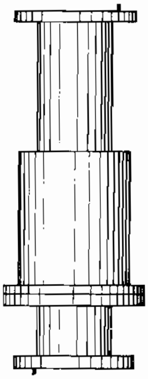

FIG. 5-37. Breakaway section.

The flexible section for 3⅛-in. transmission line is only 18 in. long; yet it can take up to a ½-in. offset in the transmissiou-line path and can also take a 30° bend. The section also accommodates much of the line vibration. Flexible sections are not made to accommodate line expansion and contraction.

c. Slug tuners, single-stub tuners, and double- or multiple-stub tuners are used in the transmission-line system to improve VSWR, to filter harmonics, or to reduce spurious radiations (see Figs. 5-39 to 5-41). A single-stub tuner is primarily used as an even harmonic filter. A single-stub tuner can be used for VSWR tuning if it is

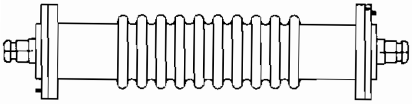

FIG. 5-38. Flexible section.

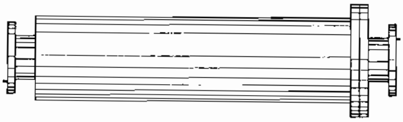

FIG. 5-39. Slug tuner.

moved along a line section, but this is mechanically hard to do. Slug tnners and multiple-stub tuners are used for VSWR tuning. They operate on the principle of moving or varying reactances in the line. In any VSWR tuning method, the tuner is usually placed near the discontinuity being corrected.

Solid-, Flexible-, and Semiflexible-cable Installation

1. Solid, flexible, and semiflexible cables are much easier to install than rigid cables or waveguide. One of the biggest advantages is that the cable, through its flexing characteristic, nullifies the effects of the thermal forces of expansion and contraction. Without the effects of these forces to consider, the need for rigid hangers, sliding hangers, spring hangers, elbows, breakaway sections, flexible sections, lateral braces, horizontal anchors, expansion loops, etc., is eliminated. This results in a greatly reduced installation cost.

2. The cable is usually shipped on a reel, and to make hoisting easier, the reel should be supported at the base of the tower on an axle so it rotates freely. The cable is uncoiled as it is being hoisted. Before hoisting can be started, of course,

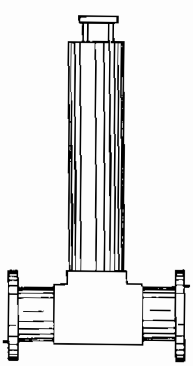

FIG. 5-40. Single-stub tuner.

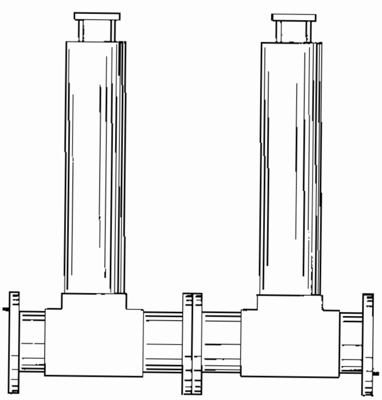

FIG. 5-41. Multiple-stub tuner.

a suitable steel hoisting line or rope that will adequately support the weight of the cable must be obtained. Next, a strong pulley must be placed high enough on the tower to allow the cable to be elevated sufficiently to make the connection to the antenna easily. A means of hoisting, such as a truck or a portable electric winch, is the main requisite for the vertical installation. Short lengths of cable can be pulled satisfactorily by tying the hoist line near the end of the cable. Do not place the weight of the line on the end fitting. A special cable grip or a suitable rope sling

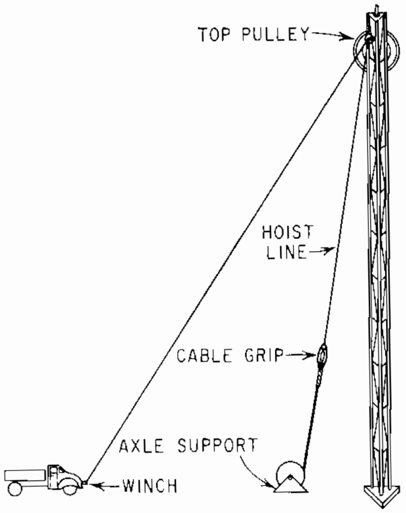

FIG. 5-42. Installation of cable.

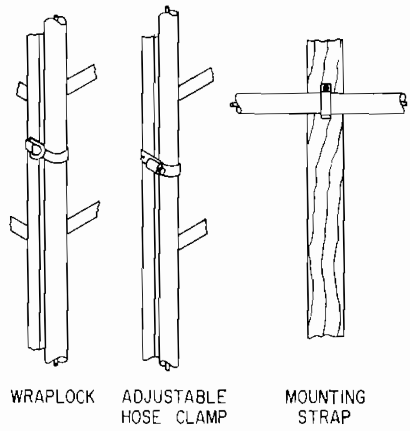

FIG. 5-43. Cable attachment.

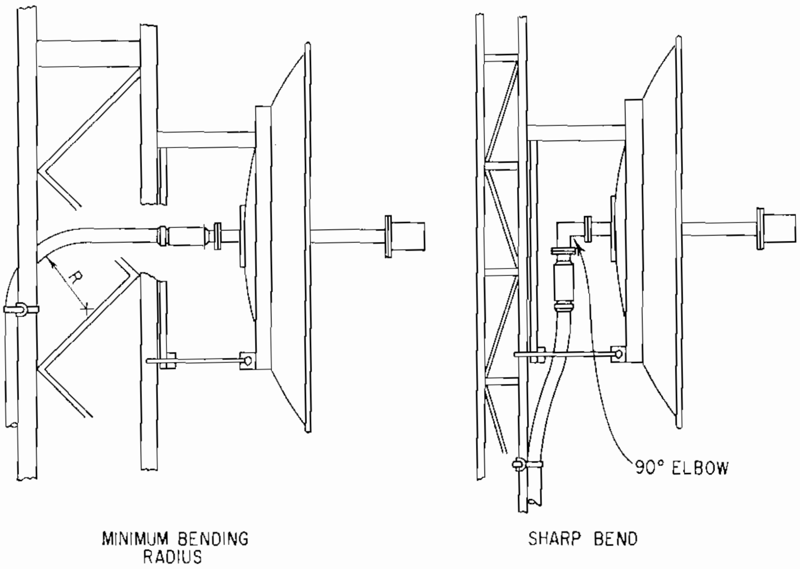

FIG. 5-44. Bending of cable.

should be used to hold the cable without damage. A cable installation is shown in Fig. 5-42.

3. The cable is attached to the tower members with Wraplock, adjustable hose clamps, or even tape for the smaller types and is supported every 5 ft along the tower (see Fig. 5-43). It can be bent around tower members, building corners, and equipment, thereby making the transmission-line path much less restrictive than is possible in rigid-line installations. The bending is limited to a radius that is ten times the cable diameter. In other words, a 1-in.-diameter cable has a minimum bending radius of 10 in. For very sharp bends, a 90° mitered elbow should be used, as shown in Fig. 5-44.

The EIA (formerly RETMA) Standard RS-158, par. 7, Bonding to Tower, states, "The outer conductor of transmission line shall be bonded as a minimum at both the top and bottom of the tower by low impedance conductors to a metallic tower or to a suitable 'down' conductor physically separated from the transmission line if the tower is non-metallic." In addition to the minimum, the cable should be grounded at the point where it enters the transmitter building, especially if there is a long horizontal run. Vinyl-covered cables must have a grounding strap attached to the cleaned outer conductor (after the vinyl has been removed at the bonding point).

4. Support the horizontal run of the cable above the ground by attaching it to a messenger wire or other horizontal supports with Wraplock or adjustable clamps. Use mounting straps when attaching the cable to wood support poles. The cable should be supported every 5 ft as on the vertical run. Semiflexible cable which is not covered should not be buried directly in the soil. It should be either wrapped or placed in a conduit. The flexible cables which are covered with a vinyl jacket can be used in any environment such as salt air, direct ground burial, or under water with no effects of galvanic or corrosive action. This complies with the EIA Standard RS-158, par. 6, Underground Burial.

5. The connections inside the building are made with the same type of cable being used for the transmission line. Where possible, the flexible cable from the antenna is connected directly to the transmitter without any short interconnections.

6. After all connections have been completed, the flexible or semiflexible air-dielectric cable should be pressurized with dry air or dry nitrogen in the same way as is done for the rigid-transmission-line installation.

Waveguide Installation

1. Installation of waveguide for broadcast use requires much more advance planning than a comparable installation of coaxial line. Each installation introduces special problems in mounting the waveguide on the supporting structure and in connecting it to the transmitter equipment. A great advantage of installing copper-clad steel waveguide is that there is no differential problem of expansion and contraction between the tower and the waveguide. This is true for two reasons: first, because the waveguide and tower are both made of steel and are identically affected by changes in temperature, and second, because of the very high efficiency and extremely low loss, no heat is created from the RF energy. Aluminum waveguide, because of its expansion and contraction, must be suspended by spring hangers in the same manner as rigid copper lines. The transitions at either end of the waveguide run are equipped with a gas barrier for pressure termination of the 3⅛-in. coaxial line. Though the waveguide is unpressurized, the antenna and the 3⅛-in. coaxial-line jumper connections outdoors usually are kept under pressure. A small copper tube is used to bring the gas supply up to the antenna.

The coaxial line between the transmitter building and the waveguide is also pressurized. Inside the building, however, the line is not pressnrized.

The following Bill of Materials gives the approximate items and quantities needed for a typical copper-clad steel waveguide installation on a 600-ft tower plus a 30-ft horizontal run:

Bill of Materials

Item	*Quantity*	*Use*
1. 90° mitered elbow, flanged	3	For changing line direction
2. Special lengths of line, unflanged	8	For custom applications
3. Soft-solder flange kit	9	For field flanging lines and elbows
4. Transition, waveguide to 3⅛-in. line	2	For RF energy passage from waveguide to coaxial line
5. Tower hanger	59	For attaching waveguide to tower
6. Horizontal hanger	3	For horizontal support of waveguide
7. Gas barrier	1	For pressure termination of line
8. Automatic dehydrator	1	For automatically pressurizing line
9. Straight couplings	7	For joining unflanged line
10. 90° elbow, flanged one end	3	For changing line direction
11. 90° elbow, unflanged	2	For changing line direction
12. Waveguide, standard 10-ft lengths	62	For main run
13. 90° waveguide elbow	1	For changing waveguide direction

2. At the top of the tower (as in the rigid coaxial transmission-line installation) a custom connection to the antenna is necessary. The coaxial connection from the antenna flange to the waveguide transition is made with two 90° mitered elbows, a special length of line cut as required, and two soft-soldered field flanges, as shown in Fig. 5-45.

3. Along the tower, the waveguide hangers are used at 10-ft intervals. They are placed at the middle of each standard 10-ft waveguide section. Do not support

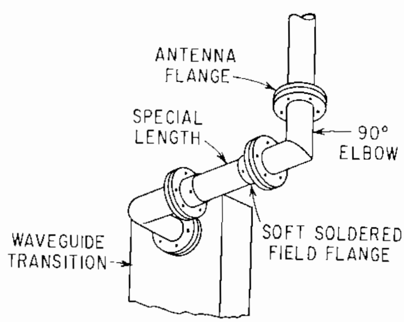

Fig. 5-45. Installation at top of tower.

more than one section of waveguide on a flange joint without using a hanger. It is much safer to leave the hoist line tied to the waveguide section until after the hanger attaches the section to the tower. The hangers used are the type that bolt directly to angle-type towers. Lateral-position adjustment is provided. Attachment to the waveguide is not difficult, as the hardware is captive and the clamping plates slide easily into place after the waveguide is positioned. A waveguide installation is shown in Fig. 5-46.

4. At the bottom of the waveguide run, a 90° waveguide bend is used. The one shown in Fig. 5-46 is an H-plane bend. Bends are usually supplied for 45 or 90°, but most suppliers fabricate special bends to customer specifications. A hanger is not required for the bend.

5. The horizontal run is supported with hangers that can be adapted to support the waveguide in either plane, as shown in Fig. 5-46. These are equipped with threaded adjustments so that perfect alignment of the waveguide sections can be made.

6. A transition is added to the end of the horizontal waveguide run for connection to the 3⅛-in. coaxial line. (In some installations, the transmitter building is very

close to the base of the tower. In such cases the transition can be installed at the bottom of the vertical run of waveguide and coaxial line used for the horizontal run.) From the transition, a 90° mitered elbow and two special lengths of line are used to

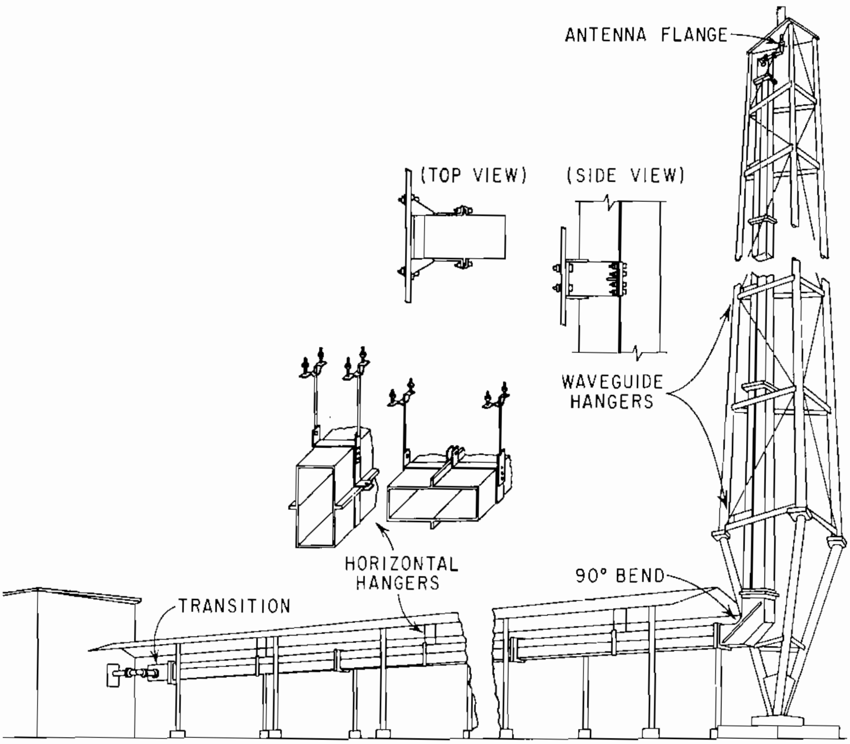

Fig. 5-46. Installation of waveguide.

bring the horizontal run inside the transmitter building. A gas barrier is then attached to the line, and the automatic dehydrator is connected to the gas barrier. For short lengths of line, a dry-air hand pump can be used for pressurization.

7. Once inside the building, all installations, procedures, accessories, etc., are the same for stations using waveguide as they are for those using rigid coaxial transmission line for the main RF feeder.

Part 6

ANTENNAS FOR FM BROADCAST

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GENERAL THEORY

The radiation pattern of an antenna, together with its impedance, can be completely specified from a knowledge of the position, magnitude, and phase of all the current in the system. The equation that specifies the electric field, which will be radiated from an element of current, as developed by Helmholz from Maxwell's equations, is

$$E = \frac{60\pi}{d\lambda} \Delta l I \cos \omega \left(t - \frac{d}{c} \right) \cos \theta \qquad (6\text{-}1)^*$$

The meaning of the symbols in formula (6-1) is as follows:

E = electric field strength, volts/m
d = distance, m
l = length, m
Δ = an increment of the quantity which follows
I = current, amp
$\omega = 2\pi f$
f = frequency, cps
t = time, sec
c = speed of light, m/sec—3×10^8
λ = wavelength, m

This is probably the most useful equation in antenna theory.

The expression is actually not complete, since E and I are vector quantities and the directions are not specified. In order to visualize the direction of E correctly, let us examine E in terms of the magnetic field H, which is somewhat less difficult to envision.

Recall, then, that the H field is always perpendicular to the direction of the current flow of the current element producing it. Now at a great distance from the antenna, it is simple to think of E and H as mutually per-

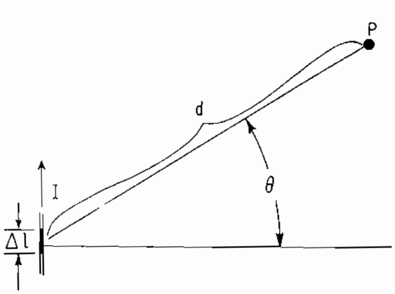


Fig. 6-1. Calculations of E at point P.

* Formula 1 and Fig. 6-1 from F. E. Terman, "Electronic and Radio Engineering," 4th ed., McGraw-Hill Book Company, Inc., New York, 1955.

pendicular and both perpendicular to the direction of transmission of the wave. Therefore, no trouble should be experienced in visualizing the directions of polarization of the field from a complex system of currents.

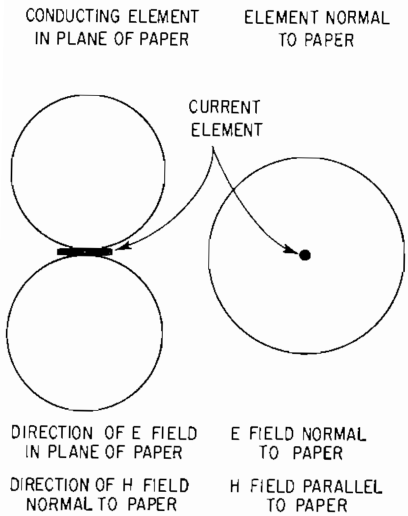


FIG. 6-2. Radiation patterns through and normal to current element.

Attention is invited to the term cos $\omega(t - d/c)$. This term expresses the sinusoidal variation of the magnitude of the vector E with time at the distance d. It does not indicate the vector direction of the field in space as discussed in the preceding paragraph.

It is of interest to consider the radiation pattern of the single-current element before considering the patterns of complex structures consisting of many such elements. The radiation patterns in a plane through the element and in a plane normal to it are given in Fig. 6-2.

The application of this principle to a horizontal end-loaded loop, such as is used in several commercial FM antennas as the radiating element, will yield the information that the radiation pattern is substantially circular in the horizontal plane and doughnut-shaped in the vertical plane.

Application to a symmetrical V-antenna element will yield a figure-eight radiation pattern. This also can be made to approach a circle in the horizontal plane if the two halves of the V are fed with somewhat unequal currents somewhat out of phase.

FIELD PATTERN OF ANY ANTENNA FROM KNOWLEDGE OF THE CURRENTS AND PHASES OF THE SYSTEM

In order to determine the distant field pattern of any antenna in which the current distribution, directions, and phases are known, simply break the radiating system down into incremental elements of current. Then sum the effects computed by Fig. 6-1, taking due account of the current phases and directions. This is a completely general procedure and can be applied to any antenna, although most useful for loops, Vs, dipoles, and rhombic radiators. It is not so readily applicable to horns and parabolas. One must be sure to include all currents not completely enclosed in metal. Currents within a coaxial transmission line, the diameter of which is small compared with a wavelength, can be neglected.

THE PRACTICAL FM TRANSMITTING ANTENNA

The practical FM antennas presently in production have filtered down into a very simple pattern. They consist of a series of small, lightweight radiating elements spread approximately one wavelength apart and fed unsymmetrically. One side of the balanced radiator only is fed, the other side is excited parasitically. The elements are fed exactly in phase by tapping them off a transmission line exactly one electrical wavelength apart.

It is a well-known transmission-line law that, regardless of whether or not a transmission line is matched, the voltages at a series of points, integral wavelengths apart, will be exactly in phase. It is also well known that loads tapped across a transmission line at points integral numbers of wavelengths apart will appear to be electrically in parallel when viewed from the generator side of the point of connection of the last load. This is shown diagrammatically in Fig. 6-3.

This provides a very simple method of putting together a multielement high-gain transmitting array.

Experience has shown that the mutual impedance between the elements of such an antenna array will be quite small and can be neglected to a first order of approximation.

Hence, the design problem is basically as follows:

Assume that an eight-element FM array is desired. The process would be to space the eight elements along the transmission feed line exactly one wavelength apart with respect to the wave velocity within the transmission line.

Tune each element to present a purely resistive load of eight times the characteristic impedance Z_0 of the transmission line at the point of connection. The transmission line will then be automatically matched at the generator side of the bottom loop, and the voltage applied to all the loops will be automatically in phase.

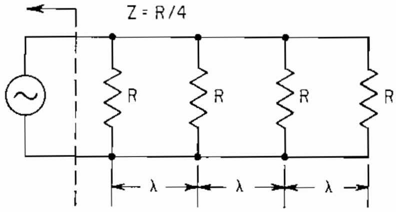


FIG. 6-3. Diagrammatic representation of loads tapped across transmission line.

Each element will receive one-eighth of the total power and (to the extent that mutual impedance can be neglected) will produce $1/\sqrt{8}$ the field of a single element taking all the power. The fields will add in phase. The power gain of a single-loop or V-antenna element is approximately unity.[1] Hence, to a first approximation, the field gain of an eight-element FM antenna, each element of which receives one-eighth of the total power, would approximately equal $8/\sqrt{8}$ and the power gain of the antenna would be 8, or equal to the number of elements in the antenna. Examination of the data supplied by the manufacturers, made a portion of this part, shows the above to be quite a good approximation.

Vertical-radiation Pattern

FM transmitting antennas, consisting of a series of V or loop elements mounted a wavelength apart and fed to produce in-phase fields, will have nulls in the vertical pattern depending on the number of elements used. To a first approximation, the single element can be visualized as having a doughnut-shaped pattern. The vertical patterns will be substantially the same for the three makes of antennas to be discussed.

A family of vertical-radiation patterns supplied for the RCA-BFA series of antennas is shown in Fig. 6-4 and illustrates the position of the pattern nulls. It will apply almost as well to the Andrew and Collins antennas.

An antenna located a substantial height above its service area, such as on a mountain top, may have a pattern null falling in the vicinity of a built-up section of that area. For example, the first null of an eight-bay antenna, 5,000 ft above flat terrain, will be seen from Fig. 6-4 to fall 7.7° below the horizontal or a distance of 7 miles from the site. If a populated area lies in such an area, it would pay to apply what is called electrical beam tilt or null fill or a combination of both.

For example, beam tilt could be obtained in such an eight-element array, if manufacturing details permit, by phasing the upper bank of four loops ahead of the lower bank. Sixty degrees of lead to the upper bank would "tilt" the beam about 2½° below the horizontal.

In addition, it would be feasible to fill the null, as is common practice with television antennas, by adjusting the power ratio between the upper and lower banks. A 60-to-40 division has been extensively used in TV.

For illustration, the pattern of an eight-loop FM transmitting antenna with 60° lead in the upper bank of four antennas and a 60-to-40 power distribution has been computed and is compared with the pattern of the normal eight-bay antenna in Fig.

[1] Referred to a half-wave dipole.

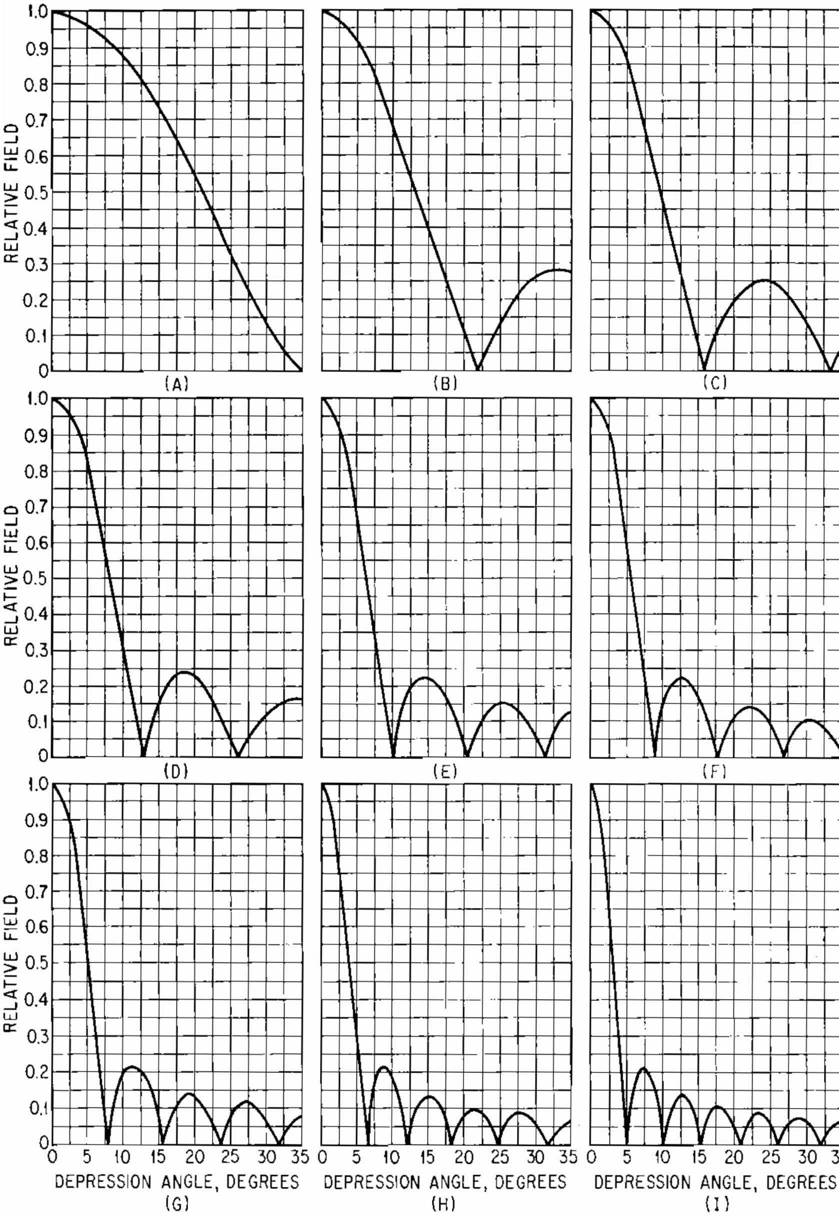


FIG. 6-4. Calculated vertical field pattern: (*a*) RCA BFA 2A. (*b*) RCA BFA 3A. (*c*) RCA BFA 4A. (*d*) RCA BFA 5A. (*e*) RCA BFA 6A. (*f*) RCA BFA 7A. (*g*) RCA BFA 8A. (*h*) RCA BFA 10A. (*i*) RCA BFA 12A.

6-5. Such a modified antenna might be very worthwhile for special mountain-top installations.

POLARIZATION

All the antennas described are for horizontal polarization. The FCC has recently denied a petition requesting permission to use vertical polarization for FM stations but will permit elliptical polarization. Either vertical or horizontal polarization can be quite simply obtained, but elliptical polarization is relatively difficult to obtain,

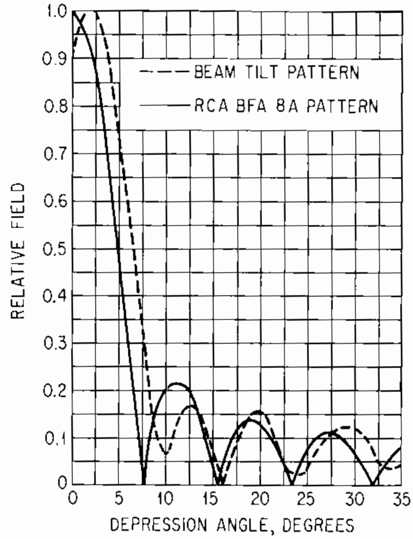


FIG. 6-5. Illustration of beam tilt and null fill for an eight-element antenna.

and there is no presently available FM transmitting antenna suitable for this purpose.

It is possible to obtain tilted linear polarization by tilting the loops, but this practice, although capable of transmitting a component of vertical polarization in some directions, produces a figure-eight pattern for vertical polarization and seems of doubtful value.

Another problem facing the development of a suitable elliptically polarized antenna will probably be the difficulty of side mounting. A greater spacing from the supporting tower is likely to be required to obtain a reasonably circular pattern with a vertically polarized, side-mounted antenna.

SIDE MOUNTING OF FM ANTENNAS

With the early development of FM transmitting antennas, it was assumed that it would be necessary to mount the antenna on top of or symmetrically around the tower. Later tests, however, indicated that in many cases the antennas will operate in a satisfactory manner when side-mounted, and most FM antennas are side-mounted today.

It is believed likely, however, that many FM antennas suffer some deterioration in both pattern and standing-wave ratio, as a result of side mounting on the tower. Experience has shown that the effect on the standing-wave ratio may not be nearly so serious as on the pattern. Hence, it is recommended that if the performance of a side-mounted antenna is seriously suspected, a check be made into the possibility that the pattern has been upset owing to side mounting.

The upset in such cases may be expected to be principally due to two factors. One is believed to be a gain reduction resulting from detuning some of the elements which might happen to fall adjacent to horizontal members in the supporting tower so that the separate elements no longer radiate equal fields. The other is the excitation of elements of the tower which could radiate appreciable fields, which might tend to cancel the direct radiation from the FM antenna in certain directions.

The following account of one case of side-mounting trouble will be of interest. The performance of a station employing an antenna side-mounted 8 in. off the flat face of an AM tower 36 in. on a side was reported to be extremely bad in the central part of the principal city. The antenna was checked for standing-wave ratio, which was found to be 1.4 to 1, while factory tests prior to shipping showed a standing-wave ratio of 1.1 to 1. Field retuning easily corrected the SWR, but no improvement in the service was reported. Checks of the tower structure showed high circulating currents and resonant voltage points. The side mounting was suspected.

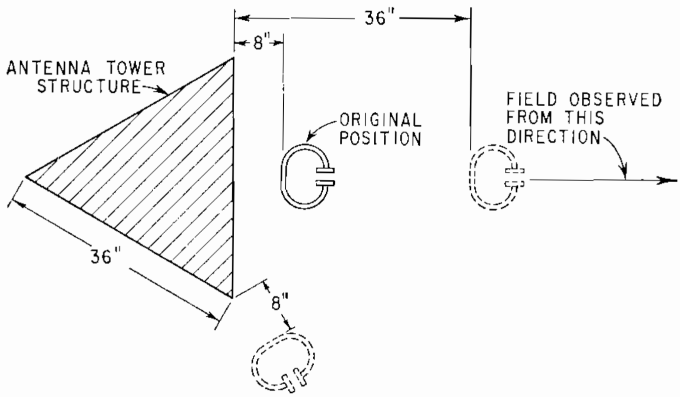


Fig. 6-6. Vertical section through an FM antenna and supporting tower.

A test was made during which the relative field in a direction roughly toward the poor service area was observed while the antenna was temporarily spaced out from the supporting tower. It was also tested on a corner instead of the flat face. A vertical section through the supporting tower and FM antenna tested is shown in Fig. 6-6. The results were as follows:

Antenna Mounting Position	*Relative Field, Db*
Normal position 8 in. off face	0
Moved to a corner	+2.7
22 in. off face	+4.8
36 in. off face	+6.9

Permanent relocation 36 in. off the face appears to have materially improved the coverage in the area previously reporting poor service.

BANDWIDTH, STANDING-WAVE RATIO, AND PROBLEMS INTRODUCED BY MULTIPLEX

FM is a comparatively narrow-band service from the antenna standpoint. For instance, the 6-Mc band of a Channel 2 TV station is 10.5 per cent of the carrier frequency while the 200 kc occupied by an FM station is only 0.2 per cent of the carrier frequency. The narrow-bandwidth requirement permits the use of physically small, lightweight, low-wind-resistance radiating elements such as loops and Vs for FM. Conversely, in the TV service, it has been necessary to resort to massive broadband elements.

At this point, it would appear in order to mention the effect of the recent trend toward multiplex operation on the antenna problem. Tests and calculations of requirements for multiplex operation have indicated that it is desirable to match the antenna feed line of an FM station desiring to use multiplex to approximately 1.1 to 1 over a frequency range of 200 kc even though standing-wave ratios of 1.5 to 1 to 2.0 to 1 have worked quite satisfactorily with ordinary FM service. The reader is referred to the part on Multiplex in Section 8 of this handbook for further information on this subject.

Analysis of manufacturers' data on the Andrew, Collins, and RCA antennas shows that if the antennas were matched closely at center frequency, their bandwidth would be perfectly acceptable for FM, including the multiplex service.

Matching of an FM antenna is usually accomplished at the factory at the desired center frequency. However, mismatch between the transmission line and the antenna can be expected when the antenna is side-mounted on a supporting tower. This mismatch can be expected to result in a VSWR of about 1.5 to 1.

Hence, if a standing-wave ratio not in excess of 1.1 to 1 is desired, a side-mounted FM antenna can be expected to require field tuning after it is mounted on the snpporting tower.

HINTS FOR FIELD TUNING OF FM TRANSMITTING ANTENNAS

The RCA antenna is furnished with an adjustable matching section mounted immediately under the radiating portion of the antenna and designed to be used for this purpose. In the case of the Andrew antenna, the procedure will be to purchase a similar device and install it immediately below the antenna in lieu of the first few feet of transmission line. This method can also be applied to the Collins antenna if desired. Since the adjustment of devices of this sort has been adequately covered elsewhere, it will not be explained here.

The Collins antenna can, if desired, be field-tuned without the addition of extra devices, and the procedure for accomplishing this is the following:

The antenna may readily be brought to within 1.1 to 1 by a combination of rotation of all discs the same amount in the same direction, coupled with a slight adjustment of the feed-line straps, again using caution to keep the adjustments together.

It is recommended that before any changes are made, the center spacing of all discs be calipered and the position of all feed straps be measured. This information should be recorded carefully.

In addition to this, the strap positions should be marked on the loops themselves and a prominent mark placed at the top of each disc to estimate rotation in fractions of turns.

Rotation of the discs should be by approximately the same amount for the discs on each side of the capacitor of each loop. By this, it is meant that if a disc on one side of the capacitor is rotated a quarter turn in a direction which reduces the spacing between discs, the disc on the other side of the capacitor should likewise be rotated a quarter turn in a direction to reduce the spacing further.

It is recommended that the impedance be checked at least at carrier, carrier + 100 kc, and carrier − 100 kc for each adjustment of either the loop capacitors or the feed straps. This data should be plotted on a Smith chart. (See Section 9 for use of Smith charts.)

Caution should be exercised that the accuracy of the signal generator used be within about 5 kc. The measurement can be made at the transmitter input to the transmission line using a General Radio admittance meter or instrument of comparable accuracy.

One should remember that field adjustment of this or any other side-mounted FM antenna to correct the upset standing-wave ratio which has resulted from interaction between the radiators and the supporting structure will not, in general, correct any noncircularity of the pattern or gain reduction which may have resulted from the side mounting of the antenna.

SOME ANTENNAS CURRENTLY IN PRODUCTION

Andrew Multi-V FM Antenna

The antenna is available for any frequency within the 88- to 108-Mc FM band at 51.5 ohms input impedance with a standing-wave ratio under 1.5 to 1 and 10-kw power-handling capacity. The eight-bay model is also available with a 50-kw rating.

The antenna radiating element is basically a folded half-wave dipole element bent into a V shape and operated several megacycles above resonance to obtain a basically circular horizontal-radiation pattern. A single element is shown in Fig. 6-7.

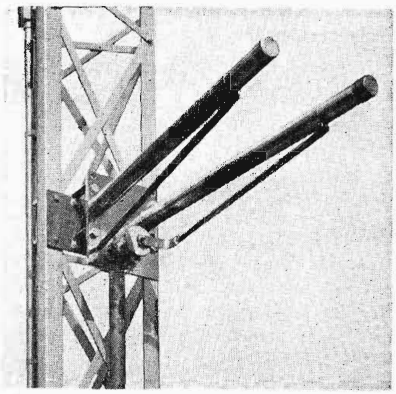


FIG. 6-7. Single radiating element of Andrew multi-V FM antenna.

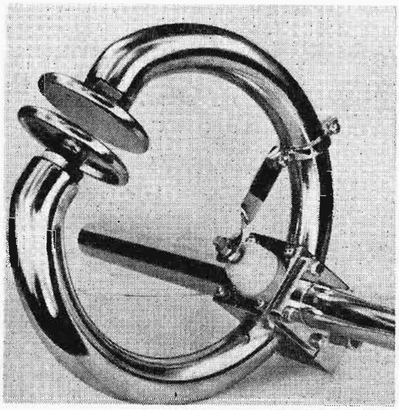


FIG. 6-8. Single radiating element of Collins 37M FM antenna.

The antenna is designed for side mounting.

The antenna is not designed for field tuning. If a 1.1-to-1 standing-wave ratio over the 200-kc band is required for multiplex operation, it is necessary to add an adjustable matching section immediately below the antenna on the tower. (This cannot be placed at the transmitting end of the line.) The manufacturer has developed a slug tuner for this purpose.

Andrew Antenna Characteristics

No. of Bays	*Power Gain*	*Power Rating, Kw*
2	1.6	10
4	3.7	10
8	7.3	10

Collins 37M Ring Antenna

The antenna is available for any frequency within the 88- to 108-Mc FM band at an input impedance of 51.5 ohms. The standing-wave ratio is set at the factory to about 1.1 to 1 but may rise to about 1.5 to 1 when the antenna is side-mounted on a supporting structure. The power rating is 6 kw when the antenna is mounted on $1\frac{5}{8}$-in. line and 27 kw when it is mounted on $3\frac{1}{8}$-in. line.

The basic radiating element is an end-loaded half-wave dipole bent into a loop so that the end-loading discs form a disc capacitor as shown in Fig. 6-8.

The antenna is designed for side mounting.

The antenna, though not designed specifically for field tuning, can readily be field tuned. Field tuning will be required if a 1.1-to-1 standing-wave ratio over a 200-kc band is required for multiplex operation. Hints on field tuning of this antenna are provided elsewhere in this part.

Deicing equipment is available and is recommended by the manufacturer in areas in which icing conditions occur.

Collins Antenna Characteristics

No. of Rings	*Power Gain*
1	0.9
2	2.0
3	3.0
4	4.1
5	5.1
6	6.2
7	7.2
8	8.3

RCA Type BFA FM Antenna

The antenna is available for any frequency within the 88- to 108-Mc FM band at an input impedance of 50 ohms.

The antenna radiating element is basically an end-loaded half-wave resonant folded dipole bent into a loop. A single element of the antenna is shown in Fig. 6-9.

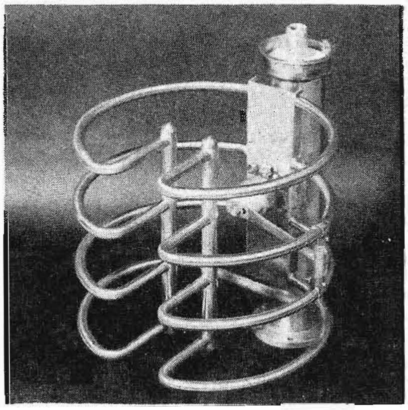


Fig. 6-9. Single radiating element of RCA BFA FM antenna.

The standing-wave ratio is set at the factory so that the mounted antenna will be 1.2 to 1 or better when top-mounted or 1.5 to 1 or better when side-mounted.

This antenna is especially designed for simple field tuning to obtain a standing-wave ratio of 1.1 to 1 or better over a 200-kc band for multiplex operation. Field tuning is accomplished without the necessity of trimming the loop adjustments. An adjustable matching transformer is furnished for this purpose and is located immediately below the antenna.

Deicing equipment is available and is recommended in areas in which icing conditions occur.

RCA Type BFA Antenna Characteristics

No. of Sections	*Power Gain*	*Power Rating, Kw*
1	0.9	3
2	1.9	6
3	3.0	9
4	4.0	12
5	5.1	15
6	6.3	18
7	7.3	21
8	8.4	24
10	10.5	30
12	12.5	36

Part 7

ANTENNAS FOR TELEVISION BROADCAST

H. E. Gihring

Manager of Antenna Engineering
Radio Corporation of America

GENERAL INFORMATION

Television broadcast antennas presently operate at the following frequencies:

Channels 2 to 6, 54 to 88 Mc
Channels 7 to 13, 174 to 216 Mc
Channels 14 to 83, 470 to 890 Mc

Television antennas are unique with respect to several characteristics.

Since each channel is 6 Mc in width, the antenna must have the proper performance characteristics over this band. Since higher gain antennas are used, especially at the higher frequencies, the vertical pattern must be suitable for the population distribution in the vicinity of the antenna so as to provide adequate field strength for television service.

Definition of Antennas

An antenna is defined as a structure associated with the transition between a guided wave such as may exist in a transmission line and a free-space wave. Such a structure usually consists of radiating elements and means for distributing the energy to these elements.

Antenna Terminals

The antenna terminal is defined as an accessible point where the entire antenna including the distribution system terminates into one [1] feed [2] line at the design surge impedance.

[1] Or two lines for a quadrature system.
[2] In accordance with Electronics Industries Association Standards.

Broadcast-antenna Requirements

Azimuthal Pattern

Definition. An azimuthal pattern is a plot of the free-space radiated field intensity vs. azimuth at a specified vertical angle with respect to a horizontal plane (relative to smooth earth) passing through the center of the antenna.

A horizontal pattern is an azimuthal pattern when the specified vertical angle is zero.

For many higher gain antennas where beam tilt is employed, the azimuthal pattern at the specified beam tilt is significant. In general it has been customary to determine television broadcast-antenna radiation by an azimuthal pattern at the specified beam tilt and a sufficient number of vertical plane patterns all taken at various frequencies in the channel.

An omnidirectional antenna is defined as one that is designed to be omnidirectional. Antennas with variations up to ± 3 db have rendered satisfactory service and are considered to be omnidirectional.

A directional antenna is one which is designed to be directional.

Present FCC Standards have limited the maximum to minimum radiation at 10 db.

Vertical Pattern

Definition. A vertical pattern is a plot of free space radiated field intensity measured in the Fraunhofer region vs. vertical angle in any specified vertical plane which contains the center of the antenna and the center of the earth.

The Fraunhofer region,[3] or "far field," as usually defined extends beyond a point where the distance between the transmitting and receiving point is $2L^2/\lambda$, where L is the length of the radiating portion of the antenna and λ is the wavelength.

Requirement for Broadcast Service. A free-space radiated field should not be influenced by the proximity of the earth in such a way as to set up a nonuniform field over the antenna aperture, and proper precautions must be taken to accomplish this.

Gain

Definition. Gain [4] is the ratio of the maximum [5] power flow per unit solid angle from the subject antenna to the maximum power flow from a thin, lossless, half-wave, horizontally polarized dipole having the same power input when the measurements are made in the Fraunhofer region.

As can be seen from the above, gain depends on several factors.

1. The amount of power concentrated in the maximum direction
2. Losses in the antenna, which include ohmic and other losses such as energy radiated at polarizations other than the desired one

The amount of power concentrated in the maximum direction can be determined by a comparison with a reference antenna [6] or by integrating the total power flow through a sphere,[7] which is done by taking a sufficient number of vertical patterns and an azimuthal pattern.

[3] Kraus, "Antennas," Sec. 1–2.

[4] *Ibid.*, Sec. 2.

[5] "Maximum" refers to the maximum in the vertical plane. For an omnidirectional antenna these maxima must be averaged for a number of vertical patterns taken at various azimuths.

[6] "IRE Standards," Antennas, Methods of Testing. C. C. Cutler, A. P. King, and W. E. Kock, Microwave Antenna Measurements, *Proc. IRE*, vol. 35, pp. 1462–1471, December, 1947.

[7] E. H. Shively and L. D. Wetzel, Pattern Measurements of RCA UHF TV Antennas, *Broadcast News*, vol. 82, pp. 14–21, February, 1955.

Both methods are capable of giving accurate results when the proper precautions are taken.

Ohmic losses are taken into account in the comparison method or can be calculated when using the power integration method. Cross-polarized radiated energy can be measured.

The measurement of gain must be carefully done with a full knowledge of all the problems that are involved.

Gain Requirements. Gain requirements for a television broadcast antenna depend on transmitter, power, economics, and field-strength requirements as determined by the terrain and population distribution.

Transmitter Power. The maximum effective radiated powers currently permitted are:

Channels 2 to 6, 100 kw
Channels 7 to 13, 316 kw
Channels 14 to 83, 5,000 kw

For the most popular transmitter sizes in each range, the following gains are needed allowing 80 per cent transmission-line efficiency:

Channels 2 to 6, 3.6 to 5
Channels 7 to 13, 8 to 18
Channels 14 to 83, 25 to 50 (to achieve 1,000-kw ERP)

Economics. Economics is a factor in antenna choice. As a general rule, combined costs of transmitters and antennas are less to achieve a given effective radiated power when a higher gain antenna is used. This is true until unsupported antenna heights are of the order of 200 ft, where structural considerations cause antenna costs to go up rapidly.

Terrain and Population Distribution. It is usually desirable to have a high uniform field strength over the primary service area. In relatively flat terrain, a higher gain antenna with a vertical pattern shaped to accomplish this is a desirable choice because of the economic factor. In mountainous terrain, under some conditions, a lower gain antenna may be desirable, especially when large amounts of energy must be radiated downward at steep angles for a distance of 5 to 10 miles such as may occur when a city is located at the base of a mountain on which the antenna is placed.

Input Impedance

Input impedance is the complex impedance looking into the antenna terminals throughout the television channel.

Most antennas are designed for the same input impedance as the standard transmission line at the antenna terminal. Impedance-matching requirements for television antennas are generally more severe than for other types to avoid reflected energy which would cause an echo or ghost in the picture when the antenna does not terminate the line properly.

Electrical Performance Changes Due to Mechanically Imposed Conditions

Deflection of Antenna and Tower Due to Wind

Guy tension in guyed towers is usually adjusted so that the tower deflects as a straight member.

Towers for broadcast service when so specified are designed for a maximum deflection of 0.5°, which means that the top plate will deflect this amount for the maximum wind velocity. For instance, a 40-lb tower will thus deflect 0.5° for a 100-mph wind. Since tower deflection varies as the square of the wind velocity, the deflection will be 0.125° for a 50-mph wind.

Structurally a free-standing antenna can be considered as a cantilever beam in which the deflection increases toward the end. Antenna deflection is usually stated as

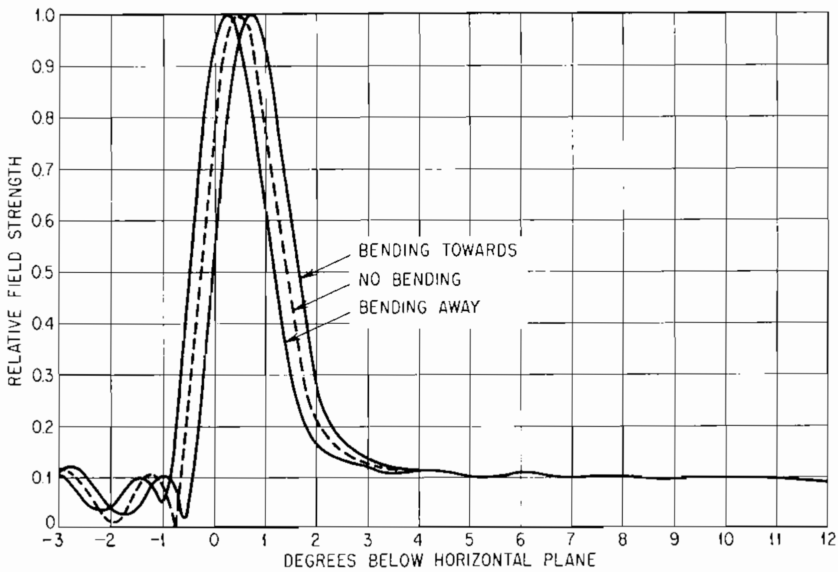


FIG. 7-1. Calculated vertical patterns of the TFU-46C antenna affected by static wind load: flat-surface wind load 10-psf, wind velocity 50 mph.

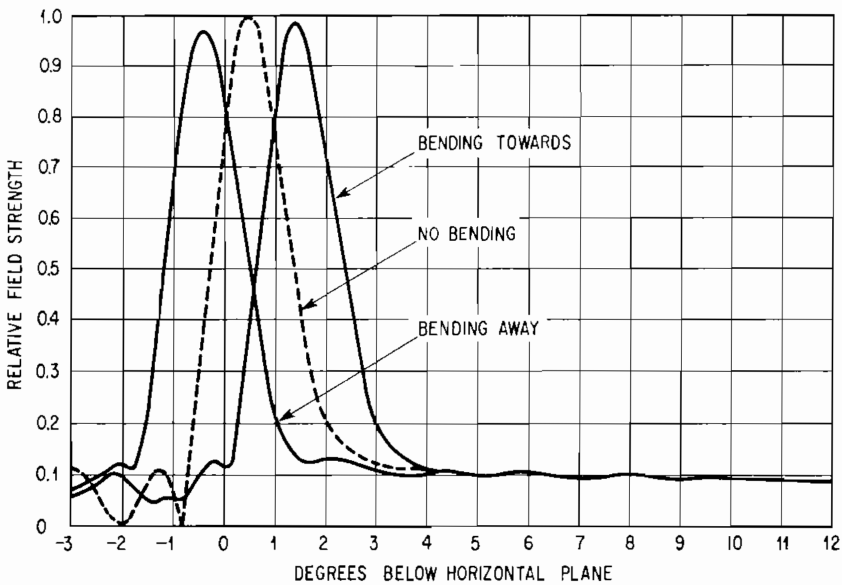


FIG. 7-2. Calculated vertical patterns of the TFU-46C antenna affected by static wind load: flat-surface wind load 40 psf, wind velocity 100 mph.

the angle that a tangent at the center of the antenna makes to the undeflected position.

In order to evaluate the effects of deflection, an example for a high-gain UHF antenna will be given.

Figures 7-1 and 7-2 show the effects of deflection on a UHF antenna of the slotted-cylinder type with a gain of 46 when the antenna is 115 ft in height. The lower half of the antenna is a 16-in. schedule 160 steel tube, and the upper half is a 14-in. schedule 60 steel tube.

The phase and amplitude of each layer of the antenna were synthesized to obtain a vertical pattern for the curved condition where the antenna was bent toward the service area and away from it.

Two conditions are shown for a wind velocity of 50 and 100 mph as summarized in Table 7-1.

Table 7-1

Wind velocity, mph	50	100
Wind load, psf	10	40
Deflection of antenna at top, in.	5.03	20.12
Deflection, wavelengths	0.235	0.94
Deflection of antenna at tangent to center, deg	0.208	0.832
Tower deflection, deg	0.125	0.5
Antenna and tower deflection, deg	0.333	1.332

Signal Variation for Deflection Extremes, db	*Toward Service Area*	*Away from Service Area*	*Toward Service Area*	*Away from Service Area*
At horizon (main beam) antenna only	−0.5	−0.3 [a]	−7.8	−5.8
At horizon for antenna and tower	−0.7	−0.4	−18.8	−13.4
At a location with respect to the vertical pattern where the greatest signal variation occurs for antenna only	+3.6	−2.7	+6	−10.8
At a location with respect to the vertical pattern where the greatest signal variation occurs for antenna and tower	+4.2	−5.3	+12.7	−5.2

[a] Values are not the same, since in this antenna, radiation above the horizon has been suppressed and the pattern is not symmetrical.

The 50-mph wind condition is one that may occur [8] twenty-five times a year at a 1,000-ft elevation above terrain and about four times a year at a 500-ft elevation.

The 100-mph wind is a design-limit figure which rarely occurs and is one during which there would probably be little television viewing. Most outdoor receiving antennas would probably be severely damaged in such a wind, and power service seriously curtailed.

Hence the 50-mph figure is one that is generally considered applicable for an evaluation of this type.

Most television receivers are designed to have a flat AGC response down to 100 mv across the receiver terminals. Hence no effects due to wind acting on the transmitting antenna will be noticeable except in fringe areas where the signal drops below this value.

In the case cited above, the signal variation in the fringe areas would be less than 1 db and could be considered negligible.

The maximum variation in the case cited above occurs at 1.75° below the horizon or at 6.3 miles for a 1,000-ft difference in elevation between the transmitting and receiving antenna. At this distance the field strength is usually at a sufficiently high level so that a 2-to-1 variation will not go below the 100-mv level at the receiver terminals.

Analyzed on this basis even the 100-mph wind condition is not too serious except

[8] Report of TASO Committee 1.3 on Television Antennas. Final Report of TASO Sub-Committee 1.3.2. on Towers, Sec. 3.6.

in the fringe area. It should be noted that the variations are limited by the fact that the antenna is designed not to have nulls near the main beam.

For lower gain antennas with a wider beam the variation would be even less than those shown.

As a confirmation of the above analysis it would be noted that six antennas of the type described with gain from 46 to 52 are in operation in various parts of the United States, some since 1956. In none of these have any complaints or problems occurred with respect to variations in field strengths due to high wind conditions.

Deicing

Desirability. The need for deicing depends on local icing conditions and the sensitivity of the antenna performance to ice.

Local conditions, with respect to frequency and severity of icing, can be ascertained from the local Weather Bureau. It should be remembered that most of their observations are at a low altitude and that conditions are more severe at the antenna height, particularly if it is of the order of 1,000 ft or more above terrain.

The sensitivity of the antenna to ice is specified by the manufacturer.

Both the reflected power and the radiation patterns may be affected. An increase in reflected power with ice as evidenced by an increase in VSWR will often result in secondary images or ghosts. In some cases a higher VSWR may also necessitate running at reduced power. Pattern changes are more subtle but could cause a loss of field strength in some areas. Television antennas are generally more sensitive to ice than other types, and manufacturers usually recommend deicers where icing is likely.

Methods. The most satisfactory method is the use of strip or rod electric heaters fastened in or near the radiating element. In some cases the radiators are heated directly. Other methods such as generating heat at the base of the antenna and distributing it by convection tend to overheat the lower portions and underheat the upper portions, resulting in a loss of both heating efficiency and effectiveness.

Various types of controls are on the market to actuate the deicers. These work on temperature alone or a combination of temperature and precipitation or humidity.

Advantage is taken of the fact that icing occurs only in a narrow range of temperature. Most deicing systems have more than enough capacity to keep the antenna free from ice if they are turned on before the ice starts to form.

Ice removal may require considerable time if a large amount has already formed, especially under high wind conditions when large heat losses occur. Hence the use of an automatic device to turn on deicers is desirable.

DESIGN AND THEORY

Elemental Radiators

Television antennas in common use are developments of one or another of a few basic types of radiator. These are the half-wave dipole, the loop (magnetic doublet), the slot, and the helical. Some of the antennas combine characteristics of more than one of these types.

For purposes of mathematical representation or as a reference for comparison of characteristics of antennas, the concepts of "point source"—a fictitious emitter so small as to have no dimensions—and "isotropic radiator"—which radiates energy uniformly in all directions—are sometimes used.

Antennas of the horn, lens, and long horizontal (Beveridge) or vertical wire types do not currently find application at television frequencies and are not considered herein.

Half-wave Dipole

If the ends of an open-wire transmission line are turned outward, as shown in Fig. 7-3*a*, they form what is known as a dipole. The electric (E) fields, at right angles to and connecting the two sides of the transmission line, extend outward, forming circles in all planes passing through the axis of the dipole, as shown in Fig. 7-3*b*. The magnetic (H) fields, which, in the transmission line encircled the separate wires and tended to cancel each other owing to the opposing directions of the flow of current in the two wires, now appear as circles about the dipole.

If the length of the dipole is made a half wavelength long at the frequency of an imposed signal, it becomes, in a sense, a resonator, with energy reflected from the ends of the radiator setting up standing waves. The energy is alternately stored in the electric and magnetic fields.

At high frequencies, the fields so formed do not have time to collapse completely before other fields, of opposite polarity, are set up. The result is that outer portions of the field never return but are pushed out of the area close to the antenna known as the "induction-field" region and move away, forming the "radiation field." It should be noted that because of the shapes of the fields this effect does not take place off the tips of the dipole whereas it is a maximum in directions at right angles to the dipole.

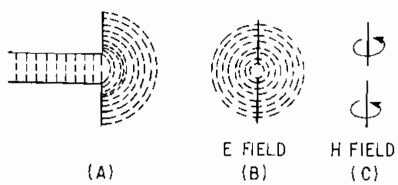


FIG. 7-3. Electric (E) field, and magnetic (H) field of a dipole.

Since the power in the field is dissipated power (I^2R) in the same sense that power appearing as heat due to ohmic resistance in the dipole is dissipated power, it is convenient to relate this power to the current which produces it by a fictitious "radiation resistance." This is in addition to the ohmic resistance in the radiator circuit.

The ratio of stored energy to dissipated energy is called the Q of the antenna circuit. As any circuit contains L, C, and R, this is a function of the relationship between the inductive reactance of the circuit and the resistance. In the case of the dipole the inductance decreases with increasing diameter of the dipole arms. Also the amount of energy reflected from the ends, resulting in greater stored energy, is reduced by increasing the size of the arms. This results in greater bandwidth. Application of this fact leads to the biconical radiators in Fig. 7-4*a* and *b* and to the slot-fed sheet radiator, Fig. 7-4*c*.

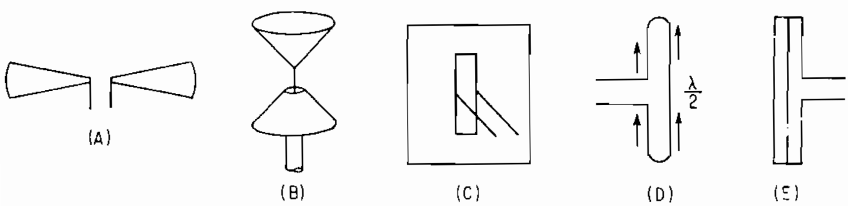


FIG. 7-4. Examples of radiators having dipolelike characteristics: (A) and (B) biconical antennas, (C) slot-fed sheet, (D) folded dipole, (E) folded dipole with additional element.

Another form of the dipole is the half-wave folded type shown in Fig. 7-4*d*. Here, the ends of a simple dipole have been joined by another closely spaced element. Since the voltage distribution is the same in both, the currents are in the same phase and direction. The result is an input impedance of 300 ohms as compared with 73 ohms for a simple half-wave dipole. Addition of rectangles as in Fig. 7-4*e* increases the input impedance by a still greater factor.

Because the folded ends act like stubs, they become capacitive at higher frequencies. This is opposite to the tendency of the series *LCR* circuit by which a dipole can be represented. The result is a cancellation to some degree of the reactances and a tendency for the impedance to remain constant, making the antenna more broadband than the half-wave dipole.

The distant radiated field of the folded dipole is the same as that of the simple dipole.

Loop

The folded dipole discussed above may be considered as a special case of a loop antenna as well as a type of dipole. In fact, any closed loop of conductor which does not carry equal and opposite currents very close together, that is, within the "near," or "induction," zone, will fall into this category and will radiate at least some of the power supplied to it.

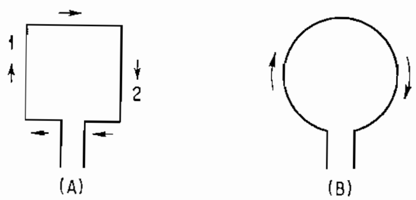


FIG. 7-5. (*A*) Square loop and (*B*) ring radiator.

The loop or ring radiator may be rectangular or circular, as seen in Fig. 7-5*a* and *b*.

Variation in the size of the loop yields radiation patterns of various shapes, in planes at right angles to that of the loop, as could be expected by comparison with the horizontal fields of two AM radiators with various spacing and phase relationship. That is, if sides 1 and 2 of the square loop in Fig. 7-5*a* are considered to he the two AM radiators, the combined radiation pattern in a plane at right angles to them will vary with the spacing between them. For loops with diameters less than 0.585λ the maximum field will be in the plane of the loop, and loops much smaller than a wavelength are therefore most commonly used as elements of television antennas. Radiation in a direction normal to the loop is always zero, regardless of the size of the loop.

Slot Antenna

As has been mentioned under Half-wave Dipole, the slot antenna has a great similarity to a dipole.

Figure 7-6*a* and *b* shows the two types, oriented so that the (*E*) fields of both are horizontal. Currents in the slot type spread out over the entire sheet, and radiation takes place from hoth sides of the sheet.

The resemblance between the two becomes even more pronounced when it is recognized that the field patterns of the two will be equivalent if the physical dimensions of the slot and the cross section of the dipole are the same. For example, the fields of the two radiators in Fig. 7-6*c* and *d* are the same. A very similar situation

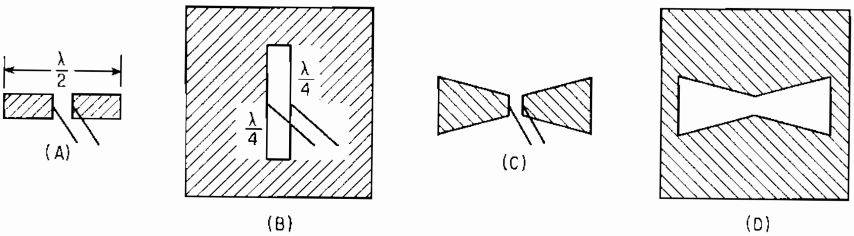


FIG. 7-6. Dipoles (*A*) and (*C*), with complementary slot-fed sheet radiators (*B*) and (*D*).

occurs in optics, where the phenomenon is known as Babinets principle. Using a term from optics, the antennas are said to be complementary where this situation exists.

Furthermore, the impedance of the slot is proportional to the admittance of the dipole of the same dimensions by the relationship

$$Z_{\text{slot}} = \frac{35{,}476}{Z_{\text{dipole}}}$$

and the bandwidth characteristics of one are the same as those of the other.

Actually, the above discussion is rigorously accurate only if the sheet is of infinite extent, but it is substantially correct if the edge of the slot is half a wavelength from the slot.

The input resistance to a slotted sheet is of the order of 500 ohms. This can be modified by shifting the position of feed along the slot. A value of 50 ohms can, for example, be obtained with the feed about 0.1 of the slot length from one end.

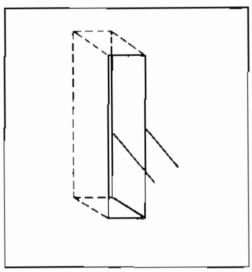


FIG. 7-7. Slot-fed sheet radiator with slot boxed to limit radiation to one side of sheet.

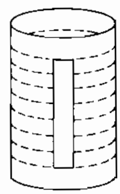


FIG. 7-8. Slot-fed sheet radiator bent to form a cylinder, showing resemblance to stack of ring radiators.

Radiation can be limited to one side of a very large sheet by boxing in the slot on the other side. If the depth of the box is such as to present zero susceptance at the feed point, the input impedance will be appropriately double that of the same antenna without the box (see Fig. 7-7).

Bending the sheet into a cylinder results in another form of slot antenna which also takes on characteristics of a stack of coaxial rings (Fig. 7-8).

Helical Element

A conductor wound in the form of a helix can be made to have maximum radiation either in the axial direction or in a direction normal to the axis, depending on the circumference of the helix and on its pitch. For radiation in the "normal" (or side-fire) mode, the helix dimensions must be small compared with a wavelength (see Fig. 7-9*a* and *b*).

The limitation on the size of a helix for normal operation imposes restrictions on bandwidth. This can be offset to some extent by phase-shifting devices along the helix which compensate for variations in impedance with frequency.

Since the helical element is used in almost a pure form in a commercial antenna to be described under Helical Antennas, further discussion will be left till that section.

Antenna Patterns

Azimuthal Patterns

In television, with the inherent limitations on coverage due to high-frequency propagation effects and the limitation on the number of stations with any area as set up in the existing allocation plan of the Federal Communications Commission, the large majority of requirements have been for omnidirectional antennas.

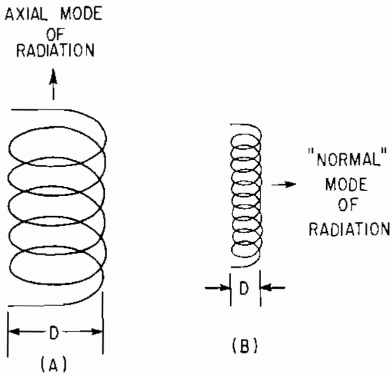


FIG. 7-9. Helical antennas, showing effect of pitch and diameter on direction of maximum radiation.

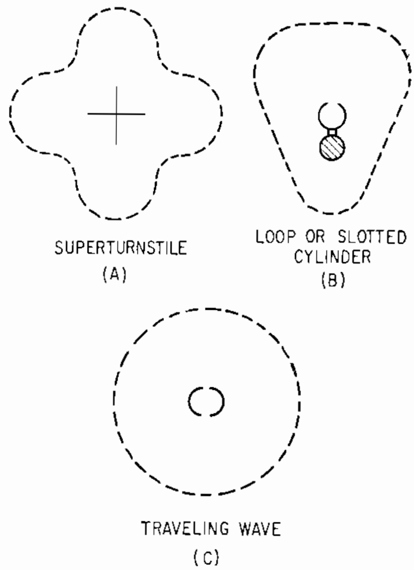


FIG. 7-10. Typical azimuthal patterns of well-known types of TV broadcast antennas.

As is pointed out in the discussion of omnidirectional patterns, the primary criterion of a truly circular or omnidirectional pattern is the intent to make it omnidirectional. In the past, variations of 3 db on each side of a true circle have been accepted as within the meaning of the word omnidirectional.

Since energy flows equally in all directions from a theoretical "point source," its horizontal pattern is a true circle. A thin dipole, vertical to the earth's surface (i.e., with vertical polarization), most nearly approaches this and has a similar azimuthal pattern. Except for these two cases, however, the finite physical size of television transmission antennas and the physical irregularities of their surfaces, due to the requirements of mechanical construction, result in the sum of the energies from various portions of the antenna as received in one direction varying from that received in another. Typical azimuthal patterns of some well-known antennas are shown in Fig. 7-10.

Except for the effects of supporting structures upon which they are mounted, rings or cylindrical antennas inherently have better circularity than other shapes. Ingenious methods have been used, however, to combine noncircular patterns of several radiators to obtain circularity. An illustration of this is the so-called turnstiling principle applied to dipoles. Figure 7-11*a* shows the typical "figure-eight" horizontal pattern of a very small dipole. If a second dipole is placed at right angles to the first, the two patterns will overlap, as shown in Fig. 7-11*b*. If both are fed in phase, addition of the radiated energies will result in a pattern such as is shown in Fig. 7-11*c*.

If the dipoles are fed 90° out of phase, the separate fields will add as shown in Fig. 7-12*a*. Here we have two dipoles 1 and 2 placed in space quadrature, with current conditions in the radiators as shown at various times. At time t_1 the current in dipole 1 and the resultant field of that dipole will be at a maximum, represented by a vector of unity length pointing upward. For dipole 2 they will be zero. The combined field will be unity. At time t_2, 30° in phase later, the field of dipole 1 will have reduced to 0.866 of its value and that of dipole 2 will be 0.5 of its maximum value. Addition of these two vectors at 90° in space phase will produce a resultant which again has a value of unity.

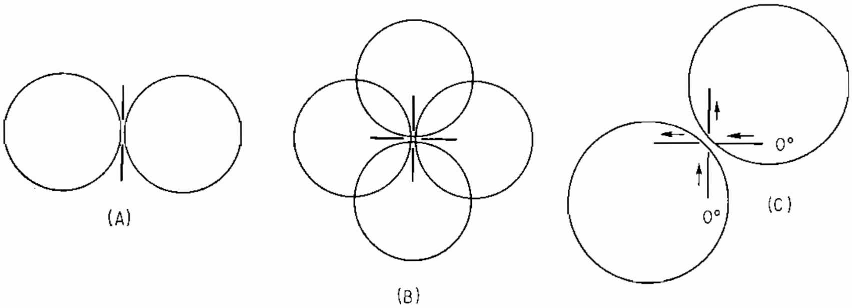


FIG. 7-11. Addition of fields of crossed dipoles. (*A*) Figure-eight pattern of a single dipole, (*B*) superposition of a second dipole at right angles, (*C*) pattern obtained when both dipoles are fed in phase.

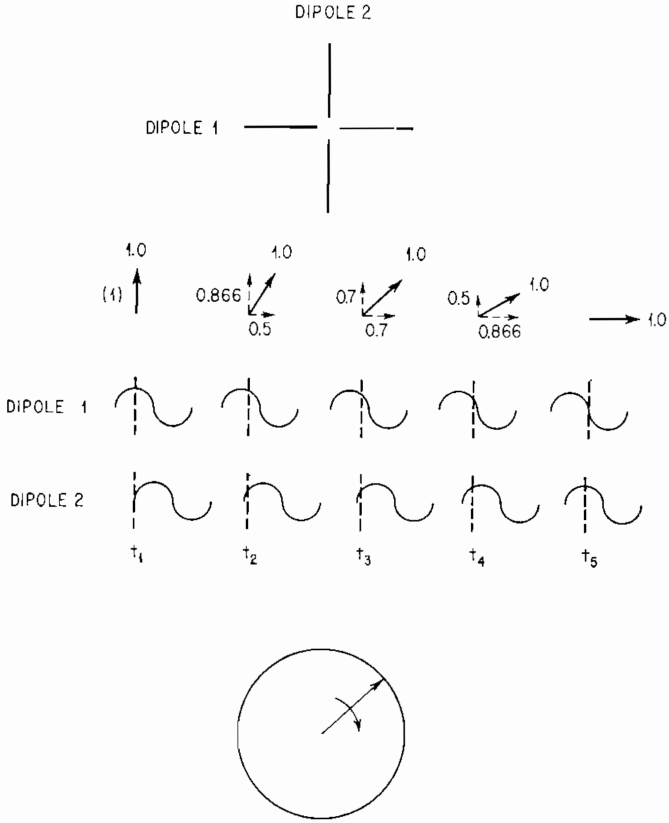


FIG. 7-12. Addition of field of crossed dipoles using "turnstiling" principle to produce circular pattern.

Analysis of the conditions at t_3, t_4, and t_5 indicates that the same total field will be obtained in each case. Ideally, then, we see that turnstiling produces a constant field rotating in the horizontal plane at the rate of the signal frequency.

In actual practice the dipoles are not infinitesimally small, and a supporting pole and feed lines tend to distort the fields of the dipoles from the ideal. The vectors do not then add in such a way as to result in the same total in all directions. The normal pattern is then scalloped, as shown in Fig. 7-10*a*, with the amount of variation from circular increasing with size of the supporting pole at a given frequency and with increase in frequency for a given-size pole.

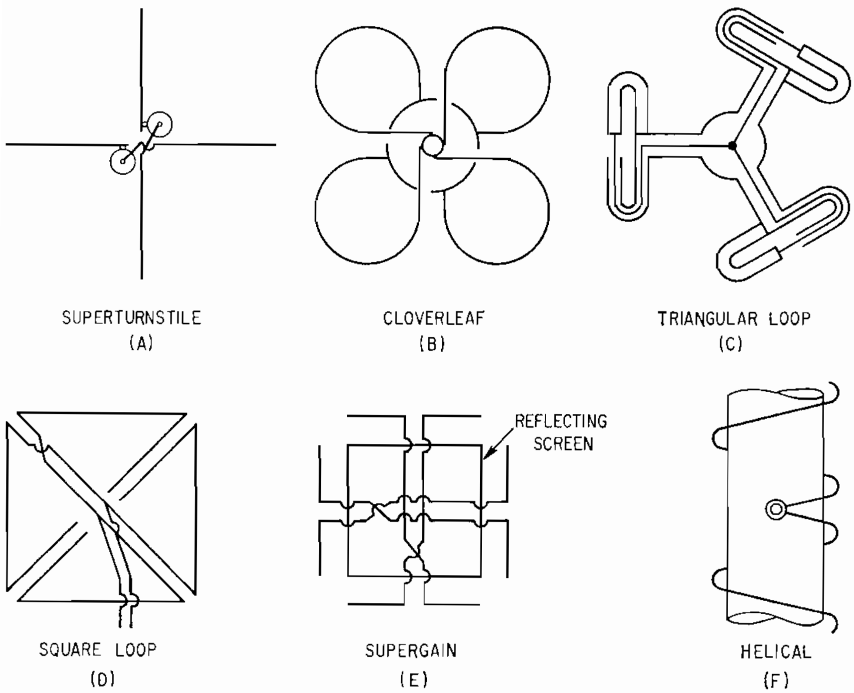


FIG. 7-13. Configuration of elements used to obtain omnidirectional patterns.

Other methods of obtaining omnidirectional patterns which have been used are the "clover leaf" of small loops (Fig. 7-13*b*), the triangle of folded dipoles (Fig. 7-13*c*), the small loop (Fig. 7-13*d*), the "supergain" with the dipoles backed by screens and fed in quadrature (as are the turnstiled dipoles) (Fig. 7-13*e*), and the helix wound around a tower structure with phase compensators to maintain correct phase relationship between successive turns of the helix (Fig. 7-13*f*).

Although omnidirectional antennas predominate in television broadcasting, there are locations where their use is impractical and even insufficient, and it becomes obviously desirable to direct the main portion of the radiated energy in both the horizontal and vertical planes to serve specific areas best. Examples in the United States are the Denver, Colo., area, where the presence of mountains to the rear of logical transmitting sites would set up undesirable reflections if the signal were allowed to radiate toward them, and the southeast coast of Florida, where the populated area borders the coast for great distances with only swamp immediately to the west.

Here the irregularities of the so-called omnidirectional patterns can be exploited to some extent, but truly "directional" patterns are more desirable. In order to obtain directional patterns, in either the vertical or the horizontal planes, correct relation in amplitude and phase of the signal coming from different portions of the antenna is necessary. This can be accomplished to some extent by physically spacing the radiating elements properly. For a given spacing, the pattern can be further modified by varying the phase and amplitude of the respective radiated signals. An example of this is shown in Fig. 7-14*a* where two point sources are fed in phase with each other but are spaced 180° apart. By the time the signal from *A* reaches *B*, the phase of the signal being radiated from *B* will have changed 180°. If the signals are equal in magnitude, they will cancel in the direction to the right. The same line of reasoning shows that no signal will be radiated to the left. Toward the top and bottom of the page, the signals will always be in phase, giving a total radiation equal to the sum of the two individual ones. Factors showing amplitude and relative phase are given in all four cases.

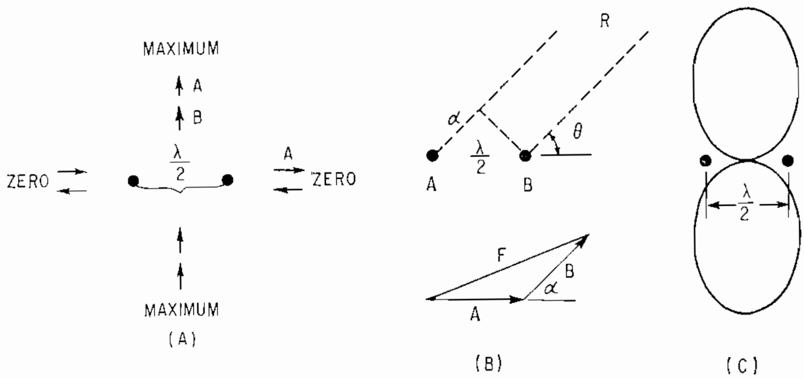


FIG. 7-14. Formation of field pattern from two sources placed a half wavelength apart, as shown in (*A*) and fed in phase. Leg of signal from source *A* in direction *R* is shown in (*B*) and the sum *F* of the signals from *A* and *B* are shown in (*C*).

At some other angle in the plane of the paper, conditions shown in Fig. 7-14*b* will pertain. At some great distance *R*, the signal from *A* will lag that from *B* by an amount α. The sum of the two will have a value *F*, somewhat less than the sum of *A* and *B*, as shown. If this process of analysis is continued for all angles of ϕ and the values plotted as relative magnitudes, a radiation pattern like the one shown in Fig. 7-14*c* (commonly called a figure-eight pattern) will be obtained.

If *A* and *B* are radiating 180° out of phase with the same spacing, signals to the right and left will reinforce each other, and they will by the same reasoning cancel at right angles to this, as shown in Fig. 7-15*c*.

For a spacing of one wavelength and a phase difference of 90° the signal from *A* will lag that of *B* by 90° toward the right, giving a resultant of 0.707 of the value of one signal. At an angle of $\phi = 60°$ toward *R*, the two will become equal but opposite in phase and the signals will cancel (Fig. 7-15*a*). Continuing this analysis yields a pattern shown in Fig. 7-15*b*.

It can be seen that varying the third parameter, amplitude of sigual, from either or both sources will increase the number of patterns which can be obtained, since the vectors now being added vary in length as well as in angle to each other.

The same method of analysis can be applied to more than two sources, with a corresponding increase in the number of vectors. In fact, the effect so analyzed actually takes place with any type of antenna which is not a point source, since each small portion of the antenna acts as a point source with particular phase, amplitude, and position relationship to every other such position.

Where individual radiators of finite size, having by themselves patterns which are directional in character (as, for example, a dipole), are grouped to form an "array,"

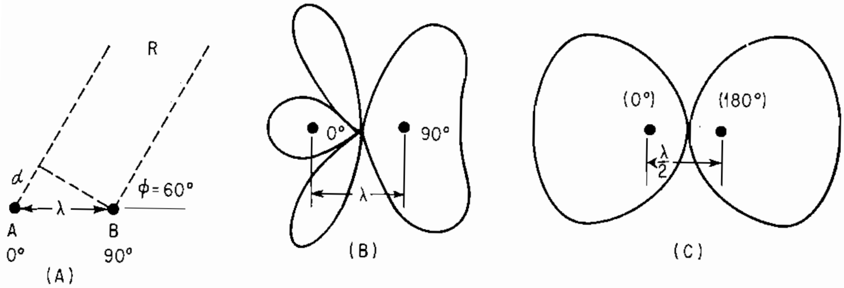


FIG. 7-15. Field patterns resulting from sources (*C*) a half wavelength apart fed 180° out of phase and (*B*) a wavelength apart fed 90° out of phase. (*A*) Formation of a null at $\phi = 60°$ for condition (*B*).

it is customary to consider each as a point or isotropic radiator in determining the phase at which their signals must be added to those of the other individual radiators, or "elements." For arrays of reasonable complexity, this relationship can usually be expressed as an equation, and the pattern which it represents is known as the "array pattern."

If the pattern of the individual element is itself expressed as an equation, the total field pattern (i.e., pattern of relative magnitudes of field intensity) of the array can be obtained as the *product* of the "element pattern" and the array pattern.

To find the phase of the resultant signal in any direction it is necessary to *add* the phase of the element pattern to that of the array pattern in that direction.

As pointed out above, an "element" may be considered in turn as a group of smaller elements. We have thus a tool for handling the calculation for quite complex arrays as illustrated in Fig. 7-16*a*. Assume that elements 1 and 2 are fed in phase and 3 and 4 are fed in phase but 1 and 3 are fed 90° out of phase. 1 and 2 give a pattern shown in Fig. 7-16*b*.

Now if 1 and 2 are considered as one single element with effective center of radiation halfway between the two and 3 and 4 are considered another element, the array pattern of the two new elements is a cardioid (Fig. 7-16*c*). Multiplying the patterns of Fig. 7-16*b* and *c* together in all directions yields the pattern shown in Fig. 7-16*d*.

If all elements of an array do not have the same element pattern, or if the array is quite complex in phase, amplitude, and geometry of elements, it is necessary to combine the element patterns on an angle-by-angle basis taking into account the

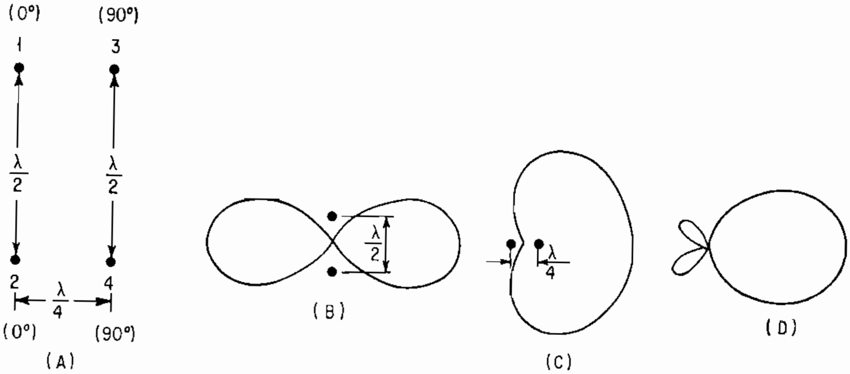


FIG. 7-16. Evolution of a pattern (*D*) by multiplication of an element pattern (*B*) by an array pattern (*C*). [Sources located and phased as shown in (*A*).]

array factor. An illustration of the method is shown in Fig. 7-17, where two point sources are fed with unequal currents in the ratio of 2 to 1 and with the upper one lagging the lower by 30°. In the direction $\phi = 60$, A lags B by $\lambda/2$ owing to its relative position. It lags an additional 30° due to the imposed phase. The unequal vectors are therefore combined at an angle of $90° + 30° = 120°$, giving a total amplitude of 1.732. Increasing the number of elements simply requires the addition of more vectors with correct relative signal strength and phase.

Examples of directional patterns of antennas in current use are shown in Fig. 7-18.

A reversal of the above procedure makes it possible to start with a desired pattern and to determine what relative phases and amplitudes are required to obtain it. A particular type of element and form of array must be presumed, of course, to make such a computation possible. This procedure is known as pattern synthesis. The speed of electronic computing devices renders this approach highly practical and effective.

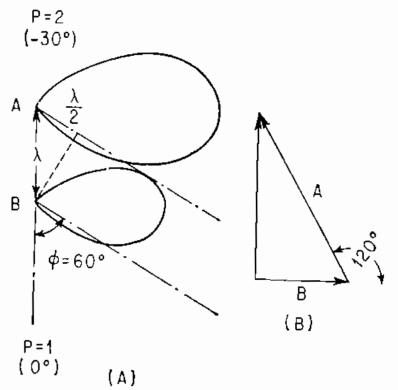


FIG. 7-17. Combination of signals from two sources having unequal currents and phase and positioned a wavelength apart.

The above discussion of the calculation of patterns has ignored the effects on element patterns of the presence of other radiators in close proximity. Mutual effects among elements alter current and phase conditions within the element and must be taken into account if the effect is appreciable.

A word should be said about the limitation on the use of directional antennas for commercial television in the United States. Where there is clear indication that directionalizing will not be against the best interests of the market area being served, the Federal Communications Commission will approve its use. The broadcaster may desire this to conserve power by limiting radiation over nonpopulated areas or to avoid multipath echoes from nearby mountain ranges. There is currently in effect a rule which provides that the difference in field strength between the maximum signal and the minimum signal in the horizontal plane shall not exceed 10 db.

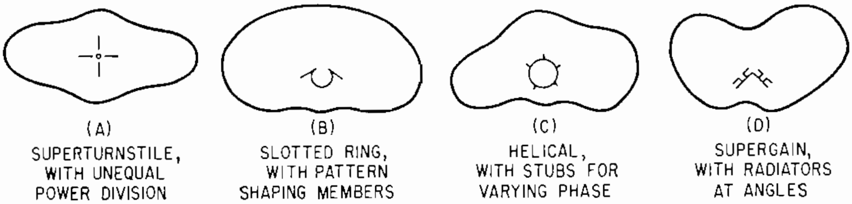


FIG. 7-18. Examples of directionalized horizontal patterns in current use.

Vertical Patterns

The need for higher gain (see under Gain) than can be obtained with a single radiating element requires "stacking" the elements one above another. This, on the undesirable side, increases the condition of "lobing," or wide variations in the amplitude of the resultant radiation pattern in the vertical planes. On the desirable side, however, it provides more separate elements by control of which the patterns can be made nearly ideal for television broadcasting.

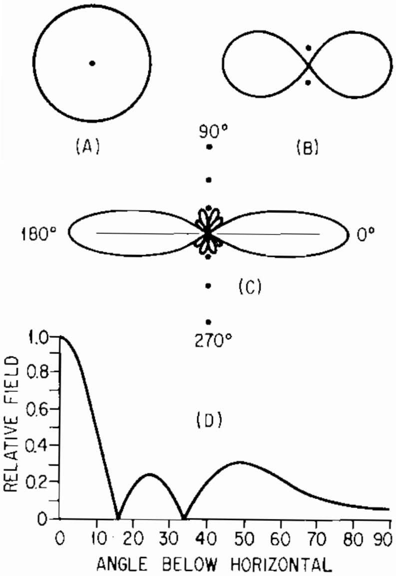


FIG. 7-19. Effect of stacking several point sources having equal currents and phase. (*A*) Vertical pattern of single source, (*B*) two sources, (*C*) six sources. Information given in (*C*) is shown in rectangular coordinate form in (*D*) for angles between horizoutal (0°) and directly below the array (270°).

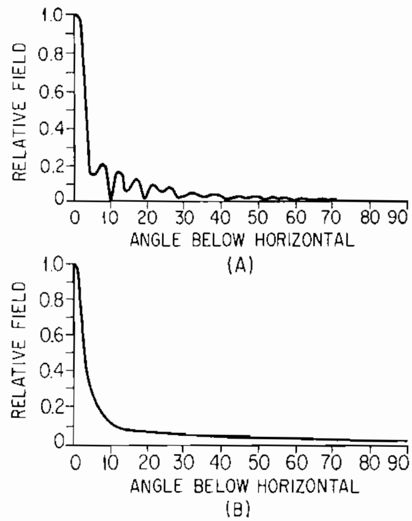


FIG. 7-20. (*A*) Vertical field pattern of antenna with a gain of 12 having twice as much power in the upper half as in the lower half. (*B*) Vertical field pattern of an antenna with many separate radiating elements with ideal phase and power distribution to obtain smooth pattern.

Reference is made to the discussion of Azimuthal Patterns for an outline of the theory of pattern formation. The same principles apply in the vertical plane. Figure 7-19*a* shows the vertical pattern of a point source or of a horizontal dipole. Figure 7-19*b* and *c* shows the effect of stacking two- and six-point sources one above another, a half wave apart, with currents of equal amplitude and phase. Figure 7-19*d* shows the same information as Fig. 7-19*c* for the portion of the pattern between $\phi = 0°$ (horizontal) and $\phi = 270°$, on rectangular coordinates, with field intensities plotted against angle below the horizontal. This is the customary method of pattern representation, enabling one to see in convenient manner the relative field strength at any angle into the area served by a broadcast station down to the base of the antenna tower.

The presence of nulls in the pattern of a television broadcast antenna is undesirable, because receiving areas at the angles where nulls are indicated received either less than the required signal or one which is the sum of reflections from objects which lie outside the null area. This latter condition often results in multiple "echoes" in the received picture.

The angles at which nulls appear for the case of a vertical array of equally spaced radiators fed by signals of equal amplitude and phase can be approximately found by the relation

$$\phi = \arctan \frac{\pm K}{nd}$$

where K is the null in question (the one nearest the main beam having a K value of 1, the next one 2, and so on). The number of elements is given by n, and the spacing of elements in wavelengths by d.

A quick rule-of-thumb method to obtain the distance of a null is to multiply the antenna height by the antenna gain and divide by K, thus

$$d = \frac{hg}{K}$$

Various methods are used in the design of antennas to "fill in" the null axis. Simple power division, whereby the upper or lower half of the elements are fed with a greater amount of power than the other half, results in the elimination of all odd-numbered nulls (see Fig. 7-20*a*).

A more complex power distribution was proposed by J. S. Stone, wherein successive elements are fed with amplitudes proportional to the coefficients of a binomial series. Thus for three elements the distribution would be in the relation 1, 2, 1, and for five 1, 4, 6, 4, 1. The result is an elimination of all minor lobes and all nulls except the ones directly at the base of the tower and directly above the antenna.

A similar result is obtained if the amplitude is exponentially tapered from one end of the antenna to the other, as in the traveling-wave antenna.

Still more elaborate is a combination of power division and phasing to obtain specific desired pattern shaping (see under UHF Antennas).

With the number of elements available in antennas having gains of 30 and upward, patterns have been obtained by these methods which are almost without a visible ripple (see Fig. 7-20*b*).

The filling of nulls, while highly desirable in cases where the area served would be otherwise affected, must be done at the expense of gain to some extent, since power is usually drawn from the main beam to furnish the filling signals. Proper pattern synthesis can, however, reduce this effect to a minimum, taking power instead from the portion of the pattern above the horizon, where it would otherwise serve no useful purpose.

Directionalizing the vertical pattern so as to direct the main lobe of energy at other than the horizontal direction is permitted by the Federal Communications Commission where it can be shown that the public can be more adequately served. Certain restrictions limit the type and amount of such directionalizing, however, namely:

1. The power radiated in the main lobe may not exceed that authorized for non-directional operation for the particular area.
2. Power radiated in any direction above the horizontal may not exceed the power radiated in the horizontal after directionalizing.
3. Requirements for Class A and Class B coverage must still be met.

Directionalizing in the vertical planes is normally accomplished by variation in phasing among elements in the array. This may be a lumped effect, as when the lower half of an antenna is fed in such a way as to lag the upper half in phase, or it may be a smooth transition of progressive phasing throughout the length of the antenna. In either case, the net result is to tilt the main beam downward, so that it points to the horizon or below. Antennas on Mt. Wilson in California, serving the Los Angeles area, offer examples of this type of directionalizing to obtain maximum coverage of the area with the least loss of power over the ocean beyond.

Combinations of electrical and mechanical "tilt" are used when the antenna is on top of a plateau overlooking a city in which a strong signal is desired. When the electrical and mechanical tilt are made equal, the total tilt toward the city is double the electrical tilt alone, with no tilt in the opposite direction along the plateau.

In considering the formation of total patterns a word should perhaps be said on the effect of distance on this formation. With antennas having a length (or "aperture") of several wavelengths, there is a distance within which the shape of the pattern is found to vary. This occurs because the distance is so small that radiation from the separate elements comes to the receiving point at different angles from the source rather than along parallel paths. Movement changes the angles and the distances from the separate elements at an unequal rate, resulting in variations in the sums of the individual signals. The field within this region has not "stabilized," and calculations which assume parallel paths of the rays do not yield an accurate result. The region from the outer border of the near or "induction-field" zone to the point at which the rays become essentially parallel and the pattern stable is known as the Fresnel zone. Beyond this region the formed pattern takes the form investigated by Fraunhofer, and the region is known as the Fraunhofer zone. For practical purposes the distance to the boundary between the zones is

$$d = \frac{2a^2}{\lambda}$$

where a is the total aperture in wavelengths.

Gain

Directionalizing horizontal and vertical patterns has been discussed in previous sections. The object is to force the energy to radiate in directions in which it can be usefnlly employed. In television broadcasting, these directions involve all the region below a plane tangent to the earth's surface and passing through the antenna. The area with which we are concerned is from the base of the antenna out to points somewhat beyond the horizon. Power radiated above this region serves little useful purpose, and it is desirable to reduce it as much as possible.

To indicate the effectiveness of this directionalizing process, the increase of signal intensity obtained thereby is related to the signal intensity which would be received from some standard reference antenna such as a half-wave dipole or an isotropic source having the same input power. The value of the ratio so obtained is called the "gain" of the antenna. A more specific definition of gain is given on page 2-222.

It should be noted that because of the fixed relationship between the shapes of the patterns of the two antennas commonly used for reference, a gain value as compared with a half-wave dipole can be converted to a corresponding value nsing an isotropic source as a base of comparison by use of a mnltiplying factor of 1.64.

As has been seen, the effect of adding more and more basic elements in a linear array with equal spacing between them and energized by equal currents in the same phase is to force the formation of a major lobe of energy. The result is greater gain in the direction of that (main) lobe. Gain can just as well be stated for any other direction, and at times this is done, but usually statements of gain are limited to the main-lobe direction.

Ideally, the determination of the value of gain of an antenna would be made by measurement of the received signal in the direction being considered followed by the same measurement with the reference antenna inserted in place of the antenna being evaluated. This is one of the methods in use. Various precautions must be taken to ensure accuracy, such as the construction of a theoretically exact reference antenna and recognition of the change in propagation conditions during the substitution process and of the difference caused by the electrical effect of the environmental condition (the supporting structure, for instance).

For all practical purposes, it has been found to be just as accurate to measure the radiated pattern of the antenna being considered in as much detail as is necessary to be able effectively to reproduce a solid, the distance to each point of which from the antenna position within it is representative of the relative value of field strength in that direction.

To determine the gain, it should be remembered that with the same input power to the two antennas being compared and omitting ohmic losses, the total radiated power will be the same in both cases. If, then, we imagine the solid referred to above as being remolded into a sphere (in the case of comparison with an isotropic source) of the same volume, this volume will be the same as that of the pattern of the reference antenna with the same power input. With this condition and holding the volume constant, if the pattern of the measured antenna is allowed to re-form to its proper shape, the main lobe will project beyond the surface of the sphere. The radius of the sphere and the distance to the tip of the main lobe will be in terms of volts. Corresponding powers will be proportional to the squares of these values. Comparison of these powers will give the power gain desired as compared with an isotropic source in this instance.

An illustration of this in one plane only is given in Fig. 7-21. The circle contains the same area as the pattern being considered and represents the field pattern of an isotropic source with the same power input. The gain in the main lobe, ignoring losses, will be

$$G = \frac{E_A}{E_i}$$

For an antenna having the same vertical pattern in all directions of azimuth, comparison using the pattern in only one plane is sufficient. Since such an ideal case never exists. However, integration of the entire pattern is required to take account of directivity of the horizontal pattern and variations in the shape of the vertical patterns.

As an example, gain determination of a superturnstile antenna is found to be quite accurate if one horizontal pattern is taken along with vertical patterns every 30° about the antenna. These patterns can, of course, be computed for a given antenna if enough information of the characteristics is available to justify confidence in the accuracy of computations. Determination of the gain in this case follows the same method as with measured patterns.

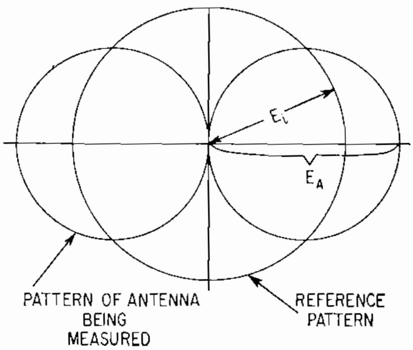


FIG. 7-21. Comparison of pattern of a measured antenna with circle of equal area to determine gain.

The method of obtaining measured field patterns of broadcast television antennas is to support the antenna in a horizontal position at a sufficient distance from ground and nearby objects to minimize the effects of reflection. By the principle of reciprocity a signal radiated from a distant source and picked up by the antenna under test will appear at the input to the antenna with the same value as if the input and output conditions of the antenna and the distant source were reversed. This simplifies the measurement, since in this way work on the antenna and measurement of the pattern can take place at the same location with the distant source fixed and the signal simply radiated.

With these conditions, rotating the antenna about a vertical axis will provide a vertical field pattern in one plane (and for both sides of the antenna). Revolving the antenna 30° about its own (normally vertical) axis will place it in a position where a new vertical pattern can be taken.

With the antenna at right angles to a line to the "source," revolution about its own axis will yield a horizontal pattern.

For any other position than that normal to the line to the source, an azimuthal pattern can be obtained for the angle being considered (for instance, the pattern of the variation of the maximum value of a main lobe tilted below the horizontal).

Since it is customary to measure the gain of an antenna in terms of the amount of signal radiated with the desired polarization considered effective, all energy with other polarizations being considered lost for effective use, measurement of this lost energy is also necessary, the amount being accounted for as a decrease in gain. This is usually done by rotating the polarity of the transmitting source and determining the amount of energy received for this condition by the antenna under test.

In the statement of gain for commercial purposes, losses in the feed system and radiating elements must also be accounted for.

Gain is proportioned to aperture, which, for the types of antennas used in telecasting, is the active height of the antenna. Length represents both antenna cost and an overturn load for which the tower must be adequately designed. The efficiency with which the aperture is used becomes an important criterion of antenna design. Gain per wavelength is a yardstick by which this efficiency is indicated. This yardstick must, of course, be used judiciously, since desired characteristics such as null fill and directionalizing must, in turn, be paid for in terms of gain. In general, omnidirectional broadcast antennas currently being built and used have gains per wavelength which vary between 1.05 and 0.80, depending on the amount of null fill.

It is interesting to note that for a uniform current sheet, with all elements of the sheet having equal phase and amplitude, the theoretically maximum gain per wavelength which can be achieved for antennas over two wavelengths is 1.22. With such a value, full nulls would exist throughout the pattern. No commercial antennas now in use attain this ideal value.

Impedance

Transmission-line theory tells us that maximum transfer of power takes place when a load terminating a line has the same impedance as the characteristic impedance of the line. Since the final load in a radiating system is space, it is desirable that the antenna match the impedance of space, or approximately 377 ohms, at the point of radiation.

The ease with which a signal is radiated determines the effective impedance of the antenna at the boundary with space. Thus, a logarithmic horn of the type shown in Fig. 7-22 flaring outward to a considerable diameter at the mouth expands the wavefront and launches it practically without interference. If the characteristic impedance of the horn (determined by the ratio of D to d) is maintained down to the entrance to the taper, that entrance (input to the antenna) will have an impedance of 377 ohms. Because the impedance throughout the elements is constant and resistive in nature, the antenna is not sensitive to frequency, signals of all frequencies being transferred equally well. This insensitivity to frequency is called "bandwidth," and the horn has nearly the ultimate in bandwidth.

A biconical dipole antenna (Fig. 7-4*a* and *b*) with flaring arms, has a similar action and an input impedance of around 300 ohms. This, too, has a large bandwidth. On the other hand a dipole with thin areas is very critical to frequency and so transfers the energy to the radiated field at a maximum rate only at the frequency where the over-all length is $\lambda/2$. At other freqnencies considerable reflection occurs and the input impedance changes rapidly. At the resonant frequency the input impedance is about 73 ohms.

The input impedance of a superturnstile antenna (see under Superturnstiles) is about 150 ohms (both batwings together), of a helical antenna 100 ohms and of a resonant fullwave slotted cylinder about 40 ohms.

In each of these cases it will be seen that the antenna has, because of its construction and electrical response, effectively transformed the impedance as seen at the space boundary to some other value. If, in the process, compensation has been made so that the impedance seen by the signal is relatively constant at all frequencies involved, the antenna will have adequate bandwidth. If compensation is not made, the bandwidth will be narrow. The superturnstile, with its broad radiators and compensation afforded by the slot between radiator and pole, is very broadband. A ring or a thin-dipole antenna, on the other hand, is extremely narrow.

If the load terminating a line does not have an impedance equal to the characteristic impedance of the line, some of the power is not transferred but is reflected back down the line. Combination of this energy with that coming up the line sets up "standing waves" similar to those found at sound frequencies in musical instruments or on a vibrating string. The ratio of the maximum to the minimum voltage of such a wave is called the voltage standing-wave ratio (VSWR) and is denoted by the symbol ρ. It is used as a figure of merit to indicate the efficiency of transferal of power.

Another such figure of merit is the ratio of reflected to incident component of voltage at the load or at an impedance discontinuity. This is denoted by the symbol Γ and is called the reflection coefficient.

The values of ρ and Γ are related by the formula

$$\rho = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

There are several undesirable results of a mismatch of impedances of line and antenna. Because of the standing waves set up, high current regions occur every half wavelength along the line. If the mismatch is of considerable magnitude, the ohmic losses resulting may overheat the line, causing damage, particularly at junction points. The high voltages of the standing wave, which also occur every half wavelength, may exceed the rated voltage of the line, causing corona or flashover.

A third effect of an impedance discontinuity and the resulting reflection of power is the possibility of creating an "echo," or repeated picture as viewed by a receiver. If the portion of the signal reflected from a mismatch in the line or antenna is not totally absorbed in the output circuit of the transmitter, it is rereflected toward the antenna. The part of this which reaches the antenna and is radiated appears as a second picture, to the right of the primary one, which may be of such intensity as to be very objectionable.

Where an echo causing mismatch occurs, it is possible to locate approximately the section of line in which the reflection occurs by measuring the distance between the initial picture and the echo on a receiver screen. Since the width of a picture represents 53 μsec of time, and since a signal can travel 26,150 ft through a transmission line and return to the starting point in this length of time, the proportion of the picture width (in inches) which the delay (in inches) of the echo represents is the same proportion of 26,150 ft which the signal traveled before striking the reflecting mismatch. That is,

$$D = 26{,}150 \times \frac{\text{delay of echo beyond initial picture, in.}}{\text{width of receiver screen, in.}}$$

where D is the distance from transmitter to discontinuity.

It has been pointed out that antennas may transform the impedance seen at the space boundary to some other impedance at the input. If, for instance, the D/d ratio of the horn shown in Fig. 7-22 was changed gradually along its length, there would be a smooth transition to some new impedance looking into the input of the value

$$Z_c = 138 \log \frac{D \text{ (input)}}{d \text{ (input)}}$$

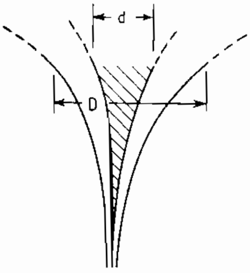


FIG. 7-22. Logarithmic horn used as ideal broad-band radiator.

Because the horn is difficult and costly to manufacture, it is customary to use simpler and more abrupt transformations in order to match two unequal impedances. A simple and effective transformer for a narrow band of frequencies is obtained by inserting between the impedances to be matched a quarter-wave section of line having a characteristic impedance equal to the geometric mean of the two impedances. That is,

$$Z_c \text{ (of transformer)} = \sqrt{Z_1 Z_2}$$

Since the length of the transformer is $\lambda/4$ for only one frequency, the bandwidth of the transformation is small. Matches over wider bandwidths can be obtained, however, by using several such transformers end to end (thus approximating the tapered horn). Choice of proper characteristic impedances for the various sections can be made by following standard techniques or by cut and try.

Another method of impedance matching is to choose a point in the line where the input admittance appears as pure susceptance. Insertion of a lumped susceptance of opposite sign (for instance, a disc of Teflon as capacitive susceptance) will balance that in the line and yield a matched condition. This method is good only for a single frequency.

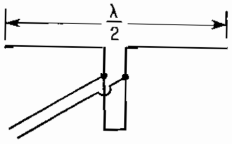


FIG. 7-23. Impedance matching by selection of point of feed of dipole with shunt stub.

Impedance matching of an antenna to a line can be accomplished by choosing a point to feed the antenna where the impedance of the antenna appears as the desired value. Off-center feed of a slot, for example, offers a considerable choice of input impedance.

The placement of input to a $\lambda/2$ dipole along a quarter-wave shorted stub offers again a large range of input impedance (see Fig. 7-23).

Bandwidth

As discussed under Impedance, the range of frequencies over which a circuit maintains a more or less constant impedance is called its impedance bandwidth. Limits of the bandwidth occur when the impedance exceeds some value agreed upon for defining the bandwidth.

Methods of obtaining this bandwidth have been touched upon. Basically they consist of so designing the antenna or intermediate transforming elements that they are not sensitive to frequency change. The horn, through its shape, presents only resistance at the input. The superturnstile (see under Superturnstiles), by paralleling a parallel-resonant circuit (which becomes capacitive with increase in frequency) with the series-resonant circuit of its radiator (which becomes inductive with increase in frequency), obtains a virtual cancellation of reactance over a considerable frequency range, rendering this antenna one of the most broadband television antennas in general use.

The same principle is applied in the traveling-wave antenna, which, instead of using quarter-wave stubs in parallel with the feed point as in the superturnstile, utilizes a slot whose shape provides the response of a parallel-resonant circuit.

On other antennas, broadbanding stubs and, at times, a series of half-wavelength transformers, spaced at proper intervals apart, are used to obtain impedance bandwidth.

Another interesting method, quite different from the above, is the use of a "power equalizer" to broadband otherwise narrow-band radiators. In supergain antennas (see under Supergain Antenna), which are quite narrow band at low channels (2 to 6), the bridge diplexer (see Aural and Visual Transmissions) can be effectively used to absorb most of the power reflected from the antenna. Figure 7-24 shows east and west radiators being fed 90° out of phase with north and south radiators.

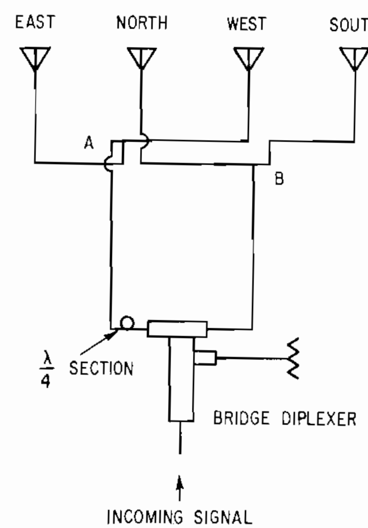


FIG. 7-24. Use of bridge diplexer as "power equalizer" in broadbanding of supergain antenna.

The incoming signal fed from a notch diplexer or filterplexer through a single-line feed enters the visual input of the bridge diplex and leaves it as two signals 180°

out of phase (or + −). After passing through the additional 90° length on the left line, the signal in this line reaches *A* 270° out of phase with that reaching *B*. With equal reflection from *A* and *B*, the reflected signals return to the diplexer.

The 90° section again shifts the phase in line *A*, and the two signals reach the diplexer *in phase.* The diplexer action is such that both reflected signals are now passed out through the aural input to a load which absorbs all the power. Since none return to the transmitter by way of the visual input, there is no standing wave, and the transmitter therefore appears to see an impedance match over the whole channel.

An antenna may have impedance bandwidth, but its radiation pattern may vary with frequency. That is, it may not have pattern bandwidth. This normally occurs because radiating portions of the antenna, being fixed in position mechanically relative to other elements, in effect change this relative spacing as the frequency changes (i.e., in terms of wavelength). The higher the frequencies of operation, the less sensitive antennas are to this as a general rule, because, for a given spread of frequencies (6 Mc for television), the present bandwidth (ratio of operating range, Mc/center frequency of range, Mc) becomes less at high frequencies. Thus, a change of 6 Mc at 600 Mc is only 1 per cent, while at 60 Mc it is 10 per cent.

The traveling-wave antenna, operating normally in the vicinity of 200 Mc, takes care of the problem by incorporating circuit elements which effectively retard the phase of the signal with increase in frequency and advance it with decrease in frequency (see Traveling-wave Antenna). The result is to maintain the wavelength constant at all frequencies of a channel and so in turn to maintain the radiating elements at constant virtual spacing from each other.

Pattern bandwidth is important to the maintenance of video response. Correct relationship of amplitude and phase of signal is important at all frequencies within the channel, within the limits of good engineering practice, particularly in color transmission.

Gain bandwidth is the range of frequencies over which the gain remains constant. This is, of course, closely related to pattern bandwidth. It is particularly important in television, where it is desirable to use a given physical size of antenna over a broad number of channels to obtain approximately the same characteristics at each channel.

Feed Systems

The feed system of a television broadcast antenna is commonly considered that portion of the transmission system having its input at the antenna terminal which is at the top of the vertical run of coaxial transmission line in the tower and its output at the radiating elements.

Most antenna gains in the manufacturers' literature take the losses of the feed system into account, which are considered as reduced antenna gain. Therefore, when system losses are calculated, the feed-system loss should be exclnded, having already been accounted for.

Types

In the television broadcasting field, three types of feed systems are in wide use. They are the branching, standing-wave, and traveling-wave feed systems. Each meets a need peculiar to its own application. Where frequencies vary from 54 to 890 Mc, where power-handling-capacity requirements vary from 500 to 100,000 watts, where gains vary from 0.5 to 60, and where pattern shapes vary between extreme limits, it is logical that good economics dictates various types of feed systems.

Branching. The branching-type feed system is used in the superturnstile antenna. It is characterized by the progressive subdivision of input signal in a more or less uniform manner, from the input of the antenna to the end seals. A large majority of the antennas using this feed system accomplish the subdivision of power by means of a junction-box assembly into which is plugged the individual radiator feed lines.

Figure 7-25 is a picture of a junction box. If filling of the first null is desired on antennas of 12 sections, the power can be divided 70 per cent in the upper six sections and 30 per cent in the lower six sections to obtain a fill.

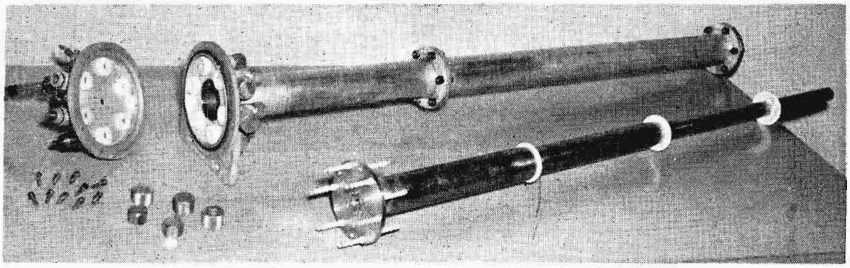


Fig. 7-25. A junction box as used in 12-section superturnstile antenna. Twelve feed lines at a 77½-ohm impedance from 12 radiators are combined. The net impedance is transferred to the line impedance of 51½ ohms by means of a three-section transformer.

Standing Wave. The standing-wave-type feed system is used in slotted-cylinder UHF antennas. For details refer to *Slot Types* on page 2–263.

Traveling Wave. The traveling-wave feed system operates on the principle of a gradual attenuation of the input signal through radiation resistance as it progresses from the input along the aperture of the antenna. An application of this principle is the helical antenna. Page 2–254 gives more details. A more recent development is the application of this feed system to a cylindrical-slot antenna known as the traveling-wave antenna described on page 2–257.

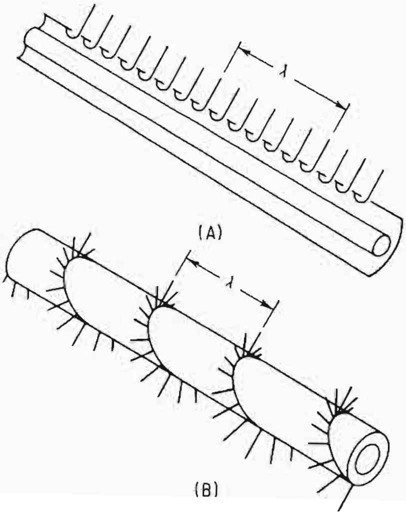


Fig. 7-26. Basic principles employed in the traveling-wave antenna feed system.

Figure 7-26*a* shows the principle of this feed system using short rod radiators to illustrate the theory. A number of radiators per wavelength uniformly spaced are loosely coupled to a coaxial line. Because of the number of radiators and the relatively slight reflection due to each, the effect is essentially that of a uniform loading. The result is a uniformly attenuated traveling wave in the line. Since a traveling wave has a linear-phase characteristic, the excitation of each successive radiator will be lagging from the previous one by an amount which depends on the spacing between the radiators and the velocity of propagation in the line. If the radiators are alike, their currents will have the same phase relationship as the excitation. Thus the radiating currents will be successively lagging, and repetition of phase occurs after every guide wavelength.

To obtain an omnidirectional pattern the radiators, instead of being in line, can be moved around the periphery to form a "spiral" as shown in Fig. 7-26*b*. For a horizontal main beam the pitch of the spiral has to be equal to the guide wavelength in the transmission line. In this arrangement all the radiators in any one vertical plane on one side are in phase and the phase difference between radiators in different planes equals the azimuth angle difference between the planes; that is, the phase rotates around the periphery. The rotating phase produces a rotating field which, because of the relatively small amount by which the magnitude of current changes from layer to layer, produces an omnidirectional pattern.

Aural and Visual Transmissions

For the broadcasting of standard television signals, the video-signal amplitude modulates a separate visual transmitter and the audio-signal frequency modulates a separate aural transmitter, the output of which is generally one-half the peak visual power output of the visual transmitter. To radiate these two separate signals, various techniques can be employed.

Separate Antennas. Separate antennas can be used, one to radiate the visual signal, the other to radiate the aural signal. When this procedure is used, a separate transmission line connects the output of the particular transmitter to the input of the respective antenna. Two precautions should be observed: (1) The isolation of the individual antennas must be sufficient to prevent interaction and cross modulation within the systems. (2) The patterns of the individual antennas must be sufficiently alike so that the ratio of the visual signal to the aural signal is neither too large nor too small. An example of this kind of installation is the use of the upper half of a superturnstile antenna for visual and the lower half for aural transmission.

Bridge Systems. The bridge diplexed system of antenna feed is used in the superturnstile antenna. The complete antenna is used in both visual and aural transmission. The superturnstile antenna is fed through a bridge network where the two inputs are in quadrature. The radiating systems are also arranged in a quadrature relationship so that the azimuthal pattern is substantially circular as described under Azimuthal Patterns. The north-south system, which radiates a figure-eight horizontal pattern is constructed in a vertical plane at right angles to the plane of the east-west system, which also radiates a figure-eight pattern with 30 db or more isolation between the two systems. Each of these radiating systems forms a termination for the two legs of the "Wheatstone-bridge-type diplexer" as shown in Fig.

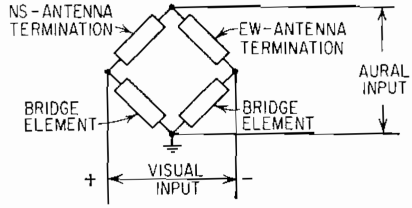


FIG. 7-27. Bridge diplexer represented as a Wheatstone bridge.

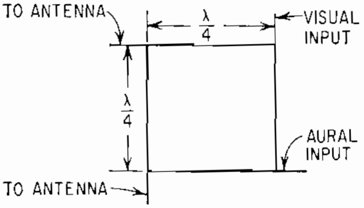


FIG. 7-28. Ring T diplexer schematic showing inner conductors only.

7-27. The visual signal is fed into the bridge balanced to ground, and the aural signal is fed in unbalanced to ground.

The superturnstile antenna can be fed with a "ring-T" type of diplexer, which also requires a two-line feed as illustrated in Fig. 7-28.

Notch Diplexer. Where an antenna has a single input, a network for combining the visual and aural signals is required. One type of circuit which accomplishes this function is shown in Fig. 7-29. The aural signal, divided by means of a balun (*bal*anced to *un*balanced network [9]), is reflected from the cavities tuned to aural frequency. These cavities are arranged so that they present a very low impedance across the line. Because of the quarter-wave separation the aural signal on the lower line in the figure travels an additional half wave to and from the cavity reversing the phase so that the signal enters the balanced antenna terminals instead of returning to the

[9] Balanced is sometimes referred to as push-pull, and unbalanced as push-push.

unbalanced aural input. Any aural energy which leaks past the cavities is absorbed in the terminating load.

The balanced visual signal enters the balanced antenna terminals. Any energy in the visual signal which is at the aural frequency is rejected and because of the quarter-wave separation of the cavities is reversed in phase and is absorbed by the terminating load. In order to obtain the proper visual response, a shaping cavity is sometimes associated with each aural cavity.

Filterplexer.[10] A vestigial-sideband filter is a device used with some types of transmitters to absorb the rather small lower sideband energy lying outside the 6-Mc channel. When a notching diplexer is used, it is desirable to combine the visual-sideband filter and the notching diplexer into a single unit.

This is accomplished in a manner similar to the notching diplexer described above. As shown in Fig. 7-30, two additional pairs of cavities are used on opposite sides

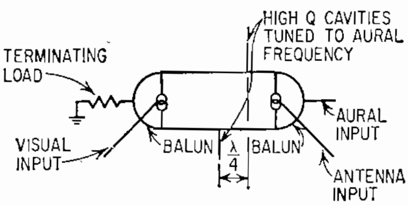


Fig. 7-29. Notching diplexer schematic.

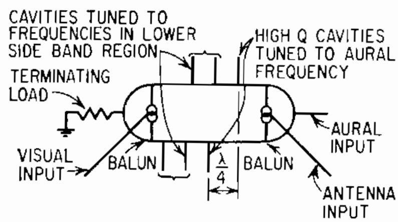


Fig. 7-30. Schematic of filterplexer.

to provide reject points in the portion of the lower sideband lying outside the 6-Mc channel. The rejected lower-sideband energy is dissipated in the terminating load.

Isolation Using Traveling-wave Feeds. On an antenna which employs a traveling-wave-type feed, the input power is radiated as the signal proceeds away from the input along the aperture. By the time the signal arrives at the end of the aperture, it should be so low that the reflected energy from the end is quite small. In practical designs this energy is about 20 db below the input. Therefore, if the visual signal is fed at the center of the aperture, the aural signal can be fed at the ends. The helical antenna described on page 2–254 uses this method of feed.

System Performance

The EIA specifications, while recognizing the need for a system specification, has never established one. By system specification is meant the performance of the entire antenna system including the antenna with its feed system, the main transmission line from the station to the antenna, switches and various fittings in the station, and the diplexer. Most antennas are built to a VSWR specification of 1.1 to 1. In some cases the same value was used for the transmission line. At times the same specification has been used for the entire system. Since there is bound to be vector addition in some parts of the band, which can be found if the measurements are sufficiently discerning, it is difficult, if not impossible, to meet a system VSWR of 1.1 if each component is designed to the same specification. Hence, in many cases it is necessary to make changes in the system, which do not improve the picture, merely for the purpose of meeting a specification which does not truly describe system performance. System performance, to be meaningful, must be related to the quality of the picture transmitted. This is best described by the ability of the system to faithfully reproduce a square-wave pulse since in essence a picture is composed of a series of such pulses. Hence a specification is currently being studied based on the relative reflection voltage returning from a radio-frequency pulse propagated along the line

[10] Also designated as a Filtrexer.

to the antenna. If narrow pulses and broad pulses are used, the complete system can be analyzed in a manner which determines true performance.

Since this study is currently in progress, full details cannot be given at this time.

Multiple Antennas

In an area where two or more television stations are providing coverage, various advantages accrue to the broadcasters if they enter into what is referred to as a multiple-antenna installation.[11] These advantages include reduced costs of individual tower and better reception, since all receiving antennas can be oriented toward the common source of radiation. Furthermore, the fact that tall towers can be located only in limited areas, owing to air-space restrictions, offers a further incentive for a common installation.

Multiplex TV Installations

The most notable multiple television installation is the Empire State tower system. At present there are seven television stations radiating signals from this structure. Three installations (in Minneapolis, Minn.; Havana, Cuba; and Hamilton, Ontario) provide three-station operation with vertically stacked antennas. Many installations provide for two stations with vertically stacked antennas.

Instead of mounting the antennas vertically, some have found it more desirable to mount their antennas on a common platform at substantially the same elevation. Illustrations of this approach can be found in Baltimore, Md., and Dallas, Tex. Such an arrangement does not limit antenna design and permits antenna modification or replacement more readily.

AM and TV Installations

There are occasions when an existing AM tower can be adapted for a television antenna. Usually two problems must be faced. First, a portion of the tower must be removed to accommodate the television antenna so as to minimize the detuning effect of the AM system, and second, the wiud load of the television antenna over the portion of tower removed and the transmission lines running the full length of the tower is increased. The ability of the tower to withstand this load must be determined. The costs of alterations must be considered in relation to the cost of a new tower.

A further consideration is the need for isolating the television transmission lines from ground in order to mount on the AM tower. This is usually accomplished by the use of insulated hangers for one-quarter wavelength along the tower. This same problem must be faced where it is intended to mount a television tower in the proximity of an AM array. The television tower is insulator-mounted, and the transmission lines are isolated with a quarter-wave run of insulated hangers.

Systems Planning

Many times, the individual aspects of a television installation are meticulously scrutinized, and yet how they work together is given secondary consideration. An exhaustive check list would be almost endless. But a few important items are listed:

1. Detailed study of coverage taking terrain and competitive signals into account
2. Antenna location relative to population centers
3. Antenna vertical pattern design for best coverage
4. Antenna mounting methods
5. Layout of transmission lines

[11] Predicting the Operating Characteristics of Closely Spaced Antennas on the Same Supporting Structure, by Irl T. Newton, Jr., and M. S. Siukola, presented at the 11th Annual NAB Engineering Conference, April, 1957.

   a. In the vicinity of the tower top
   b. Main tower run
   c. Horizontal run to station
6. Transmitter and associated equipment locations
7. RF filter networks and load locations
8. Station layout
9. Emergency provisions
   a. Emergency antenna
   b. Emergency transmission lines
   c. Standby provisions
   d. RF switching features

A few of these will be discussed in more detail.

Propagation Study

In hilly terrain, especially at higher frequencies, shadow areas will occur which cannot be predicted from FCC curves. A method of predictiug is outlined in the following paper, A Method of Predicting the Coverage of a Television Station by J. Epstein and D. W. Peterson, *RCA Rev.*, vol. 12, no. 4, December, 1956.

Antenna Mounting Methods

The method is determined by the antenna manufacturer, and the tower must be built to accept the antenna. Common methods in use are:

Buried pole section in which a pole socket at the bottom of the buried pole supports the dead weight of the antenna.

A guide flange supports the antenna laterally near the tower top.

A guide flange and pole socket are normally supplied by the antenna manufacturer, but the tower should be drilled to receive them.

Pedestal Mounting. The pedestal is mounted on the tower and receives the butt end of the antenna.

Flange Mounting. The base flange of the antenna rests directly on the tower top which is drilled to receive it.

For these methods a much heavier tower top must be designed. In each case the tower design must be coordinated with the antenna.

Layout of Transmission Lines

In the Vicinity of the Tower Top. Usually, it is desirable to avoid as many elbows in a system as possible. However, near the tower top, it has been found advisable to have a pair of 90° miter elbows at the end of the vertical run in order to provide access to the system. It also provides a measure of mechanical flexibility, depending on the horizontal length of line between elbows. This flexibility is very desirable. The amount required is dependent on the movement, due to antenna sway, expected from the lines coming down from overhead.

Where complicated circuitry involving power-dividing Ts, transformers, phasing sections, and cut-over elbows (for an emergency feature) are used, considerable thought should be exercised in planning the hanger supports and line layont in cooperation with the tower designer.

Since mismatches at or near the antenna are the most potent source of echoes, any equipment in this area should be very well matched.

Main Tower Run. Normally, in tower-transmission-line runs composed of 20-ft sections, the top section is supported with two fixed hangers spaced 10 ft apart and the sections below on spring hangers located on 10-ft centers. Care must be applied at installation to locate the transmission-line sections so that the hanger springs do not cross over or rub against the transmission-line flanges. When the spring hangers are installed, they should be stretched according to the chart supplied by the manufacturer. If this is not done properly, it may require an excessive pull to separate the line in hot weather and the line may not be supported adequately by the springs in cold weather. At the base of the tower, clearance must be provided to accommodate the differential expansion of the steel tower and copper transmission line.

Horizontal Run to Station. If the run from the tower to the station is short, 20 ft or less, and the tower run is 500 ft or more, the mounting of the horizontal line must be arranged to allow for the vertical movement of the line due to differential expansion between the tower and tower-transmission-line run.

If the run from the tower to the station is long, 100 ft or more, the horizontal run can be anchored at the station wall. At the base of the tower, the differential expansion of both the horizontal and vertical runs must be considered. Proper hangers and mounts should be used to secure the line, providing for the expansions involved and yet restrict its movements for high wind conditions. In areas where icing conditions are troublesome, protection from falling ice should be provided over the horizontal run.

RF Filter Networks and Load Location

The sideband filter, filterplexer, and similar networks should be located with sufficient clearance so that easy access to all portions for servicing and cleaning is possible. While ceiling mounting conserves floor space, accessibility of all elements should still be a consideration. Since many of these devices use cavities which cannot be pressurized, a clean atmosphere is important, since dust accumulation inside the cavity will eventually cause trouble. Cavities should be arranged so that they are in the same ambient temperature. A difference in height when a high-temperature gradient exists or sun heating of one cavity may result in unbalance. Since hot air is less dense than cooler air, a hot location will reduce the safety factor for voltage breakdowns.

Emergency Provisions

It has always been the desire of the broadcaster to keep the ratio of nonscheduled "off-the-air" time to schedule "on-the-air" time as small as possible—preferably zero. An efficient maintenance procedure is excellent insurance. Emergency facilities can also help to keep this ratio small. A great variety of items are available. A word of caution—do not make the emergency provisions too complex and check their operation periodically.

Emergency Antenna. The simplest emergency-antenna provision is that found in the superturnstile, where, if one portion of the antenna fails, the power going to that half can be absorbed in a load while the other half continues to provide some measure of service with a figure-eight pattern. In various antenna designs the power is distributed to the upper and lower halves through combining networks mounted at the tower top. Simple change-over equipment permits the selection of either the upper or lower half for emergency service. Relatively low-gain antennas have been used mounted on the sides of towers and some inside towers for emergency use. It must be remembered that the tower will distort the antenna pattern somewhat. At UHF this distortion may be small. However, at low VHF the pattern is practically unusable, depending on what degree of pattern distortion, and system reflections will be tolerated for this type of service. Some very elaborate emergency systems have been installed to the point where every item of transmission has been duplicated for emergency purposes.

Emergency Transmission Line. One extra provision of insurance can be provided by the installation of a spare transmission line so located that it can be inserted in place of the main run with a minimum of change-over connections at the input and output. It is wise to use gas stops at both ends and keep it pressurized.

Standby Provisions. How much insurance one wishes to buy in the form of standby equipment can be based on the losses incurred by interrupted service. Where broadcasters have expanded their operations to higher power, the replaced transmitters have been retained for standby use. In some new installations broadcasters have obtained duplicate transmitters and worked them both on alternate schedules. In addition to this excellent emergency feature, a large portion of maintenance work can be scheduled during regular working hours. A standby Diesel generator set, duplicate microwave equipment, duplicate RF networks, and duplicate tower and antenna all contribute to potentially more reliable service.

RF Switching Features. Perhaps the most common emergency feature is the cutback circuit from transmitter amplifier to driver. This usually is performed quite rapidly using motor-driven RF switches. Where a standby system, including transmitter and RF networks, is available but a common antenna is used, motor-driven RF switches can be inserted to transfer the input of the antenna from the main transmitter to the standby system. Many elaborate cutover and cutback systems have been proposed.

In many switching applications the speed of the motor-driven switch is not required and a manual transfer panel is adequate. To terminate various points in the RF system with a dummy load, it has been found convenient to install a single-pole double-throw switch to break open a line so that the load termination can be made by way of a separate multiposition manual-transfer panel.

TYPES OF ANTENNAS

The development of television was such that Channels 2 through 13 (54- to 216-Mc band) were assigned first and, later, with the demand for more stations, Channels 14 through 83 (470- to 890-Mc band) were assigned. The lower of these two bands, referred to as VHF, resulted in antenna types suited to those frequencies. The higher of these two bands, referred to as UHF, required a type different from those previously developed.

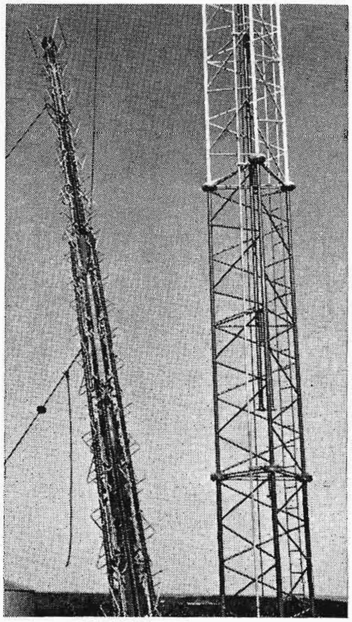


FIG. 7-31. Erection of a TF12AH superturnstile antenna at KTBC-TV, Austin, Tex.

VHF Antenna Types

Even within the VHF band various applications dictated antennas of differing designs for both electrical and mechanical reasons.

Superturnstiles

The first antenna developed for commercial service was the superturnstile.[12] It consists of a central sectionalized steel pole upon which are mounted the individual radiators, or "batwings." These radiators are mounted in groups of four around the pole in north-south and east-west planes to form a "section," and the sections are stacked one above the other to obtain the desired gain. Figure 7-31 illustrates this construction showing a 12-section high-band Channel 7 to 13 antenna.

In this type, each of the radiators is fed separately by its own feed line to whose impedance that of the radiator is carefully matched. The feed lines, in turn, are combined in sets of 12 at junction boxes, which perform the dual function of feeding power simultaneously to all feed lines and of transforming the combined impedance of these lines to that of the 51½-ohm transmission line which carries the power from the base of the antenna.

[12] R. W. Masters, The Superturnstile Antenna, *Broadcast News*, January, 1946.

This latter function is achieved by the use of three-stage transformers immediately below the junction box.

At the base of the antenna at the tower top, a combining network is used when there are more than two junction boxes. These networks accomplish power division between portions of the antenna if so desired. These antennas are manufactured in various gains from 3 to 12 for Channels 2 to 6 and 6 to 18 for Channels 7 to 13.[13] They can also be obtained for various types of null fill[14] (see under Vertical Patterns) and wind loading. They have also been used in stack and candelabra installations.[15] Antennas can be split by the use of additional junction boxes for emergency use and for other purposes. Elliptical azimuthal pattern can be obtained by changing the power division between the north-south and east-west planes.

Supergain Antenna

The supergain antenna[16] consists of half-wave dipoles mounted in front of reflecting screens. The construction of the diploes is modified to achieve a high degree of mechanical strength. The addition of a power-equalizing[17] circuit (see under Bandwidth) for Channels 2 to 6 is required to assure the necessary bandwidth.

The reflecting screen forms a square, each side of which is one-half wave in length. This antenna lends itself to stacked arrangements for a number of channels as carried out in the Empire State installation.[18]

A single layer of supergain consists of the tower screens and four dipoles directed in the four principal horizontal directions. In order to increase gain, these layers are stacked vertically. Feed lines from the north-south dipoles terminate in one set of junction boxes, and those of the east-west in a second set. The power equalizer divides the power equally between these two systems and through the use of a terminating load absorbs the reflected power from the dipoles.

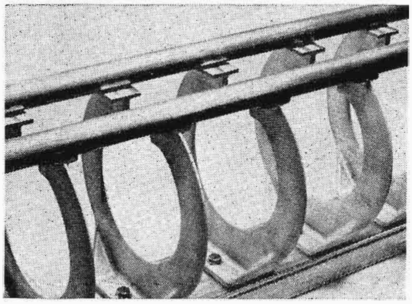


FIG. 7-32. Portion of a slotted-ring antenna.

AMCI Slotted-ring Antenna

Description. The AMCI slotted-ring antenna is designed for VHF television broadcast transmitting service. It consists of a series of slotted rings mounted on a channel as shown in Fig. 7-32. The rings are lenticular in cross section with the long axis in the plane of the rings so that the wind resistance of the structure may be as low as possible. Two rods are mounted to the rings, parallel to each other, one along each side of the open portion of the rings to form a continuous slot and to act as a

[13] H. H. Westcott, New 50 KW VHF Superturnstiles, *Broadcast News*, May–June, 1953.

[14] Irl T. Newton, Jr., and H. H. Westcott, The New 12BH High Gain Antenna, *Broadcast News*, March–April, 1954.

[15] Matti Siukola, Predicting Performance of Candelabra Antenna by Mathematical Analysis, *Broadcast News*, October, 1957. R. H. Wright and J. V. Hyde, The Hill-Tower Antenna System, *RCA Engr.*, August–September, 1955.

[16] L. J. Wolf, High Gain and Directional Antennas for Television Broadcasting, *Broadcast News*, vol. 58.

[17] R. W. Masters, A Power-equalizing Network for Antennas, *Proc. IRE*, July, 1949, p. 735.

[18] J. B. Dearing, H. E. Gihring, and R. F. Guy, Multiple Television and Frequency Modulation Transmitting Antenna Installation on the Empire State Building, *Proc. IRE*, March, 1953.

balanced transmission line. Figure 7-33 shows a larger portion of the slotted-ring antenna mounted on a supporting mast. In certain instances, the antenna can be mounted directly on the side of a tower.

Each bay consists of two radiating elements ("half bays") arranged one above the other and fed with a single 3⅛-in.-diameter rigid coaxial transmission line.

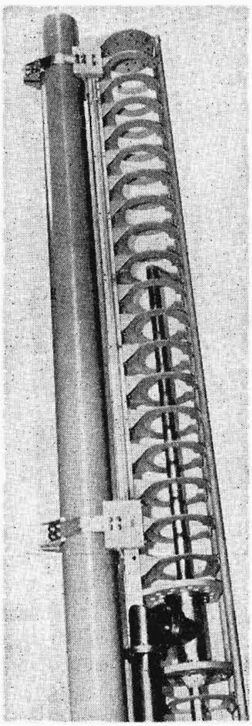


FIG. 7-33. Portion of a slotted-ring-antenna bay.

The antenna is provided with a feeding arrangement of a type which enables each bay to handle high power and allows the entire exposed feeder along with every other active part to be deiced. When necessary, tubular sealed heaters are supplied as a part of the antenna for deicing purposes.

Each bay is approximately 3.4 wavelengths long and has an average power gain of approximately 4. As many as five bays can be stacked one above the other to give additional gain, the gain being proportional to the number of bays used.

When several bays are stacked to give a higher gain, they are joined through the use of a rigid coaxial transmission-line harness into a single feed line for the entire array. This type of feed requires only a single transmission line from the transmitter up the tower to the array.

Null fill-in and/or beam tilt, where required, are achieved through the proper selection of line transformers and transmission-line lengths in the coaxial feed lines between the bays.

The horizontal-radiation pattern of the slotted-ring antenna itself is essentially circular, with slight maxima along a diameter which passes through the slot of the antenna and with slight minima at approximately right angles to this diameter as shown in Fig. 7-34*a*. Since the potential at the point of attachment to a supporting mast is small, masts of adequate size can be used without substantially affecting the operation of the antenna or its horizontal circularity.

Directional horizontal-radiation patterns are achieved by the addition of pattern-shaping members to the basic antenna. Usually, there are two beam-shaping members connected to each alternate active ring in a directional antenna. The rings provided with these members act differently from simple rings in that a substantial portion of the current which normally flows in a ring is directed into the beam-shaping member. The radiation pattern of a directional-antenna bay, then, depends on the configuration of these additional members and on the proportion of modified loops. Figure 7-34*b* shows a typical directional horizontal pattern of a modified slotted-ring antenna.

Theory of Operation.[19] The operation of the slotted-ring antenna can best be understood by considering a balanced transmission line shunted by a number of small loops or rings. It is possible by arranging the separation and cross-sectional area of the rings substantially to increase the phase velocity at which a high-frequency wave is propagated along the transmission line. Figure 7-35*a* shows such a loaded transmission line which has been short-circuited at one of its ends and is fed with an RF source at the other. The standing waves which are set up along the line have an apparent wavelength, λ. When the number of rings along the balanced transmission line is of the order of 12 per free-space wavelength and the diameter of each ring is of the order of 0.14 free-space wavelength, the apparent wavelength will be approximately twice the free-space wavelength.

[19] A. Alford and H. H. Leach, High-gain Antenna Arrays for Television Broadcast Transmission Using a Slotted Ring Antenna, *IRE Conv. Record*, part 7, pp. 87–94, 1956.

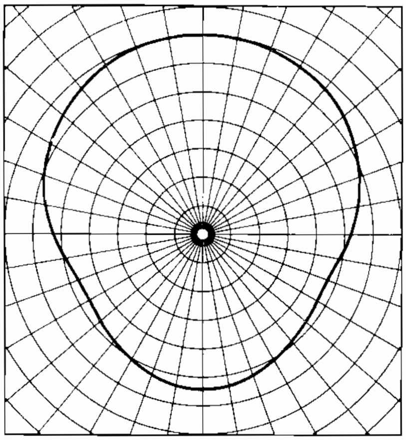


FIG. 7-34*a*. Typical omnidirectional horizontal radiation pattern, relative field.

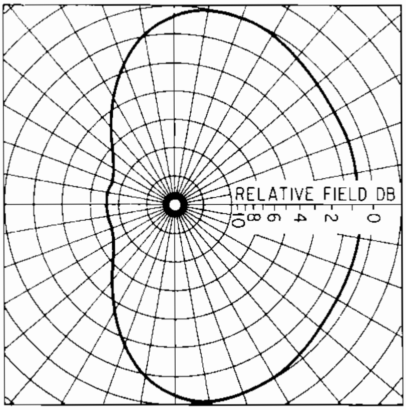


FIG. 7-34*b*. Typical directional horizontal radiation pattern, relative field.

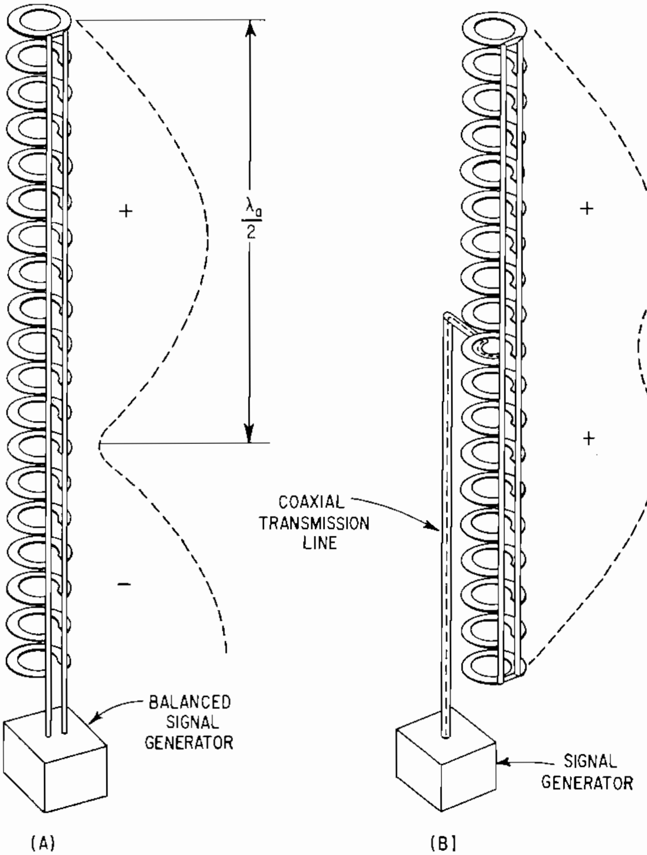


FIG. 7-35*a*. Balanced transmission line loaded with shunt rings.

FIG. 7-35*b*. Unbalanced transmission line loaded with shunt rings.

If this same arrangement is fed at the center through a length of transmission line as shown in Fig. 7-35*b* and short-circuited at both ends, then a wave propagates from the center feed point toward each of the two short circuits. The reflections from these short-circuited ends set up a standing wave, and the difference of potential between the conductors of the balanced transmission line is distributed approximately as shown by the dotted line. The phase of this difference of potential is substantially constant over the entire length of the line.

The potential which exists between the balanced conductors causes circumferential currents to flow in the shunting rings. Since the potential and hence the currents are very nearly cophasal, the over-all behavior of the loaded line is similar to that of an array of closely stacked loops. This fact results in a substantial concentration of the power radiated by the rings in the direction of a plane passing through the halfway point along and perpendicular to the balanced conductors.

Construction. Corrosion-resistant aluminum alloys, both wrought and cast, are the primary materials of construction in the AMCI slotted-ring antenna. Stainless-steel screws and bolts are used throughout the antenna. The total weight of a bay is approximately 300 lb when designed to operate at Channels 7 or 8, with the higher channel bays weighing slightly less.

There are two Teflon seals per bay. The diameter of the inner conductors which pass through these seals is approximately 1¾ in. The outer-conductor diameters are approximately 3 in.

The antenna itself is designed to withstand wind velocities exceeding 200 mph and to present a small surface area to the wind. The antenna can be mounted on a standard mast (designed for a wind loading of 50 psf on projected flat surfaces), on special masts (designed for larger wind loadings), or, in certain instances, on the corner of a tower.

VHF Helical Antenna General Description

The VHF helical antenna is essentially a coil of uniform pitch wound around a usually round mast section. A left-hand and a right-hand helix are used, joined at the center. In some cases a triangular or square tower section is used instead of a round mast. The tower section is partially covered by screens to back up the helix.

In operation, a radio-frequency wave is established which travels between the helix wire and ground "plane" formed by the meet. The wave thus travels circumferentially around the mast, turn after turn. It progresses axially up or down the mast because of the pitch of the helix.

The antenna is designed to radiate in "side-fire" fashion. That is, the beam maximizes at right angles to the helix axis. In order to have successive turns of the helix work together to give additive side-firing fields, each helix turn has a circumferential length equal to an integral number of wavelengths, such as one, two, three, or four. The two-wavelength turn is most commonly used because it yields good structural dimensions.

While the wave travels circumferentially around the helix, it radiates power and becomes attenuated. The attenuation rate depends on the spacing of the helix coil from the mast. A value of attenuation of 3 to 6 db per turn is used, depending on the channel, gain, and bandwidth requirements.

In traveling axially up or down the helix, the radiating wave distributes the radiation over the length of the helix. This results in excitation of a fairly large aperture from a single feed point and so gives a considerable gain per feed. Nominal values of gain per feed are between 3 and 5 rms over a dipole. This makes it possible to simplify the feed harness because of the fewer number of feed points required for high-gain antennas.

The turn-to-turn phase of the radiating traveling wave determines how well the side-fire beam is formed. This phase varies as the frequency changes from its optimum center value. Over a certain frequnecy range, there is a sort of "locked-in" mode over which the beam formed is quite uniform in its main characteristics. Outside this range the beam broadens and gradually breaks up. The frequency range over which a certain sized helix can be used depends on its attenuation rate and number of turns. For example, a helix pair giving a gain of 5 per feed forms a good beam over about 6 to 7 per cent frequency range. For a gain of 3 per feed, this increases naturally to about 10 per cent. The beam-forming bandwidth can be increased further by suitable electrical "loading" of the helix, which alters its phase-velocity vs. frequency relationship.

The radiating traveling wave does give very good VSWR characteristics, because there is very little resonant energy in the helix. The wave energy reflected from the ends of the helices is down about 40 db when it returns to the feed, and so it affects the feed impedance very slightly.

The wave dies down by about 20 db before reaching the end of the helix. This makes it feasible to put a second feed here. Two different signals can then be diplexed directly into the same antenna. The visual normally is fed in the center and the aural at the ends in this "self-diplexing" scheme. Though 20 db of isolation is sufficient operationally, more is needed to prevent a visual ghost. This ghost would result from visual signals going down the aural feed line and reflecting back to be reradiated as a delayed signal. To increase the visual to aural isolation, a visual reflecting cavity is placed on the aural input near the antenna. This increases the visual to aural isolation to about 40 db.

For certain requirements, the helical antenna lends itself to "wrap-around" construction. This is done by assembling the helix around a tower already in existence, using techniques similar to those used for the low-channel helical as described on page 2–257.

In those cases where horizontal directional patterns are desirable, the azimuthal radiation of the helix can be modified. This is usually done by attaching radial or tangential stubs directly to the helix. These stubs are short compared with a wavelength and are nonresonant.

To maintain optimum performance under icing conditions, the helical antennas can be provided with deicing means. The helix itself, being made of copperweld material, is used as the heater. Several hundred amperes of 60-cycle current are caused to flow through the helix from a transformer located at the tower top. A nominal deicing power intensity of about 2 watts per square inch of helix is used for normal conditions. Figure 7-36 shows an aural feed point with deicing connection.

High-channel Helical Antenna, Channels 7 to 13, Specific Description. These antennas are built in a standard series by General Electric. Gains vary from 4 to 25, from one to five bays being used. The physical length is constant (for fixed number of bays) through the channel range, and so the gain varies over the channel.

The mast is made from 24-in.-diameter steel tubing or piping, varying in thickness from ¼ to ¾ in. for different sections.

The helix is made from 0.365-in.-diameter copperweld material. It is supported on insulators made from Steatitic, Teflon, Cymac, or Stycast. A low-loss, low-dielectric-constant material is preferred. Height of the insulators is adjustable by plates under the mounting to accommodate helix-diameter changes needed for on-channel moding. Figure 7-37 shows an antenna during assembly.

Feed systems provide either single- or two-line feed up to three bays and single line only for four and five bays. Space limitation reduces the size of feed lines that can be used if dual feeds are wanted for four- or five-bay antennas. The standard feed harnesses use 3⅛-in. EIA-type line as a minimum. The one-bay antenna may use 6⅛-in. lines to permit full ERP operation from one bay, say with a 100-kw transmitter. The feed lines include a quarter-wave series-isolating capacitor which isolates the 60-cycle deicing current from the remainder of the transmission-line system.

Nominal feed impedance at the helix is about 100 ohms. A quarter wave of 70-ohm line is used to transform this to the 50-ohm EIA standard. An elbow with end-seal mounts through a hole in the mast provides means for attaching and feeding the helix. A close-up of a feed point showing the helix attachment is given in Fig. 7-38. This elbow is 70 ohms and is part of the quarter-wave transformer.

Mechanically, the feed harness is so arranged that pieces of harness can be lowered inside the mast after loosening bolts from outside the mast only. A rope is dropped

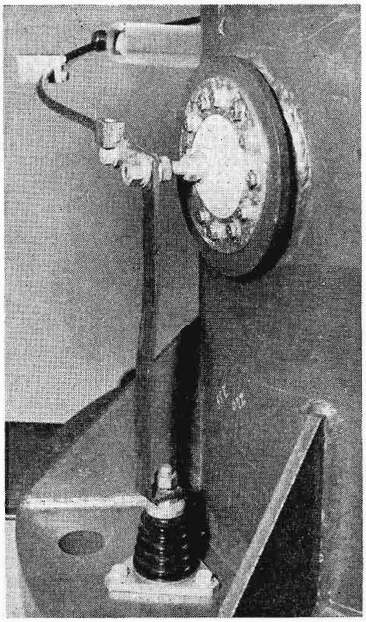


FIG. 7-36. Aural feed point on self-diplexed two-line-feed high-channel helical antenna. The deicing current connection is also shown. It is a quarter-wave long to the bypassing feed-through capacitor, thus not upsetting electrical performance. The small slug on the helix is for fine matching. (*GE photograph.*)

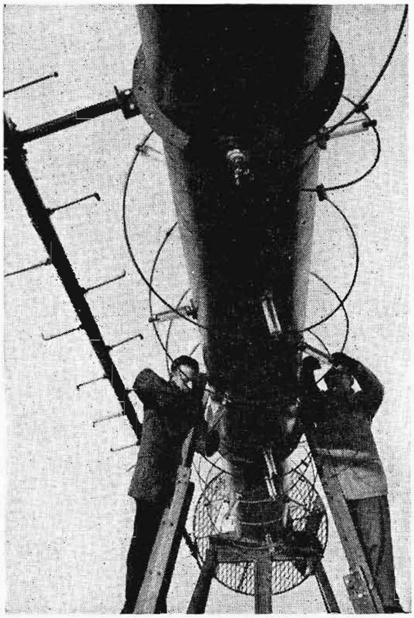


FIG. 7-37. A view of a high-channel helical antenna during assembly. The climbing pole is outrigger-mounted from the antenna mast. The metal "slugs" on the helix near the feed are for fine matching. (*GE photograph.*)

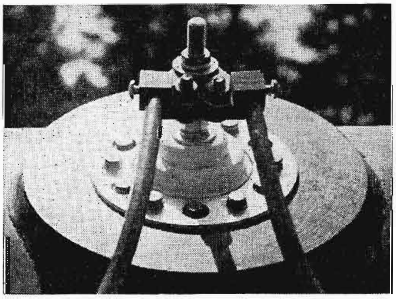


FIG. 7-38. This view shows the end-seal feed mounting in the mast and the helix attachments. Before shipment, the helices are brazed into the attachment blocks and the temporary set screws are removed. (*GE photograph.*)

through the mast from the top and fastened to the elbow, using a handhole in the mast for access.

Low-channel Helical Antenna, Channels 2 to 6, Specific Description.[20] The basic operating principles of the low-channel antenna are identical with those already described. As mentioned earlier, the bandwidth of the helical antenna is controlled mainly by its beam-forming characteristic. To form a fairly constant beam over a

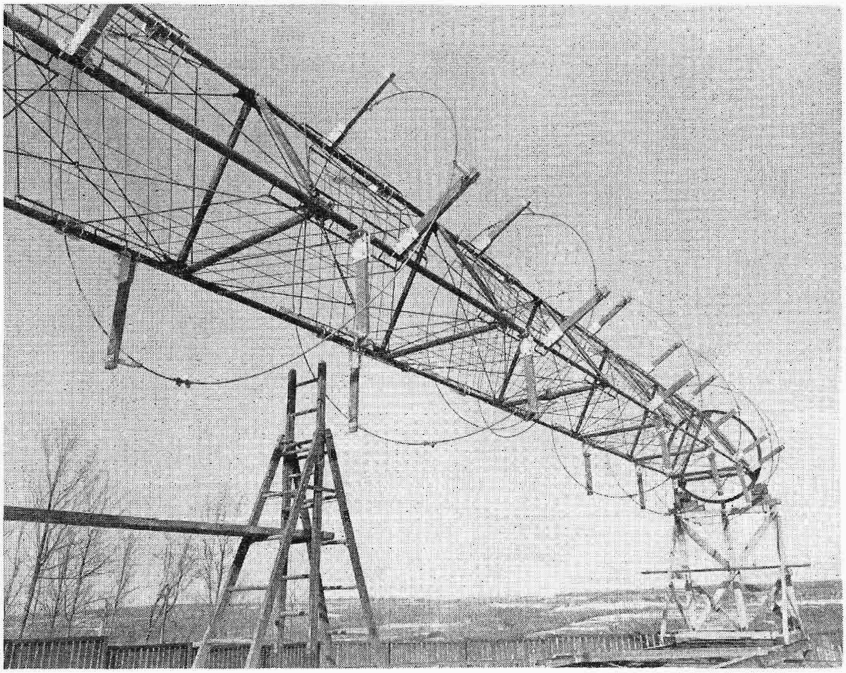


FIG. 7-39. A low-channel helical-antenna prototype in pattern test. Note the open grids mounted on the triangular tower section. The insulating helical supports shown are temporary for the prototype work only. (*GE photograph.*)

wider frequency range, the active aperture must be reduced. Fewer turns with higher attenuation per turn are the basic answer. In addition, further increase in beaming bandwidth can be achieved by electrically "loading" the helix.

Use of a triangular tower section for the mast accomplished some "loading" due to corner discontinuities. Also, a standard tower section for a "mast" is preferable because of the size. Backup screens of open-grid construction are placed under the helix by fastening to the tower section. See Fig. 7-39 for a picture showing a low-channel prototype.

Traveling-wave Antenna

The traveling-wave antenna embodies principles found in the operation of the superturnstile, the slot antenna, and the helix but employs these principles in a manner which results in its being different from any of them.

[20] See also "The TV Helical Antenna Adapted to Structural Tower Shapes" by Ronald E. Fisk, General Electric Company, presented at the 12th NAB Engineering Conference, Los Angeles, Calif., 1958.

In form, the antenna is a coaxial line, with pairs of slots in the outer conductor spaced at intervals of a quarter wavelength throughout its length. Probes at the center of each slot distort the field within the line to place voltages across the slots. These, in turn, drive currents on the periphery, setting up a radiated field. Attenuation of the signal by withdrawal of a portion of the power at each slot reduces it to a very low value at the upper end of the antenna. There, a special pair of slots, designed to match the line, extracts the remaining portion and radiates it.

Figure 7-40 shows the physical shape of the antenna. The signal, entering through

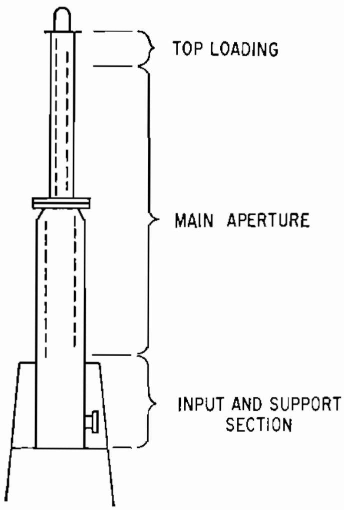


FIG. 7-40. The traveling-wave antenna—external appearance.

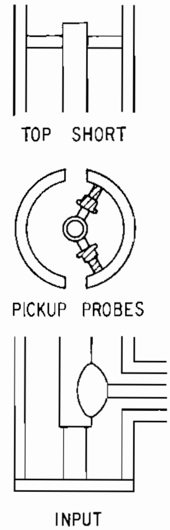


FIG. 7-41. Cross section of traveling-wave antenna at input, aperture, and top.

the input section (normally in the buried portion below the tower top), is progressively attenuated as it passes through the main aperture. The portion reaching the top is radiated from the "top-loading" section.

Figure 7-41 shows cross sections of the antenna in the three main portions. It will be noted that the entire inner connector is supported by the base plate of the antenna and can be removed through this base.

Operation of the antenna can be better understood if the section of the aperture having pairs of slots are recognized as being, in effect, dipoles. Figure 7-42 shows this similarity.

Successive pairs of slots are alternately in one plane and in another at 90° to it, so that the antenna can be simulated by stacked dipoles with a 90° angle between successive layers.

In a given plane, reversal of the direction of feed every half wavelength (by placing the probes on opposite side of the slots), together with the half-wave change in phase of the signal as it passes along the aperture through this distance, results in all the "dipoles" in that plane being fed in phase. The same action takes place in the other plane except that they are fed 90° out of phase with the first plane owing to their 90° displacement along the antenna.

The result is shown in Fig. 7-43.

Each plane of dipoles radiates essentially a figure-eight pattern. Since the planes are fed in quadrature, addition of the patterns results in a circular pattern, as outlined under Azimuthal Patterns. Because of the circular cross section and the lack of obstructing radiators, the resulting horizontal pattern is almost a true circle, varying from circular by only about 0.5 db in a typical case.

As slot spacing is actually 90° only for a specific frequency in the channel, variation in frequency across the channel would be expected to result in a progressive lag or lead in the signal as radiated from successive slots inasmuch as the spacing becomes

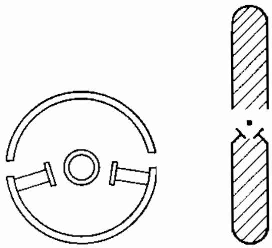


FIG. 7-42. Cross section of traveling-wave antenna at a slot pair level, showing resemblance to a dipole.

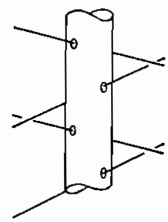


FIG. 7-43. Stack of half-wave dipoles which traveling-wave antenna resembles in operation.

greater than 90° for higher frequencies and less than 90° for lower frequencies. Correction for this effect would obviously be accomplished if, at each slot pair position, another circuit element were added which, with change of frequency, had the opposite effect on the phase.

Such an element is available in the form of a parallel-resonant circuit with resistive loading with its familiar reactance characteristics (Fig. 7-44). The resistive portion is the radiation resistance.

In the region between 1 and 2 (Fig. 7-44), increasing frequency results in a lower inductance (higher capacity) while decreasing frequency yields a more inductive circuit. If this circuit is placed across the transmission line at a slot position, the effect will be to cause the voltage at this position to lead the voltage at the preceding

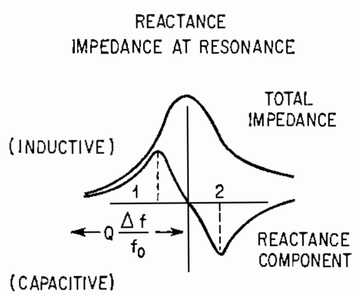


FIG. 7-44. Universal curve (high-Q parallel-resonant circuit).

slot at higher frequencies and to lag it at lower frequencies within the frequency range 1 to 2 (Fig. 7-44).

By adjustment of the values of inductance and capacity the slope of the response curve can be changed until a compensation is obtained over a considerable frequency range for the apparent change in line length between slot pairs due to frequency change.

The above circuit is obtained by shaping the slots to obtain the required value of inductance and capacity, the length of the slot and the shape of the end portions controlling the former and the width of the slot at the center of the latter.

A further control of the phase at each slot is obtained by the insertion between slots of compensating probes. By means of these, the phase can be made progressively more lagging from top to bottom, bringing about a downward tilt of the main beam if desired.

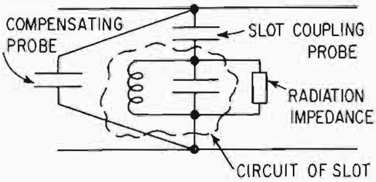


Fig. 7-45. Equivalent circuit of one slot pair section of traveling-wave antenna.

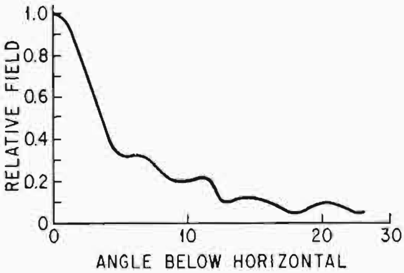


Fig. 7-46. Vertical field pattern of traveling-wave antenna with gain of 12.

Omission of particular slot pairs is a method which has been used to obtain special effects such as reduction of signal at a particular angle in the vertical plane to "protect" areas where radiation is undesirable. Such a situation has arisen where important radio-frequency measurements on equipment being manufactured in a particular location would have been disturbed by the reception of television signals.

This equivalent circuit of each layer is shown in Fig. 7-45.

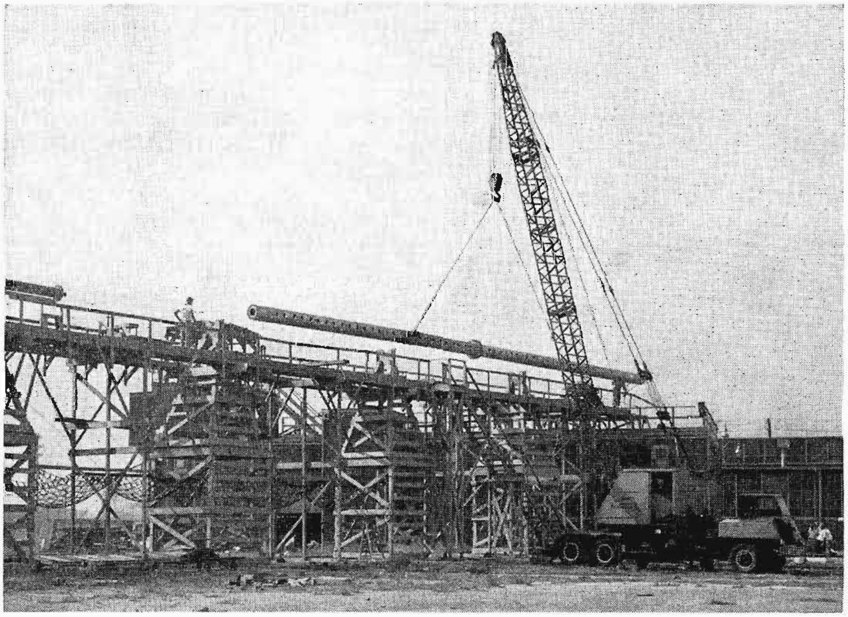


Fig. 7-47. Section of traveling-wave antenna being lifted to high horses for check of attenuation and phase velocity.

The coupling probes are all set at the same depth. As a result, the same percentage of power arriving at the slot location is picked up and radiated at each slot. The amount of power so radiated is therefore decreased exponentially from the bottom to the top of the antenna, giving the effect of a constantly changing power division except for the elimination of slots necessary for the insertion of flanges, and for the change at the top-loading slots the result is a smooth vertical pattern without any nulls. The flanges and top loading cause a small ripple in the pattern, but the effect is slight. Figure 7-46 shows a typical vertical pattern of a traveling-wave antenna with a gain of 12.

Because the slots are a quarter wave apart, giving an impedance-compensating effect similar to that of insulators similarly spaced in a coaxial transmission line, and because the slots are only lightly coupled into the line, there is almost no reflected energy returning to the input of the antenna. The action of the top loading further reduces the chance of energy reflection. As a result the standing-wave ratio at the input is inherently low, and no input-matching transformers are required to broadband the impedance.

As the antenna is primarily a large-size transmission line, the power-handling capacity is very high.

The antenna tubing is of steel, hot-dip galvanized. The inner conductor is copper tubing. Hardware is of stainless steel with the exception of the probes, which are of aluminum treated to resist atmospheric corrosion. The slots are covered with polyethylene covers to keep out rain, snow, and ice.

Figure 7-47 shows a portion of a traveling-wave antenna being lifted to the test platform for a check of the attenuation and phase velocity. This type of high support is used to ensure that no errors are introduced by reflection from the ground. The shape of the slots employed to obtain the electrical compensation referred to above is shown.

UHF Antennas

Need for High Gain. The power gains used for UHF transmitting antennas are higher than those customarily used for VHF, since it is more economical to obtain effective radiated power in this manner. This is true, since the costs of generating power generally trend upward with frequency. Conversely, the cost of obtaining antenna gain is less, since for a given height, gain is related to frequency. For instance, with an antenna 100 ft in height a gain of 6 is obtained at Channel 2. At Channel 30, however, a gain of 46 is obtained for this same height. Gains of this order, however, result in problems in coverage which must be solved. Figure 7-48 shows a vertical pattern of an antenna in which all the radiating elements have the same current and phase. Such an antenna provides a maximum gain for a given height. However, in covering the service area, nulls, or areas of low signal strength, occur periodically from the base of the antenna out to 7.4 miles, which seriously affects the coverage.

Null Filling. To overcome this problem a number of methods have been used. Earlier types of slotted-cylinder antennas used power division in which more power per layer was radiated from the lower elements than the upper. This resulted in a certain degree of null fill as shown in Fig. 7-58 (TFU-24DL). The power division helps fill the first null closest to the main beam, but to fill the second null effectively requires tilting the main beam below the horizon. Since this gives rise to a secondary lobe above the horizon, the gain is reduced depending on the degree of tilt.

Eliminating Nulls. Another solution resulting in a smoother pattern can be obtained by varying the current distribution of each radiating element of the whole antenna. For instance, if successive radiators, spaced less than one-half wavelength, have current ratios of 1 to 4 to 6 to 4 to 1 as shown in Fig. 7-49, the vertical pattern resulting from such a distribution will be as shown in Fig. 7-50.[21]

Beam Tilt. Since UHF antennas have a relatively narrow main beam as compared with VHF, being of the order of 1.5 to 2.5° wide across the half-power (or 0.707-

[21] Kraus, "Antennas," Sec. 4–7, p. 94.

voltage) points, it is desirable to tilt the beam downward to aim at the horizon or even lower when there is insufficient effective radiated power to reach the horizon. For an antenna 1,000 ft above terrain the beam should be depressed 0.5° to aim at the horizon.

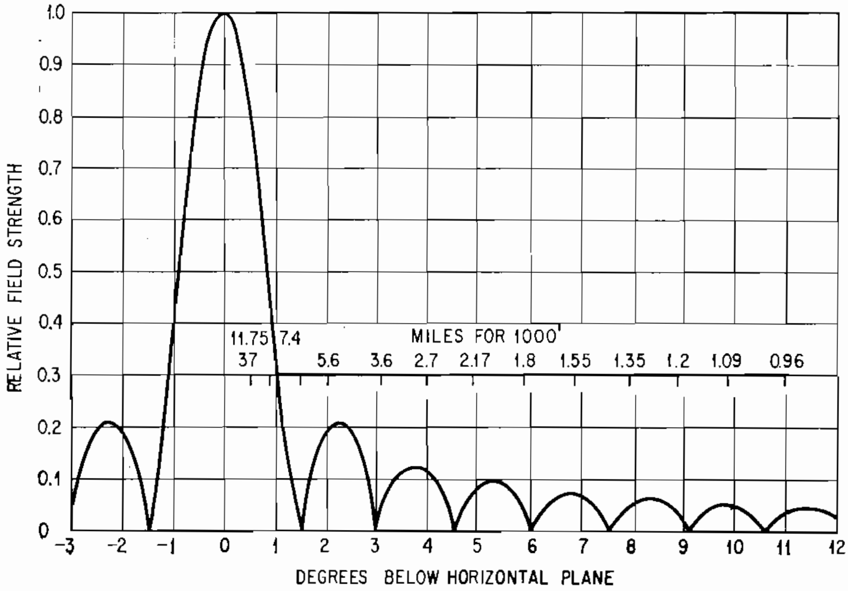


FIG. 7-48. Vertical pattern of an antenna having uniform distribution for an aperture of 38 wavelengths with sources in phase.

It is possible to tilt the beam and retain the smooth vertical pattern of Fig. 7-50 by progressively changing the phase of each radiating element—advancing the phase in the upper half of the antenna and retarding it in the lower half.

Reducing Radiation above the Horizon. In Fig. 7-50 as much energy is radiated above the horizon as below, assuming that the maiu beam is aimed at the horizon.

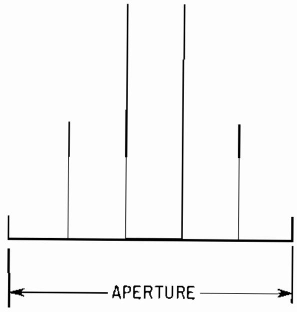


FIG. 7-49. Binominal distribution.

This means that only one-half of the energy is effectively used. It is possible by properly choosing the phase of each radiating element greatly to reduce radiation above the horizon and thus make the energy available for use below the horizon, thus increasing the gain for a given height of antenna.

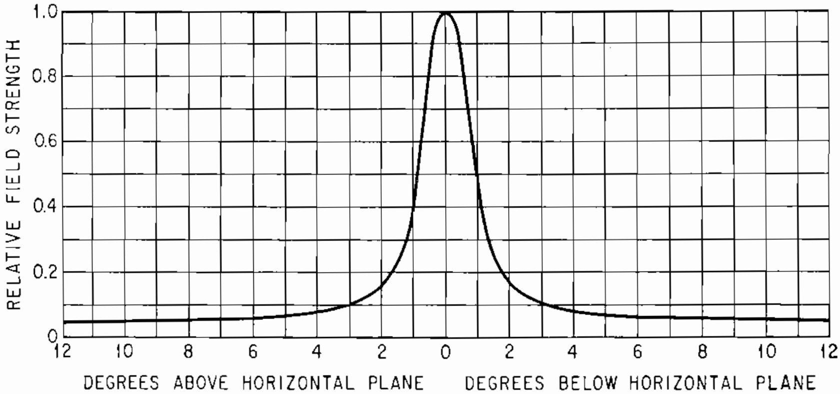


FIG. 7-50. Vertical pattern resulting from binominal distribution.

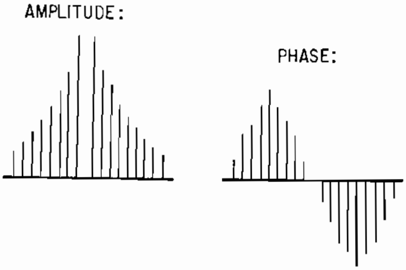
Pattern Synthesis. In order to accomplish the objectives discussed above, namely:

1. The elimination of nulls
2. Beam tilt by progressive phasing
3. Reducing energy radiated above the horizon

a method of synthesizing the desired pattern is possible.[22]

The vertical pattern depends entirely on the current amplitude and phase of each radiating element. With the use of an amplitude and phase distribution such as shown in Fig. 7-51, a pattern as shown in Fig. 7-52 can be achieved. The method is quite flexible, and a great variety of patterns for various needs can be synthesized.

FIG. 7-51. Amplitude and phase distribution required to achieve a smooth pattern with minimum radiation above the horizon.



Slotted-cylinder Type

These antennas consist of a self-supporting galvanized-steel pole using slots as radiating elements.[23]

Energy is coupled to the slot either inductively or capacitatively from the feed system inside the cylinder so that a voltage appears across the slot. This causes currents to travel around the cylinder at right angles to the long slot dimension, which generates an RF field which is horizontally polarized. The amount of cross polarization is quite small with this type of antenna.

If the path around the cylinder is of such length that the current attenuates ap-

[22] P. M. Woodward, A Method of Calculating the Field over a Plane Aperture Required to Produce a Given Polar Diagram, *Proc. Inst. Elec. Engrs.*, London, 1946.

[23] O. O. Fiet, A New UHF Television Antenna TFU-24B, *Broadcast News*, March–April, 1952. Kraus, "Antennas," chap. 13. Jordan, "Electromagnetic Waves and Radiating Systems," Sec. 15.11. See under Slot Antenna in this Part.

preciably owing to radiation, the circularity is affected. Advantage is taken of this fact in designing directional antennas. To maintain the circularity required, a number of slots similarly fed are used at the same level.

The feed system is of the standing-wave type as shown in Fig. 7-53. Each coupling loop extracts sufficient energy so that the VSWR reaches a low value at the feed point. It should be noted that the phase steps in the region of high VSWR, which exists over most of the antennas, are well defined. This is important in achieving pattern and impedance bandwidth.

Mechanical Description. The cylinders vary in diameter from 3 in. for an antenna which has a single slot and a gain of 6 to 16 in. in diameter for an antenna which has

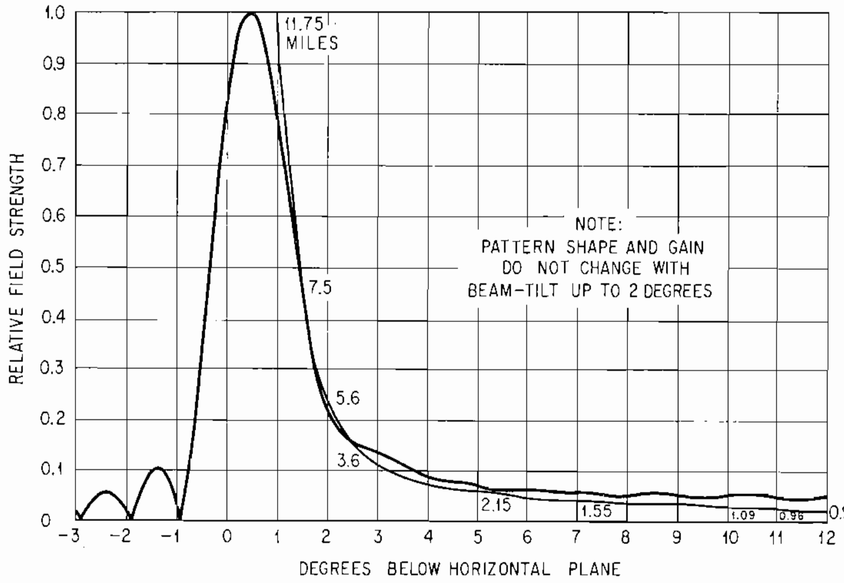


FIG. 7-52. Pattern of an antenna with a nominal gain of 50 using pattern synthesis.

four slots and a gain of 46 and is 134 ft in length at Channel 14. The larger cylinders are constructed of hot-dipped galvanized steel tubing. Radiation results entirely from currents traveling on the surface of the cylinder. The diameter of the cylinder, except in special cases, is determined by structural requirements only.

The lower half of the feed system is a single coaxial copper transmission line with an end seal near the center of the antenna. The upper half consists of the outer conductor only. The feed system appears as a continuous copper tube of constant diameter with an end seal at the center. Energy is picked up from this feed system by coupling loops or cylindrical couplers described below, there being no actual contact with the feed system. The feed system can be removed by sliding it out of either end of the antenna. Nothing inside the antenna needs to be disconnected.

Deicing is accomplished by long electric strip heaters placed adjacent to the slots.

Ultragain UHF Slotted-cylinder Antenna. A specific design is an antenna having a gain of 46 for Channels 14 to 30 shown in Fig. 7-54. The antenna is ready for a pattern test which is made on the turntable shown in the background. Figure 7-55 shows the correlation between the calculated and measured pattern. This antenna has a minimum 10 per cent fill for areas where good coverage in the first few miles is required for city locations.

A unique method of coupling is used in this antenna consisting of cylinders of varying diameters placed adjacent to the slot.

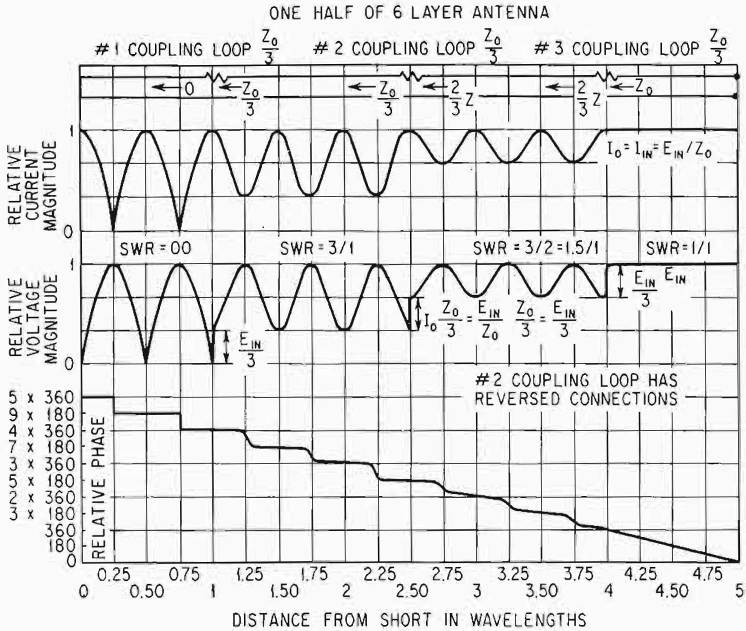


FIG. 7-53. Simplified illustration of current- and voltage-distribution principle used in the standing-wave feed system in the slotted-cylinder type.

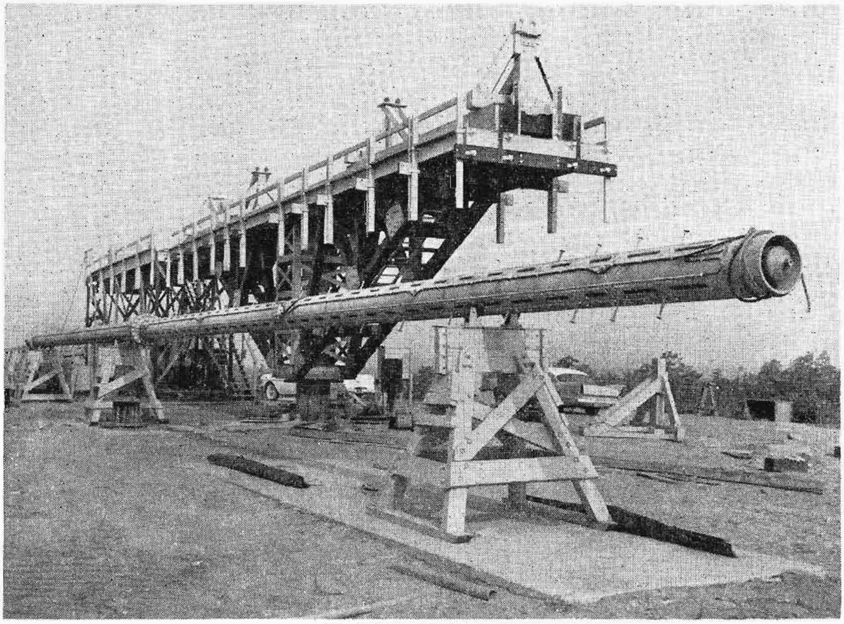


FIG. 7-54. UHF antenna of the slotted-cylinder type with a gain of 46 ready for pattern tests.

The cylinders are shown in Fig. 7-56, and their relation to the slot in Fig. 7-57. They are capable of handling high power and also make achieving the necessary bandwidth possible because a desirable loading can be chosen independent of the illumination.

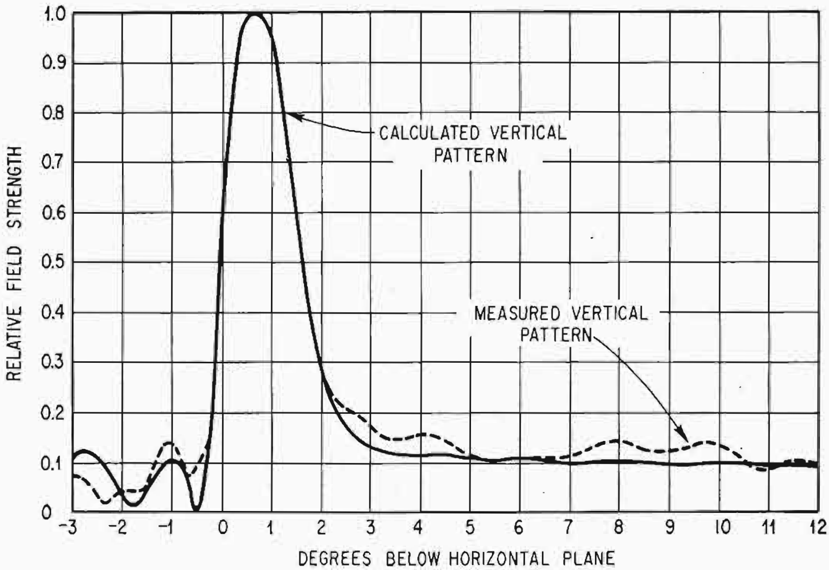


Fig. 7-55. Calculated and measured performance of an antenna with a gain of 46 having a 10 per cent fill.

Medium-gain UHF Slotted-cylinder Antenna. The same coupling means and the method of synthesizing the pattern described above can be applied to lower gain antennas. Figure 7-58 shows the vertical pattern of an antenna with a nominal gain

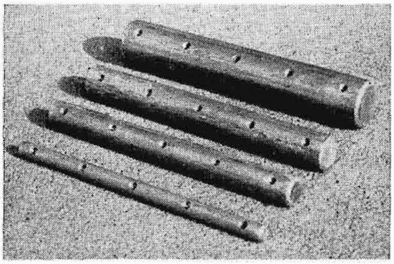


Fig. 7-56. Coupling elements used in slotted-cylinder antennas which have replaced coupling loops used in earlier types.

of 25 and a power rating of 60 kw. The pattern of an earlier type of antenna using loop coupling is shown in comparison.

Increasing ERP by Means of High Gain While Maintaining Local Coverage. In some cases it is desirable to have the local coverage of a lower gain antenna and the

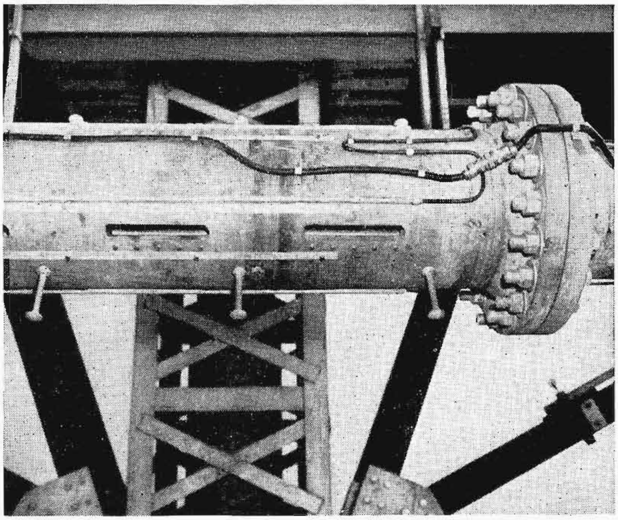


FIG. 7-57. Coupling elements shown in relation to the slot. Sleet melters are shown adjacent to the slot. The beacon cable is also shown.

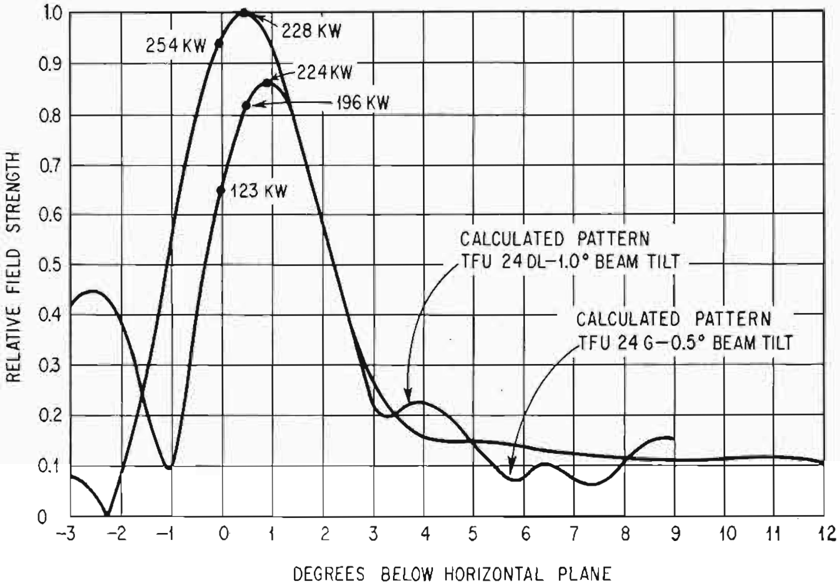


FIG. 7-58. Comparison of vertical patterns of a later and earlier type of low-gain antenna. Pattern synthesis and cylindrical coupling elements are used on the TFU-G type.

effective radiated power of a higher gain antenna. A closer approach to a good compromise is possible by the use of pattern synthesis as shown in Fig. 7-59.

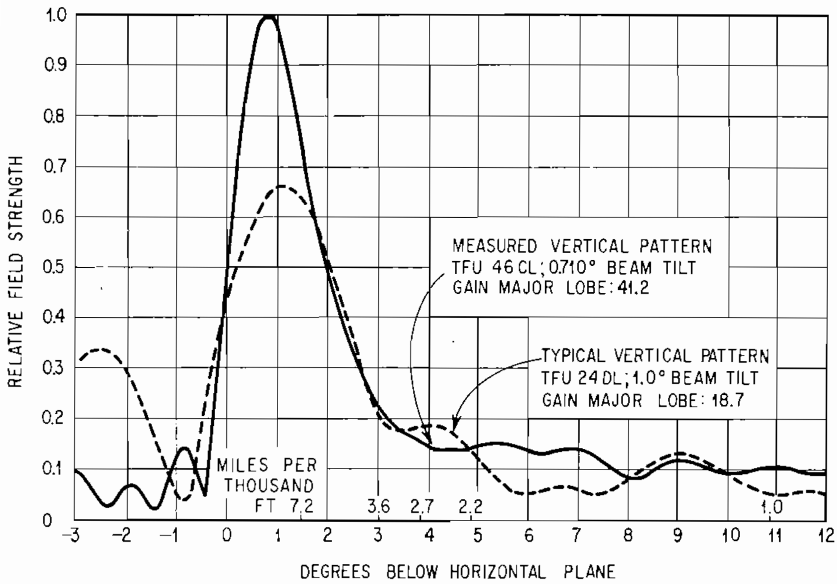


FIG. 7-59. Vertical patterns which can be synthesized for special conditions such as providing the same local coverage with a higher gain antenna as previously obtained with a lower gain antenna.

UHF Helical, General Description [24]

The basic operating principle of the UHF helical antenna is as already described under Helical Antennas. The UHF antenna differs from the VHF antenna primarily in its method of feed. The helix is made from 0.247-in.-diameter copperweld.

At UHF, the per cent bandwidth becomes small, and it is feasible to end-feed the vertical array at least up to gains of 25. If matched condition is maintained along the feed as power drops off at the different bays, the beam will tilt with frequency an amount 57.3 $\Delta F/f_0$ degrees, where f_0 is the mid-frequency and ΔF is the change in frequency relative to f_0. With a gain of 25, a half-power beamwidth of about $2\frac{1}{4}°$ is obtained and a $\pm\frac{1}{4}°$ tilt causes no difficulty.

UHF Helical Antenna, One to Five Bays. The basic UHF antenna bay has a gain of 5. Its length is varied with channel, so that its gain is constant. These bays are stacked together end to end, up to five bays.

Each bay is like a coaxial of about 90 ohms Z_0, with a capacitive feed probe coupling out power to the helix.[25] The top bay couples out all the power remaining. Impedance match is maintained throughout the feed for optimum impedance bandwidth.

Phasing of the bays relative to one another is done by relative rotation of the bays. (Because the wave travels circumferentially around, the phase varies with azimuth.)

[24] *Electronics*, August, 1951, pp. 107–109.

[25] Additional information on the feed may be found on p. 130 of Convention Record of the IRE, 1954, part 1, Antennas and Propagation, as part of paper "A Comparison of Antenna Problems at UHF and VHF-TV" by Lloyd O. Krause, General Electric Company.

Swivel flanges are used to fasten the sections together to make this rotation easy to perform. Rotation of the upper one or two bays can even be done after erection for slight modification of pattern contouring if desired.[26] Figure 7-60 shows a five-bay UHF helical antenna.

UHF Helical Antenna, 10-bay.[27] This antenna is made by stacking two five-bay antennas one above the other. A structural adapter is used to mount the top antenna above the bottom one. These antennas have half-power beams about 1° wide, and

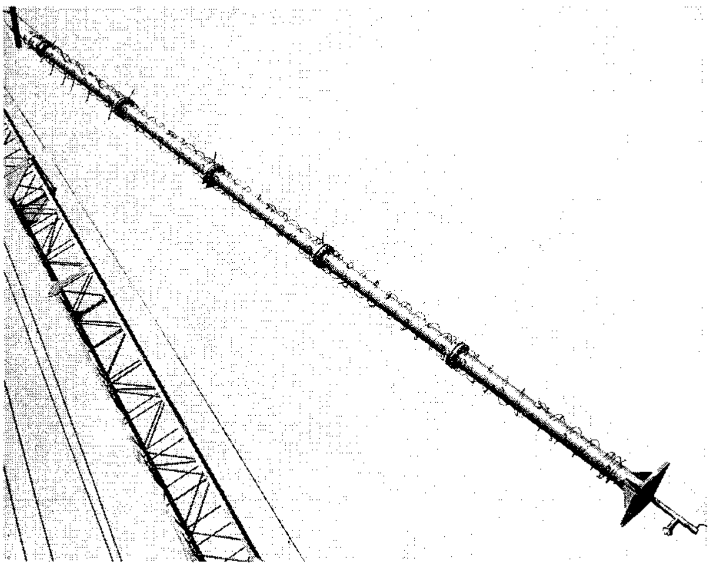


FIG. 7-60. This is a complete five-bay UHF helical antenna. Note the five feed points, one at center of each bay. The input adapter is mounted at the bottom for connection to standard 50-ohm EIA line. The projecting "spikes" are climbing steps. (*GE photograph.*)

structural rigidity becomes important. For this reason, the center of the antenna is guyed to outriggers at the tower top.

To ensure proper coverage, the beams from these antennas are usually carefully contoured and extensive pattern measurements are made during manufacturing test. A view of such an antenna in position for pattern test is shown in Fig. 7-61.

The feed for the upper five-bay antenna runs along the lower five bays and connects to a feed adapter mounted in the structural adapter. See Fig. 7-62 for a closer view of this arrangement.

Because of the special nature of these antennas, a table of standard characteristics is not warranted.

[26] Simple contouring of patterns is discussed in a paper "Contouring TV Antenna Patterns" by L. O. Krause, Tele-Tech & Electronic Industries, April, 1954.

[27] Description of a particular 10-bay antenna may be found in the paper A Simplified 5 Megawatt Antenna for the UHF Broadcaster by R. E. Fisk, *IRE Trans. on BTS*, PGBTS-9, December, 1957, pp. 46–51.

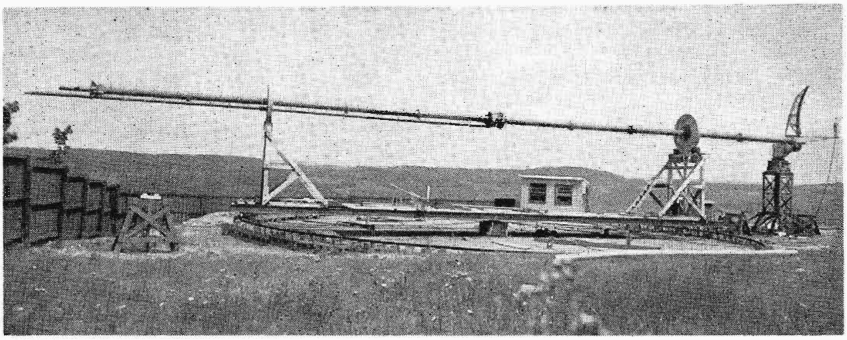


FIG. 7-61. A view of a complete 10-bay UHF helical antenna in position for pattern test. The feed line to the upper five-bay antenna is readily visible. The large rollers are made from wood and nylon for easy antenna rotation for taking horizontal patterns. (*GE photograph.*)

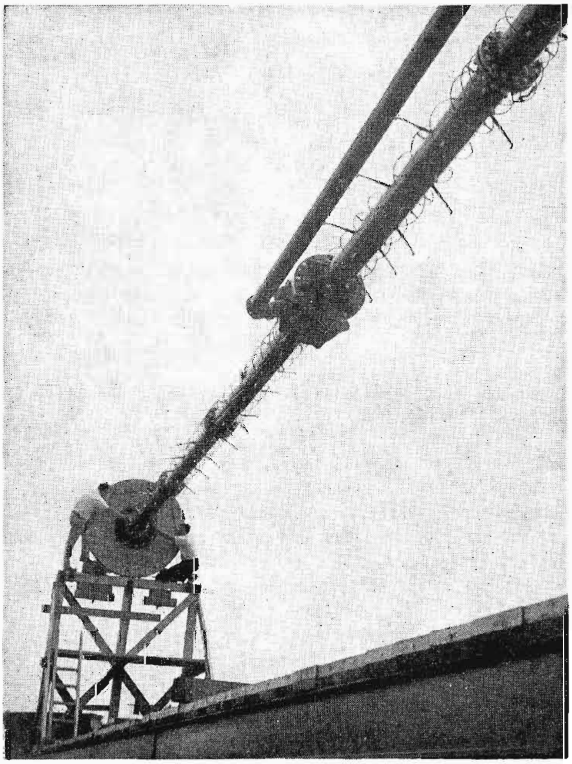


FIG. 7-62. A closer view of a one-bay UHF helical antenna, showing the feed and mounting arrangement for the upper five-bay antenna. (*GE photograph.*)

ANTENNA TESTS

Before Shipment

Antennas are tested to meet the necessary requirements for impedance and patterns. This is usually done for all prototype antennas but not necessarily on the repeat antennas of the same type before shipment.

Custom antennas are usually impedance-tested before shipment, and in most cases patterns are taken unless sufficient background exists to make this unnecessary.

Impedance is tested by taking VSWR measurements over the channel at the input of the antenna. In order to facilitate work on the antenna, the antenna is placed in a horizontal position parallel to the ground. Since objects in the field of the antenna, including the earth, affect the impedance, it is necessary to measure the antenna only when such objects are two to three wavelengths removed in order to reduce this effect to a negligible value. In order to reduce the error when the two- to three-wavelength height is impractical and to reach design ceuter as closely as possible, space cloth can be used below the antenna, which is a material having the impedance of space, or 377 ohms. When the cloth is backed by a metal surface or screen removed one-quarter of a wavelength, energy at that wavelength is absorbed, so that the reflected euergy from the earth does uot affect the impedance.

Measurements are usually made with a slotted line which indicates the voltage standing-wave ratio (VSWR). If the impedance of the slotted line is the same as that intended for the antenna, then a unity standing-wave ratio indicates a match. The resistance and reactance component of the impedance can be obtained with a slotted line when a reference point, called the antenna point, is taken at each frequeucy at which the standiug-wave ratio is to be measured by placing a short circuit across the transmission line that is to be connected to the antenna. This antenna point is a voltage node that falls on the slotted line some multiple of a half wavelength from the short-circuited transmission line.

After the short is removed and the input system is connected to the antenna, the standing-wave-ratio measurements are made. Voltage nodes, called E-min points, are obtained by moving a probe box along the slotted line in the same manner the antenna points were obtained. The slotted line is 12 ft long aud therefore provides enough length to obtain E-min points for the lower-band as well as the medium- and high-band channels. The difference between the antenna point A and E-min divided by the wavelength at each frequency gives the rotation on the Smith chart at a radius of the standing-wave ratio obtained at that frequency. These points A-P-E-min/wavelength, are then plotted on the Smith chart, (1) toward the load and (+) toward the generator, giving an impedance plot of the antenna system at each frequency under consideration.

For superturnstile antennas these measurements are made on both the north-south and east-west systems and all effort possible is made to make the one system identical with the other at the best standing-wave ratio obtainable. Individual radiator adjustments can be made to help improve the input impedance by varying the length or width, or both, of the slot between the radiator and pole.

Pattern Tests

The object of a pattern test is twofold. One of the objectives is to determine the gain as compared with a dipole for which perhaps a substitution method could be used. The other objective, however, is to determine the amount of radiation at all vertical and horizontal angles which have an influence on the coverage. Both objectives can be accomplished by taking patterns as described under Gain, since the gains can be determined by integrating all the power flow through an imaginary sphere.

To pattern-test the antenna it can be placed upon 25-ft-high wooden turntable which has a speed-controlled motor drive.[28] Figure 7-61 shows such a turntable.

[28] The RCA Test Facilities for TV Antennas, *Broadcast News*, October, 1958.

From the reciprocity theorem it is possible to use the antenna as a receiving antenna as well as a transmitting antenna and obtain the same resulting pattern. This is done for the sake of convenience, since it permits the pattern recorder and the antenna under test to be located at the same point, thus allowing quick analysis of the results. The transmitting dipole, remotely controlled to turn either vertical or horizontal, is placed some distance away. To obtain the required patterns, the transmitting dipole is placed in a vertical position, since the antenna under test is in the horizontal position of the turntable. In this manner, the exact radiating and receiving positions of both antennas are simulated as if the antenna being tested was actually standing vertical and was radiating an electric field which the receiving dipole would have received in its normal horizontal position. The signal in the antenna under test is amplified in a receiver, and the pattern is drawn out on a recorder. A voltage regulator is inserted between the recording instruments and the supply line to avoid line-voltage fluctuations. From the recorded patterns, the actual coverage can be determined as well as the gain. The gain [29] is determined by integrating $E^2 \sin \theta$ over the entire sphere, which is simulated by eight or more equally spaced longitudinal lines, which are the vertical patterns, and one latitudinal line, which is the azimuthal pattern.

After Shipment, before Erection

After the antenna is erected, the difficulties of working on it are greatly compounded. Since few engineers climb, the work must be done entirely by riggers, who do not have the background to do electrical testing. Furthermore, the time during which work can be performed on the antenna is very limited, owing to both scheduled operation and the weather, which frequently prevents work or even climbing. Hence, it is extremely important that thorough tests be made on the ground before erection. Both electrical and mechanical tests should be made.

A thorough mechanical inspection should be made to see that the required components are in their proper places and securely fastened using the specified fastening materials. The pressurized portions should be pressure-tested for a long enough period to be certain that there are no slow leaks. A loss of over 2 lb in 24 hr should be investigated. The fit of major mechanical assemblies should be checked on the ground, since any discrepancies during the rigging operation can become major problems. Such fits include field joints between portions of the antenna and the fit of the pole into the pole socket or pedestal.

Electrically, resistance measurements should be made, when applicable, to assure proper electrical contact at all points. End seals and insulators should be checked with high voltage or with a megger if the antenna requires this test. The most important electrical test is the impedance test or VSWR vs. frequency across the channel. Continuous readings or frequent readings taken across the channel are advisable. This information is extremely difficult to obtain after the antenna has been erected. Since VHF antennas are usually less than two to three wavelengths above the ground, the impedance may not conform to the required values. If any doubts exist, the antenna can be picked up and suspended above the ground at a greater height in order to obtain a more accurate measurement. For some types of antennas it is desirable to recheck a few points after the antenna has been hoisted to a vertical position just prior to erection. This will assure that nothing has radically changed when the normal strains are imposed on the components. All auxiliaries should also be tested. Full power should be supplied to the sleet melters to see that they operate, and the beacon lighting should be checked also.

[29] Pattern Measurements of RCA UHF TV Antennas, *Broadcast News*, vol. 82, February, 1955.

After Erection

Over-all Test

After the complete antenna system is installed, it should be checked. New RF and d-c pulse techniques are currently being evaluated which will be more discerning than previous VSWR measurements. The antenna system should then be connected to the line, and over-all measurements taken.

Reflectometer Test

In order to protect antenna and line components properly it is mandatory that a reflectometer be used on both visual and aural transmitters to interrupt power when the VSWR exceeds a predetermined value. If an arc occurs in the antenna system, it usually loads the transmitter so that meter readings may fail to give a warning resulting in major damage to the antenna system.

Hence, before application of power to the antenna system the reflectometers shonld be checked for proper operation.

INSTALLATION

Advance Planning

The instruction book for a particular antenna usually contains considerable useful information which should be carefully read and followed. There are a number of items, however, common to most antennas which will be discussed.

Preinstallation Procedure

Usually it is advisable to have the manufacturer's serviceman take care of assembly supervision and testing. Some detailed procedure is outlined below.

Antenna Mounting Trestles

Most antennas are impedance-tested on the ground before erection. This is a wise precaution, since any corrective work, if required, is extremely difficult to accomplish once the antenna is at the tower top. The impedance of the antenna is affected by the ground, and trestles are required to obtain adequate clearance. Usually the furnishing of the trestles is the responsibility of the station, although the design is furnished by the manufacturer. They should be on hand when the antenna arrives located on reasonably level ground close enough to the base of the tower so that the antenna can be hoisted directly but far enough away so that assembly work can be done on the antenna without danger of falling objects from the tower while the riggers are working on it. The antenna should be placed so that the tower is not in the radiated field of the antenna, which would affect the impedance during the ground test. This will vary with the type of antenna and the frequency, and the manufacturer's recommendation should be obtained.

Precautions during Unpacking and Assembly

Antennas are usually heavy and appear to be quite rugged. Riggers used to handling heavy, rugged components often overestimate the ruggedness of the antenna, since many of the components can be damaged by rough handling.

If lifting lugs are not provided, the usual practice is to use cable wrapped around the mast with a 2 by 4 "corset" to protect feed lines, slot covers, or other components mounted on the pole. Special oak 2 by 4 lumber should be used for this purpose, since regular lumber crushes, causing damage to components.

Long poles can be given a "set" or internal components damaged if the pole is not properly supported over its entire length when it is lifted from a horizontal position. Strains can be set up under this condition which exceed the maximum wind-load conditions.

To ensure proper handling, a qualified rigger who has a reputation for making successful antenna installations is desirable. Some manufacturers will, if the customer desires, provide a "package" for the tower, line, antenna, and all installation work. This avoids split responsibilities and has many other advantages.

Checking Shipment

It is a wise precaution to check the shipment in detail against packing lists and see that no damage has occurred during shipment. The per-diem rate for a crew of riggers is costly, and any delays due to missing or damaged parts will prove expensive. If there is any damage or shortage, the shipper should be notified immediately.

Pressurized Equipment

Equipment that is normally pressurized should be either stored in a dry place or kept under pressure during storage. The latter will also establish whether any leaks have resulted from shipment.

Assembly

Usually the manufacturer furnishes detailed instruction for the assembly which should be carefully followed.

Special tools are sometime furnished or called for in certain operations which should be used.

Since the antenna is primarily a piece of electrical equipment, cleanliness at points of electrical contact is mandatory.

Electrolysis can occur if proper hardware specified is not used.

Forcing parts into place will usually result in future difficulties. The reason should be investigated.

All hardware should be tight and secure.

If anything does not appear to be correct, consult the manufacturer rather than take a chance.

If any field welding is required, certified welders should be used, since failure could result in loss of human life.

Tests before Erection

It is extremely important that certain tests both mechanical and electrical be performed before the antenna is erected, since the difficulties of working on it after erection are greatly compounded. These tests are described under After Shipment, before Erection.

Erection

The erection procedure should be left in the hands of a qualified rigger. It is highly desirable to erect the antenna in one piece when this is feasible. If not, the rigger must be thoroughly instructed in the assembly procedure. The orientation of the antenna should be carefully established and well marked so that there is no misunderstanding.

In some antennas when transmission lines pass through the top plate of the tower, orientation is doubly important.

Vertical Alignment

For a buried-pole or pedestal-type mounting, vertical alignment is relatively simple. For flange mounting, shims should be used. Vertical alignment is best checked with transits from several directions. Allowance must be made for wind deflection. Accurate vertical alignment is especially important at UHF, where beamwidths are much narrower owing to the use of higher gain antennas.

Tests before Application of Power

These tests are important to ensure that the over-all requirements are met and also to be certain that the system is ready to receive power. Much damage can be done if there are loose or open connections or if the reflectometer circuits in the transmitter are not properly adjusted.

MAINTENANCE

Daily Operation

A drop in gas pressure (in excess of 2 lb in 24 hr), an increase in VSWR as indicated by the reflectometer, or the appearance of an echo on the monitor indicates an unusual condition in the antenna system.

Gas leaks can usually be located by sectionalizing parts of the system. An increase in VSWR may denote icing or a change or failure of some part of the system. Power should be reduced when the VSWR rises, since the power-handling capability is inversely proportional to the standing-wave ratio.

The appearance of an echo is a symptom of some change in the system which should be investigated. New pulse techniques will make the location of faults much simpler.

Weekly

In superturnstile antennas it is advisable to take resistance readings between the inner and outer conductor for each side of the line. Any significant change from the initial readings should be investigated.

Semiannually

A qualified rigger who is thoroughly familiar with all the aspects of the line and antenna should inspect the system. He should inspect for signs of corrosion, loose clamps or hardware, condition of slot covers, need for paint, physical damage, etc., as the particular antenna requires.

SAFETY IN WORKING NEAR RF FIELDS

It is always necessary to have the power off when working on or near the antenna. At times, however, it is necessary to go through or work near to the field of an emergency antenna located on the same tower.

Frequencies under 1,000 Mc can cause deep heating of which the individual may not be aware. If the field is too intense, the body may not be able to dissipate the excess heat. Body temperatures under certain conditions may go up to 106° with heat exhaustion, heat stroke, possible collapse, or destruction of body cells. The blood circulation permits adequate cooling at 0.01 watt/sq cm. The U.S. Navy in areas such as radar rooms where people are exposed for fairly long periods tries to keep fields below 0.01 watt/sq cm. Complete knowledge does not as yet exist on this subject, but the following data have been reported in papers.

0.01 watt/sq cm = 60 volts/m is considered safe for continuous day-to-day exposure as in a radar room aboard an aircraft carrier for instance.

0.1 watt/sq cm = 190 volts/m is considered safe for limited exposures. This figure has been used when engineers were exposed during a test of an antenna lasting a number of hours.

1.0 watt/sq cm = 600 volts/m according to one paper will cause brain damage at UHF frequencies in 45 min.

For a given effective radiated power in kilowatts for free-space propagation these fields will occur at the following distance in feet:

0.01 watt/sq cm at $12.1\sqrt{P \text{ kw}}$ ft
0.1 watt/sq cm at $3.82\sqrt{P \text{ kw}}$ ft
1.0 watt/sq cm at $1.21\sqrt{P \text{ kw}}$ ft

In areas where the exact power or field configuration is not known, a simple dipole can be built with a ¼-watt unmounted neon bulb (no base) connected across the open center of the dipole. For 0.1 watt/sq cm, 47 volts will exist across the center of the dipole. The neon bulb generally requires 85 volts to ignite and will stay lit as it is gradually removed from the field down to 50 or 60 volts. Hence, the area in which it just extinguishes will correspond approximately to 0.1 watt/sq cm.

Part 8

THE MEASUREMENT OF FM AND TV FIELD STRENGTHS (54–890 MC)

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INTRODUCTION

The coverage of a broadcasting station and the technical quality of the service provided are determined by the received signal and field strengths. Presently available methods of estimating field strengths within the service ranges of FM and television stations are only approximate, and even the best methods of calculating field strengths often fail to take into account variations due to important local conditions. For operating stations the best determination of station coverage is provided by properly made field-strength measurements.

This part describes equipment and techniques for measuring field strengths over the frequency ranges employed for FM and television broadcasting. These services are assigned to several bands between 54 and 890 Mc, as shown in Table 8-1.

Table 8-1. Frequencies Employed for FM and Television Broadcasting

Service	*Frequencies, Mc*	*Channel Nos.*	*Channel Bandwidth*
TV	54–72	2–4	6 Mc
TV	76–88	5–6	6 Mc
FM	88–108	201–300	200 kc
TV	174–216	7–13	6 Mc
TV	470–890	14–83	6 Mc

The quality of service is related to the field strength by considerations of receiver sensitivity and noise figure, receiving antenna gain and transmission-line loss, and tolerable signal-to-noise ratios. The required fields vary with the class of service and frequency assignment. Interfering signals from other transmitters on the same or adjacent channels may limit service to higher values of field strength. Table 8-2 lists values of median field strength required for various grades of FM and television service in the absence of interfering signals, as established by the Federal Communications Commission's Technical Standards.[1,*] There are also included revised estimates of the

[*] Superscript numbers refer to References at end of Part 8.

Table 8-2. Median Field Strengths Required for Various Grades of Service in the Absence of Interfering Signals

FM Broadcasting (All Channels)

Grade of service	μv/m	dbu *
Principal city	5,000	74
Urban	1,000	60
Rural	50	37

Television Broadcasting

(FCC Technical Standards)

Grade of service	Ch. 2–6		Ch. 7–13		Ch. 14–83	
	μv/m	dbu	μv/m	dbu	μv/m	dbu
Principal city	5,000	74	7,000	77	10,000	80
Grade A	2,500	68	3,500	71	5,000	74
Grade B	225	47	630	56	1,600	64

(Based on TASO Data)

Primary	250	48	1,400	63	7,500	75
Secondary	50	34	200	46	630	56
Fringe	20	26	55	35	180	45

* This abbreviation was coined by the FCC for television service and signifies the field strength in decibels above 1 μv/m. 0 dbu = 1 μv/m.

fields required in the television bands to provide acceptable grades of service based on the practical experience of operating stations and the findings of the Television Allocations Study Organization (TASO).[2] These latter have not as of the present date (May 15, 1959) been officially adopted by the Commission.

Service is defined in Table 8-2 in terms of the median field at a receiving antenna at a height of 30 ft above ground. In these frequency bands, the field usually varies appreciably with antenna height, generally tending to increase with increasing antenna height. However, the variation in field with height may not follow simple laws, as discussed more fully in subsequent paragraphs.

The presence of trees, buildings, and terrain irregularities[3–7] often results in considerable variation in the signal from one location to another, even within relatively small areas. The variation in field strength with location must be taken into account in measuring the field strengths as well as in specifying service. Service is usually defined in terms of the *median value* of field strength, which is the value exceeded for at least 50 per cent of the time at the best 50 per cent of the receiving locations.

The results of field-strength-coverage surveys are customarily presented as contour maps, showing lines of constant median field strength which represent the outer limits of various grades of service. A typical map of measured television-station coverage is shown in Fig. 8-1. Methods of preparing contour maps are described in detail under the heading "FCC Standard Method."

Much of the present knowledge of wave propagation in these frequency bands has been derived from field-strength-coverage surveys on operating FM and television stations. The information gained from these commercial coverage surveys has added to the body of scientific knowledge, but field-strength-measurement surveys employing

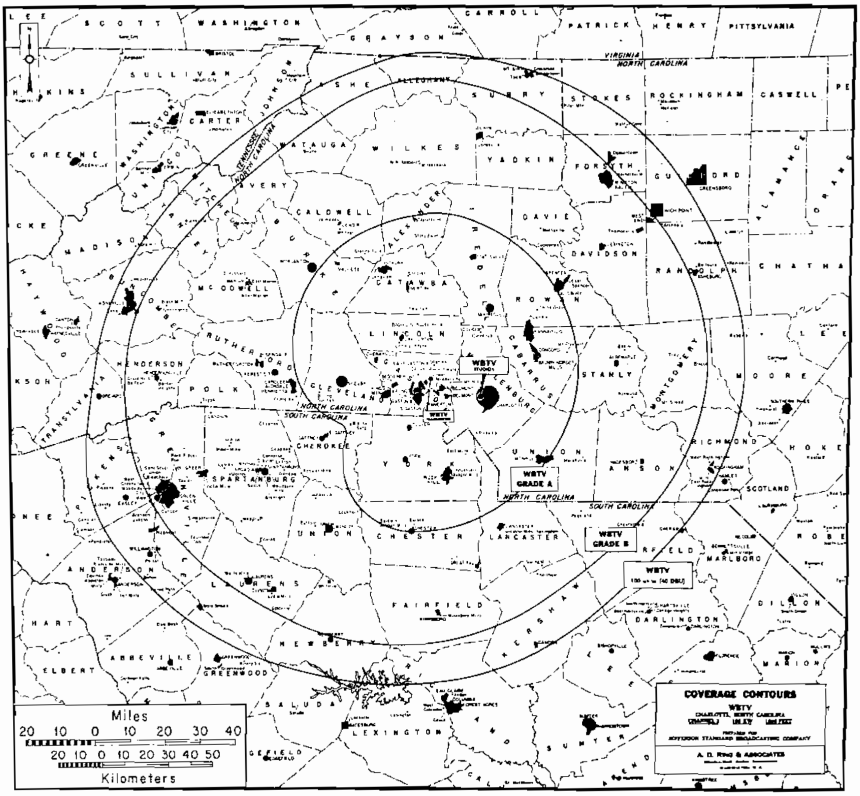

FIG. 8-1. Map showing measured service contours for an operating television station. (*Courtesy of Jefferson Standard Broadcasting Company.*)

special techniques are often needed to supply data for special propagation problems. Examples of such special techniques are discussed under "Recommended TASO Method for Special Studies."

BASIC EQUIPMENT PRINCIPLES

Field strengths in the VHF and UHF bands (30 to 3,000 Mc) are ordinarily measured by determining the voltage which the field induces in a half-wave dipole. The basic relationships can be expressed in several forms. The power transferred between two half-wave dipoles in free space separated by a distance d is given by

$$\frac{P_r}{P_t} = \frac{(1.64\lambda)^2}{4\pi d} \tag{8-1}$$

where P_r = received power
P_t = transmitted power
λ = wavelength in same units as d

In terms of the field at the receiving dipole, the power delivered to a matched load by a half-wave dipole in a field of E volts/m is

$$P_r = (0.0186E\lambda)^2 \qquad \text{watts} \tag{8-2}$$

where λ is expressed in meters. For a resistive load of R ohms, the voltage V developed across a matched load by a dipole in a field E is

$$V = \frac{E\lambda}{53.2\sqrt{R}} \tag{8-3}$$

The fundamental problem presented, therefore, is that of measuring the developed RF voltage by a practical instrument of acceptable accuracy.

Figure 8-2 is a graph showing the available power and voltage developed across a matched 56-ohm load as a function of frequency for a half-wave dipole in a uniform field of 1 volt/m at the frequency indicated. This graph summarizes the relationships shown in Eqs. (8-2) and (8-3).

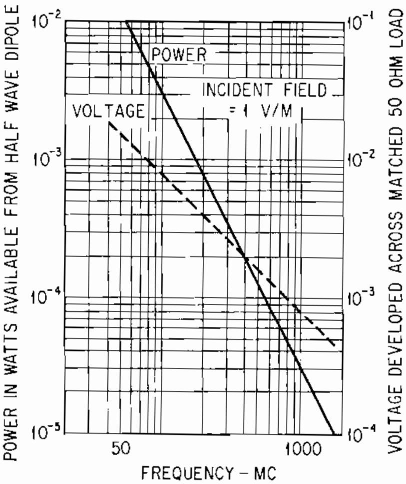

Fig. 8-2. Power and voltage extracted by a half-wave dipole in a field of 1 volt/m as a function of frequency in megacycles.

The voltage-measuring device is ordinarily separated from the antenna by a length of cable. The cable may introduce losses, and any impedance mismatch must be sufficiently small that calibration errors are not introduced by differences between the antenna and cable impedance and the internal impedance of the calibrating oscillator.

PRACTICAL FIELD-STRENGTH METERS

Figure 8-3 is a block diagram of a practical field-strength meter. The antenna delivers its received power to a transmission line leading to the receiver input. If the receiver input is unbalanced to ground, a balance-to-unbalance transformer ("balun") is required. The transmission line between the antenna and the receiver is shielded to avoid stray pickup.

The RF attenuator shown serves two purposes: to avoid overloading of the receiver input on strong signals and to improve the impedance match when the receiver input impedance is substantially different from the characteristic impedance of the transmission line. It is frequently omitted when not required for either of these purposes.

The signal at the receiver input is amplified and converted to the intermediate frequency. Amplification and attenuation at the intermediate frequency permit operation over a wide range of field strengths; further range is provided by the receiver gain control. The rectified receiver output operates the indicating meter.

In operation, the attenuators and gain control are adjusted to provide an on-scale reading of the indicating meter. The receiver input is then switched between the output of the transmission line and the output of the calibrating oscillator, which is tuned to the frequency being measured. The output of the calibrating oscillator is adjusted to a predetermined fixed value using the RF power monitor, and the calibrated attenuator is adjusted until the indicating meter deflection is the same as that obtained from the antenna and transmission line.

For this condition, the voltage at the output of the calibrated attenuator is the same as that from the antenna and transmission line. By taking line and balun losses into account and applying Eq. (8-3) above, the field at the antenna required

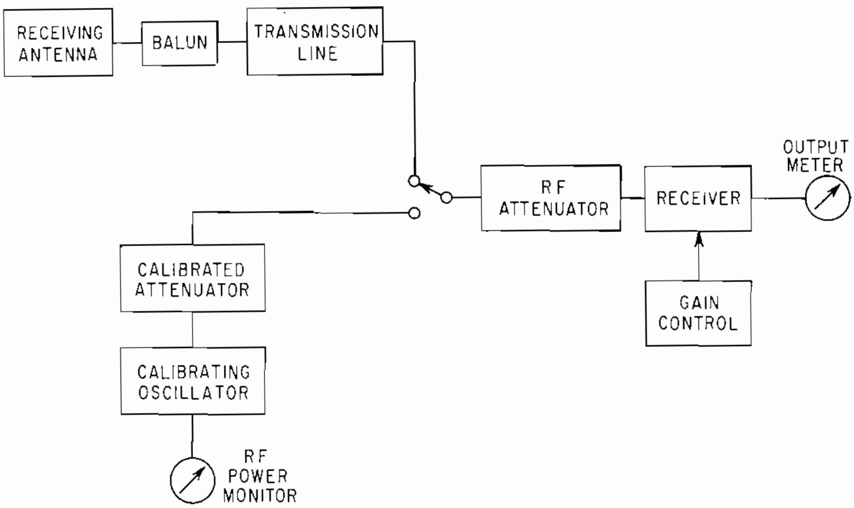

Fig. 8-3. Block diagram of practical field-strength meter.

to produce this voltage can be determined. The relationship between field strength and receiver input voltage is usually expressed as $E = KV$, where K is a function of frequency. Figure 8-4 is a typical graph showing values of K for a UHF field-strength meter.

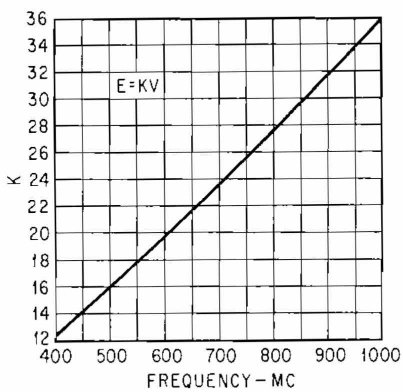

Fig. 8-4. Graph of K for typical UHF field-strength meter. $E = KV$.

A typical commercial field-strength meter of professional quality is shown in Fig. 8-5. The instrument shown is a Nems-Clarke type 107-A, covering the VHF FM and television band from 54 to 216 Mc. A companion instrument, similar in appearance, covers the UHF television band from 470 to 890 Mc.

Accurate instrument calibration is essential in measuring RF fields. During use, the calibration of the instrument described is provided by the calibrating RF voltage source, which is usually an integral part of the field-strength meter (see Fig. 8-5). The calibration of the oscillator and the over-all calibration of the instrument as a whole must in turn be established and maintained by reference to laboratory standards.

The most direct laboratory calibration of the complete field-strength meter is established by generating a known standard field in which the receiving antenna is placed. Standard-field ranges have been developed and constructed at VHF [8] and are sometimes used in primary calibration of VHF field-strength meters. Most commercial laboratory calibrations at VHF, however, are made by removing the dipole elements from the standard antenna and applying a known RF voltage at the proper frequency to the dipole terminals in series with an impedance equal to the receiving-antenna impedance. The calibration of the balun, line, and receiver is established in terms of this applied voltage, which is then related to field strength through Eq. (8-3) above.

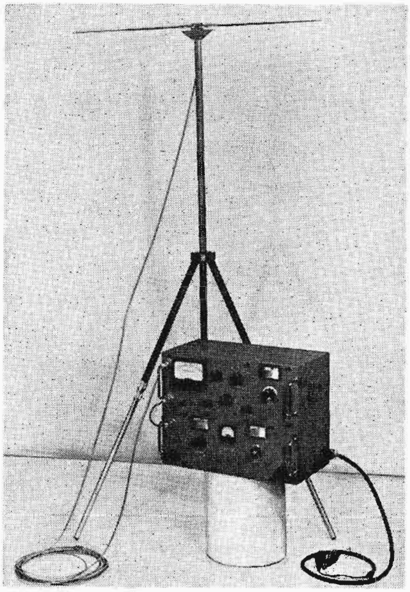

FIG. 8-5. A VHF field-strength meter of professional quality. (*Courtesy of Nems-Clarke Company.*)

Standard-field ranges have not yet been developed at UHF, and both primary and secondary calibrations are made in terms of the voltage appearing at the receiver input. The line and balun losses are measured or calculated from line-attenuation data.

The calibration of the internal reference oscillator section includes the calibration of both the oscillator proper and the variable-output attenuator. The attenuator is usually of the inductively coupled piston type,[9] which depends only on its dimensions for proper functioning; this can be checked against the correct dimensions or against a laboratory standard attenuator. The oscillator can be compared with a standard oscillator, or its output can be measured with a laboratory standard such as a bolometer bridge.[10] This calibration is normally performed only by the manufacturer.

If measurements are made on the visual carrier of a television station, the difference between the peak and average powers of the transmission must be taken into account. This can be done by establishing a calibration in terms of average power for a still scene (such as test pattern or black picture), or a peak-reading voltmeter can be employed to indicate the level of the synchronizing peaks. Such peak-reading voltmeters are an integral part of many of the commercial field-strength meters such as the one illustrated in Fig. 8-5. A schematic diagram of a typical peak-reading voltmeter is shown in Fig. 8-6.

In addition to the field-strength meter, several accessory items are needed in making a field-strength survey. The principal items and their use are described in the following paragraphs and include (*a*) a special receiving antenna, (*b*) an antenna-supporting mast, (*c*) a chart recorder, and (*d*) power supplies. The size and weight of the equipment usually dictate that it be mounted in an automobile or light truck. Figure 8-7 shows a large station wagon containing permanently mounted equipment for field-strength surveys.

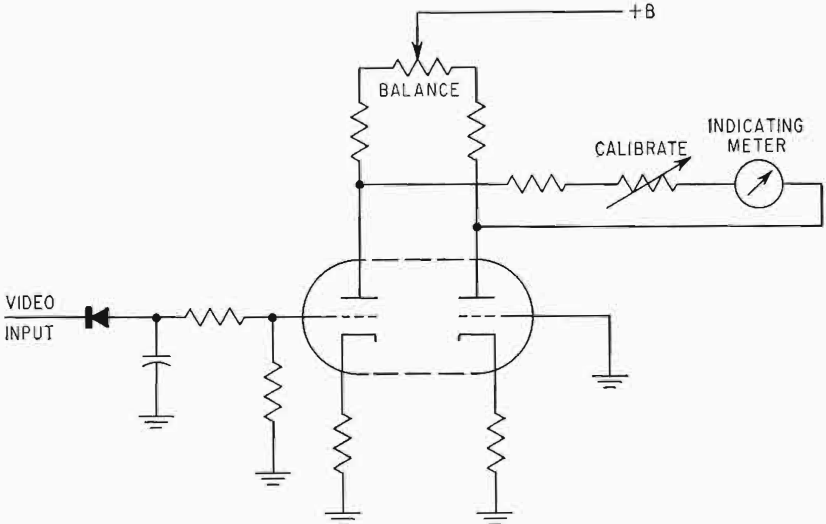

FIG. 8-6. Schematic diagram of bridge circuit for reading voltage corresponding to synchronizing peaks. The component values in the grid circuit are chosen to provide a long time constant.

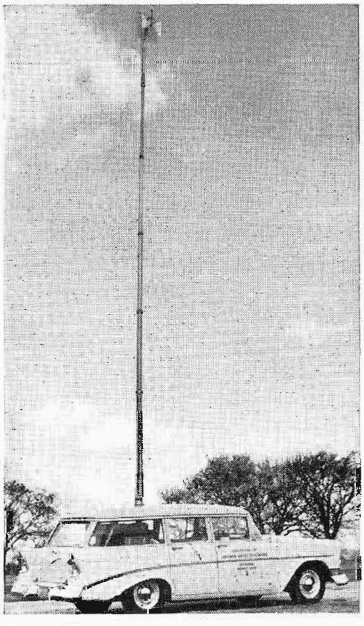

FIG. 8-7. Station wagon equipped for making field-strength-coverage measurements showing 30-ft hydraulic mast. A UHF receiving antenna is mounted on the mast. (*Courtesy of Association of Maximum Service Telecasters, Inc.*)

RECEIVING ANTENNAS

The measurement survey can be made employing the standard dipole antenna furnished with the field-strength meter, or other antennas can be utilized. An antenna which is essentially omnidirectional in the horizontal plane does not require orientation as the vehicle is moved. Figure 8-8 shows a typical nondirectional receiving antenna designed for this purpose. Directional receiving antennas can be employed when their gain is needed (principally for UHF measurements) or when their rejection is desired to eliminate unwanted signals from sources other than the transmitter being measured.

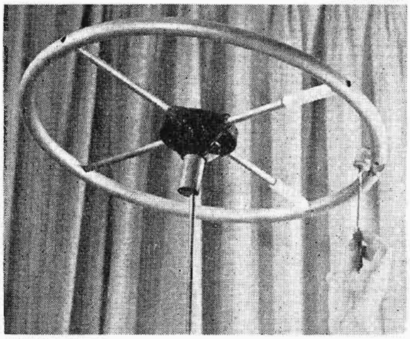

FIG. 8-8. Nondirectional VHF receiving antenna for making coverage surveys.

The antenna employed for the measurements must be calibrated on the measurement vehicle.[11] The received field is first measured using the standard dipole antenna removed from the vehicle. The antenna to be used in making the survey is then mounted on the vehicle at the height to be employed in making the survey, and the receiver input voltage determined with the receiving antenna at the same spot in the field. If an omnidirectional receiving antenna is employed, the circularity of the pattern of the antenna as mounted on the vehicle must be determined. Unless the vehicle can be rotated, this can be done by driving the vehicle in a small circle in an area of uniform field and recording the received signal.

The gain of the service antenna can be established relative to the dipole antenna by means of measurements with the antennas stationary, but more consistent results are often obtained by making short mobile runs over identical paths and recording the signals from the two antennas. For either procedure, the voltage gain of the service antenna G_s relative to the standard dipole antenna G_d is $G_s/G_d = V_s/V_d$, where V_s and V_d are the voltages delivered to the receiver input using the service and standard dipole antennas, respectively.

If the transmission line or balun between the antenna and receiver is different from the standard cable and balun supplied with the instrument, the antenna calibration must include the cables and baluns.

ANTENNA-SUPPORTING MAST

The receiving antenna is ordinarily supported at a height of 10 to 30 ft above ground, depending on the measuring technique employed. For the 10-ft height, a simple mast of metal tubing can be used. For the 30-ft height, a special mast is required to raise and lower the antenna, and the mast arrangement should permit the vehicle to move over limited distances with the mast elevated.

The measuring unit shown in Fig. 8-7 employs a telescoping mast of five sections of aluminum tubing * elevated by low-viscosity oil forced in under pressure; the mast descends under gravity when the pressure is relieved. A handle inside the vehicle permits the mast to be rotated to orient the receiving antenna.

CHART RECORDER

For measurements made with the vehicle in motion, a chart recorder is employed. The chart can be driven from the vehicle speedometer or a drive motor.

* The mast shown was manufactured and installed by the Thomas Mold & Die Company, Wooster, Ohio.

The pen element of the chart recorder is driven by a galvanometer coil; excitation of the galvanometer is provided by a d-c amplifier, which may be built into the field-strength meter or may be a separate accessory.

When the chart recorder is employed, the recorder pen element must be calibrated against the receiver output indicator of the field-strength meter. The d-c amplifier is adjusted for balance at the ends of the meter scale, and a calibration curve is prepared for intermediate values.

POWER SUPPLIES

The power drain of the measuring equipment can be fairly substantial, especially if much accessory equipment is employed. It is usually preferable to provide a power source for the measuring equipment separate from the vehicle battery. This may consist of a separate battery bank to operate the meter and accessories, or a separate 115-volt a-c generator may be mounted in the vehicle.

MEASURING PROCEDURES AND TECHNIQUES

The FCC FM and TV Technical Standards prescribe measuring methods to be employed in making measurements to be submitted to the Commission. These methods are also usually employed in making station-coverage surveys, although variations from the official procedure are frequently taken. The Television Allocations Study Organization report recommends a number of changes in the FCC procedure and also recommends the testing of a radically new measurement technique. The following paragraphs summarize the present requirements of the Commission's Standards and indicate the changes recommended by TASO. The proposed revised method is also described.

FCC STANDARD METHOD [12]

The Commission's Technical Standards require field-strength-measurement surveys to be made with mobile equipment along roads following as closely as possible to radial lines from the transmitter, laid out along bearings separated by 45° beginning with true North. Measurements are required out to a point in each direction somewhat beyond the field-strength contour which it is desired to establish. Continuous recordings of the field strength are made along the roads employing the chart recorder. A minimum chart speed of 3 in. per mile is required. Figure 8-9 shows a sample of a typical chart recording obtained by this method.

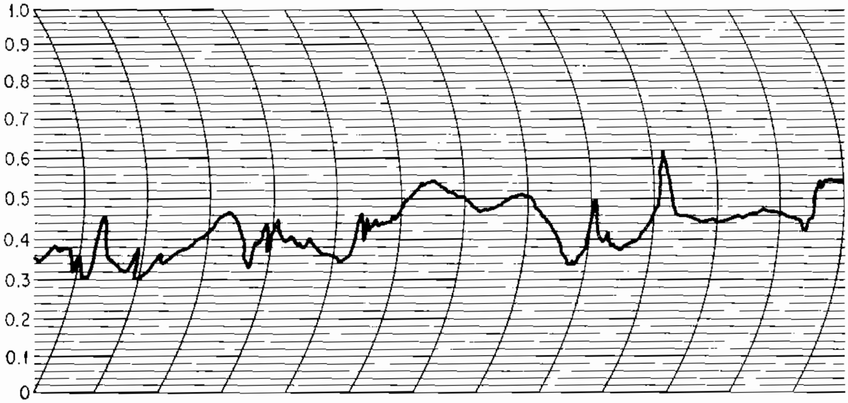

FIG. 8-9. Sample of typical recording chart showing the chart record obtained in making mobile field-strength recordings.

The completed recorder charts are divided into not less than 15 sections in each direction. Each section of the chart is analyzed to determine the median (50 per cent) field for each section. The chart median values are then converted to received field strength by combining the individual calibrations of the antenna, transmission line, field-strength meter, d-c amplifier, and chart recorder as discussed above.

The received fields must be corrected for the field expected at a receiving antenna height of 30 ft above ground. The Commission's Standards do not specify the conversion factor to be employed, but it has been common practice to assume the field strengths to increase linearly with antenna height, as indicated by classical propagation theory. For this assumption the relationship between the field E_{30} which would be expected at 30 ft and the field measured at a receiving antenna height H_r is $E_{30}/E_H = 30/H_r$. For example, the ratio of the field at 30 ft to the field at 10 ft is 30/10 = 3.0, or 9.5 db.

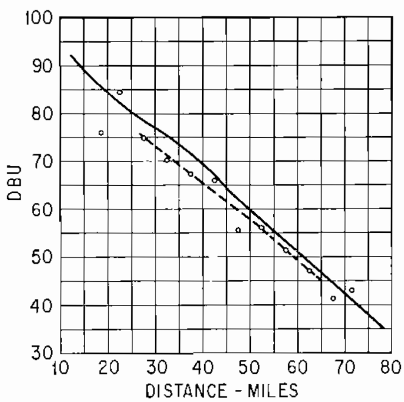

FIG. 8-10. Graph of measured field strength vs. distance for a typical radial route series of measurements. Each circle represents the median value of field strength for a 5-mile recording interval. The dashed line is a best-fit curve through the points. The solid line is the expected field strength computed using the FCC F(50,50) curves.

The median fields as established in accordance with the procedure described above are plotted as a function of distance from the transmitter, and a smooth curve is drawn through the plotted points. Figure 8-10 is a typical graph showing the plotted field strengths as a function of distance from the transmitter, together with the smooth curve through the plotted points. The dashed curve in Fig. 8-10 is the predicted field strength calculated using the propagation curves and prediction methods specified in the FCC Television Broadcast Technical Standards.[13]

Individual graphs of median field strength vs. distance as shown in Fig. 8-10 are prepared for each of the directions along which the measurements were made; the distances to the desired field strength contours, selected from Table 8-2, are determined in each direction. These distances are then plotted on a suitable map, and contours are drawn to produce a finished map such as shown in Fig. 8-1.

TASO RECOMMENDED CHANGES IN FCC PROCEDURE

TASO has recommended that the radial route-measuring pattern be modified to permit wider discretion in the selection of the measuring routes. A minimum of eight routes is recommended, selected to encounter representative terrain and to permit reasonable interpolation between adjoining radials. Additional routes, including branch routes, are recommended where needed.

In the analysis of the recorder tapes, TASO has recommended that the sections of the route chosen for analysis be as uniform as possible, with a minimum length of 2 miles.

One of the most important changes recommended by TASO in the present procedure is in the antenna height-gain correction factor. The application of the linear height-gain function discussed above is recommended only in relatively flat terrain, and in rolling or rough terrain the following height-gain factors (in decibels) are recommended to convert from 10- to 30-ft fields:

Channel	*Smooth Unobstructed Terrain*	*Rolling Hilly Terrain*	*Rough Terrain*
2–6	9.5 db	8 db	7 db
7–13	9.5	7	5
14–83	9.5	5	2

NEW METHOD RECOMMENDED BY TASO FOR FIELD TRIALS

TASO has also recommended field trials of a radically new method of measurement. The measuring pattern for this method is laid out as a series of five concentric circles centered on the transmitter rather than along eight radial lines as now employed. Four hundred measuring points are established on these five circles distributed in approximate proportion to the square root of the radii of the circles.

Field-strength measurements are to be made at each of the 400 points so located. If the designated point is inaccessible, the measurement should be made at a location as close to the designated spot as possible and as nearly as possible at the same ground elevation. Each of the 400 measurements is to consist of a single spot measurement made with the receiving antenna at a height of 30 ft above ground.

The data collected are to be analyzed by dividing the area surveyed into eight or more sectors not exceeding 45° in width. These sectors are to be chosen so as to include reasonably homogeneous terrain in so far as possible. For each constant-radius arc within each sector, the mean value of the spot measurements is determined.* This analysis provides five values of field strength as a function of distance in the direction of each section, from which curves of mean field strength vs. distance for the sector can be drawn. Linear interpolation can be employed for intermediate distances between adjoining circles.

RECOMMENDED TASO METHOD FOR SPECIAL STUDIES

For purposes of scientific investigation of field-strength behavior, measurements are often required employing special techniques. One such method, recommended by TASO in making measurements to be analyzed in terms of the terrain profiles between the transmitting and receiving antennas, is briefly outlined in the following paragraphs.

A precise radial line is laid out from the transmitter on topographic maps to the distance to which measurements are to be made.† Along this radial line, measuring locations are marked at exact 2-mile intervals, beginning at exactly 10 miles from the transmitting antenna. The actual measurements are made precisely on the radial, at locations as close as possible to the exact 2-mile marks established as described.

The individual measurements consist of short mobile runs (100 ft along the road) at each location so chosen, with the receiving antenna at the 30-ft height. The chart recorder is used, and the median, minimum, and maximum values of the field for each recording are determined from the chart recording.

PRACTICAL PROBLEMS ENCOUNTERED IN MAKING FIELD-STRENGTH SURVEYS

Before any field-strength-measurement survey is undertaken, the radiated power of the transmitting installation must be established as closely as possible. The transmitter output power should be determined by means of the dummy load and maintained as closely as possible to the proper value throughout the survey. The

* When the signal is below the noise level at one or more locations in each group, the median value rather than the mean value should be established.

† Precise methods of calculating accurate radial lines for this purpose are described in detail in the TASO report.

radiated power is established from the measured transmitter output power, taking into account the antenna power gain and the transmission line and diplexer losses.

The use of a 30-ft receiving antenna mounted on a vehicle requires special permission from police or highway authorities in most states. These requirements vary among the individual states, but full details can be obtained from the state police or highway headquarters in the various state capitals.

The operation of a 30-ft mast presents safety hazards which require the exercise of utmost caution in the use of an elevated mast. The TASO field-strength measuring specification includes a special appendix dealing with safety requirements. When measurements are made with an elevated antenna, the need for caution must be borne in mind at all times.

FADING OF SIGNALS NEAR THE RADIO HORIZON

Fairly substantial variations in field strength with time are frequently noted near and beyond the radio horizon. These variations may be relatively rapid, occurring over a period of a few minutes, or slow variations may appear over periods of several hours. Average field strengths in this region are usually lowest during winter afternoons, and higher average fields may be observed during the evening hours and during summer. The variations in field strengths with the passage of time must be taken into account in planning and making field-strength-coverage surveys.

The observed fluctuation of the field near the horizon is believed to be due principally to variations in the refractivity gradient of the lower atmosphere, which in turn is determined by the temperature, humidity, and barometric-pressure gradients. Measurements for coverage surveys should not be made beyond the radio horizon during periods when unusual conditions of temperature, humidity, and barometric pressure are believed to prevail. In particular, such measurements should not be made during changing weather conditions or if weather fronts are known to be in the area.

The variations in field with time often result from causes which are not readily apparent, and it is frequently difficult to determine whether typical propagation conditions prevail. One method which has been proposed and tried with some success is that of establishing fixed recording stations in one or more directions, at locations near the expected outer limit service, and recording the received signal over a period of several days. These recordings will give an indication of the signal to be expected under average conditions; the coverage survey measurements beyond the horizon can be made during a period when the recordings indicate propagation conditions to be typical. Measurements should not be made on days when these recordings indicate excessively high or excessively low field strengths.

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Part 9

FIELD-STRENGTH MEASUREMENTS (540–1600 KC)

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INTRODUCTION

Shortly after broadcasting began in the early 1920s, when "wavelength" was checked by a Kolster Decremeter, power was estimated from the product of plate voltage and plate current, and antennas were flat tops or cages hung on a roof, broadcasters sought some uniform and reliable means of describing their service areas. Expressions such as "You're coming in loud and clear" or the more flattering "You're coming in like a ton of bricks" needed to be reduced to some accurate descriptive system.

These desires for better information about coverage or service gave birth to the field-strength meter. In the beginning, this device consisted of a standard signal generator and a stable loop antenna receiver. This apparatus was so bulky that it was usually permanently mounted in a car, and where the car couldn't go—well, there were no measurements. Later on in the twenties, Western Electric wrapped the whole works up in one unit about the size of a piano, but one still required a medium-sized truck to transport the device.

In the early thirties RCA made the first step, albeit a short one, in the right direction. They put handles on a couple of boxes and advertised them as "portable." One contained the field-strength meter and the other an assortment of dry batteries, loops, and plug-in coils. Most of the hunchbacked engineers alive today got that way because their bosses believed that word "portable" in the ads.

In the late thirties Jim McNary in cooperation with Federal reduced the size and weight to somethiug less than backbreaking, but this meter was still far from what engineers needed to do a really good and complete survey job.

At last, shortly after World War II, Allen Clarke of Silver Spring, Md., brought forth that sweetheart of an instrument called the 120-D or WX-2, depending on whose nameplate it bears. Self-contained, direct reading throughout the broadcast band, and not much larger than a press camera, it almost makes the job of measuring field strength a pleasure (see Fig. 9-7). Its only drawback is that we no longer have an excuse that some desirable measuring sites are inaccessible. Wherever we can walk, there we can take this meter and measure the field strength.

FACTORS TO BE CONSIDERED

Now that the equipment situation is in hand (no pun intended), let's take a look at the FCC Standard Broadcast Technical Standards and Rule 3.186 in particular. This section only partially details the requirements for good, supportable, and intelligent field-strength measurements. Along with the instructions given in the Standards there are many more factors to be considered and applied that make the difference between acceptable and questionable data. Some of these factors are applicable to all field-strength measurements, and some assume greater importance in specific applications of field-strength measurements.

Reasons for Measurements

Of the many reasons why we may desire field-strength measurements, the following may be considered the most usual:

1. Location of contours of specified intensity or the determination of quality of service (This started it all!)
2. Interference range of the transmitter
3. Proof of performance of a directional antenna
4. Proof of efficiency of a nondirectional antenna
5. Site survey—to determine the adequacy of a proposed transmitter site
6. Determination of the amplitude of the radio-frequency harmonic radiation of the transmitter
7. Evaluation of the sky-wave-signal intensity from a distant station

RADIAL MEASUREMENTS

General Considerations

In all the above situations with the exception of 6 and 7, strict adherence to the radial bearing from the transmitter is most important. Lay the radial out on the best available map (topographic preferred), and then stick to it! Examine the radial in fine detail and measure as often as practical in unobstructed locations (see Fig. 9-1). This is particularly important when establishing the unattenuated field strength at 1 mile. What do we mean by "unobstructed"? Well, we mean, stay away from overhead wires or similar conducting obstructions. Stay away at least five times the obstruction height and if at all possible ten times the obstruction height. Don't worry about whether this puts us off the "tenth-mile" or "quarter-mile" distance referred to in Sec. 3.186 of the Rules. The bearing is of primary importance; the distance is unimportant as long as it is known and as long as we have a sufficient number of measurements in each distance range. Something slightly in excess of a passing glance at a sheet of log-log paper or semilog paper will impress the idea upon you.

Also, stay away from underground cables, pipelines, etc., in the same manner. These nuisances are usually shown on topographical maps and are usually marked by painted stakes where they cross rights of way. These "gadgets" are particularly obnoxious when they happen to run radially from the transmitter site.

How do we know when we are at a sufficient distance from such obstacles? Usually, that little field-strength meter is a reliable source of such information. Just note the direction of the approaching wavefront. Is it coming from the direction of the transmitter? If not, the measurement is suspect. Note the depth of the null as the loop is rotated. Is it sharp and deep? If not, the measurement is suspect. What do we do? We record the signal measured and note the observed effect in our measurement log. Maybe when we get to plotting it along with the other measured data, it fits the curve nicely and fills in a blank space we need. On the other hand, if it is out in left field, we just forget we made that one and go looking

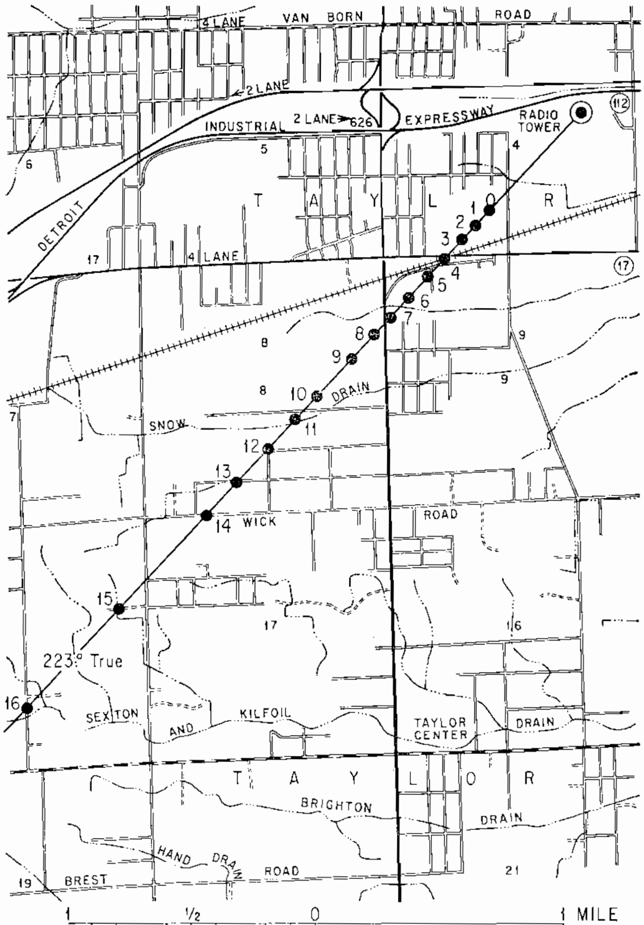

Fig. 9-1. Typical radial with numbered measuring points.

for another place or places in that area where we can get some better information to fill in the blank spots.

Detailed Plotting

Let's try a typical radial. Also, let's assume that we are going to try to prove a protected radial from a directional antenna. This just about covers all the more important factors which will concern us in making ground-wave measurements, with the exception of determining the location of distant service or interference contours.

Preferred Maps

First, obtain the most accurate map available for the path to be measured. U.S. Geological Survey maps are to be preferred if they are of recent issue and/or are the result of an adequate survey. The map should say: "This map complies with National Map Accuracy Standards" on the lower edge. It should be accepted subject to careful checking if it says: "Surveyed by Reconnaissance Methods." If these are not available, county road maps can be employed. However, some road maps are not very accurate, and they should be checked by an auto odometer before placing full reliance in them. On the map, carefully locate the transmitting antenna site. Any significant error in the antenna location will result in a distorted pattern and consequently inaccurate radial data. Then carefuly project a meridian (true North line) through the transmitter site. With the site as the origin and with a good protractor, lay out the radial bearing and continue its projection for at least 15 or 20 miles from the site. (The precise determination of radial bearing recommended by TASO is not required in the standard broadcast band.)

Nondirectional Measurements

Now we are ready to begin a radial with the antenna operating nondirectionally. Nondirectional data are required by the Commission because they usually give smoother attenuation information than will be obtained in a deep null (see Fig. 9-5).

STATION WZZZ
APRIL 31, 1958
RADIAL 123° TRUE

POINT NO.	e-MV/M	DIST	DESCRIPTION
1	398	.432	HARDEL – DEAD END
2	329	.534	BIRCH & BEVERLEY
3	225	.604	N. OF ECORSE & RWY AT NEW CASTLE
4	243	.689	100' S. OF ECORSE ON PINE OPP.# 23481
5	265	.799	GUIDOT AND BUTZEL
6	189	.9	SW OF FACTORY AT HAYES AND CORNELL
7	170	1.015	E. OF TELEGRAPH 100' ON CROWLEY
8	152	1.125	W. OF TELEGRAPH - FACTORY LINES UP WITH ARRAY
9	134	1.23	BEVERS RD. 0.15 W. TELEGRAPH BEHIND BARN
10	124	1.36	CHERNICK RD. 0.3 W. TELEGRAPH N. OF REDHOUSE
11	113	1.56	CHERNICK RD. 0.4 MI W. OF TELEGRAPH
12	101	1.68	INTERSECTION HAIG AND GULLEY
13	90	1.85	HASKELL
14	80	2.06	WICK
15	65	2.2	

FIG. 9-2. Example of radial measurement log.

Now, beginning at a distance of about five times the height of the antenna we start looking for unobstructed measuring locations *on the radial*. Upon reaching the first acceptable point on the radial, we observe the field strength, paying particular attention to the direction of the arrival of the wavefront and to the depth of the null on the meter when the loop is rotated 90° to the direction of the transmitter. Having recorded the value of the signal in our notebook, we mark the location on our map, number the location, and most important, describe the location in sufficient detail so that we can return to the exact same spot in the future (see Fig. 9-2).

We proceed along the radial, obtaining as much data as we can and preferably obtaining more data than are required by 3.186 of the FCC Rules. If because of topography or if we encounter large reservations in which we cannot measure, then we try to obtain additional data in other distance ranges to compensate partially for the missing distance range. As a minimum, we should have measured at least 25 points along the radial within a 15-mile distance. If the directional antenna, which we are going to try to prove on the basis of these data, is a complicated one, then we should get more than 25 and probably as many as 40 points on the radial. The reason for the additional points becomes apparent when we rerun the radial directionally (see Fig. 9-5).

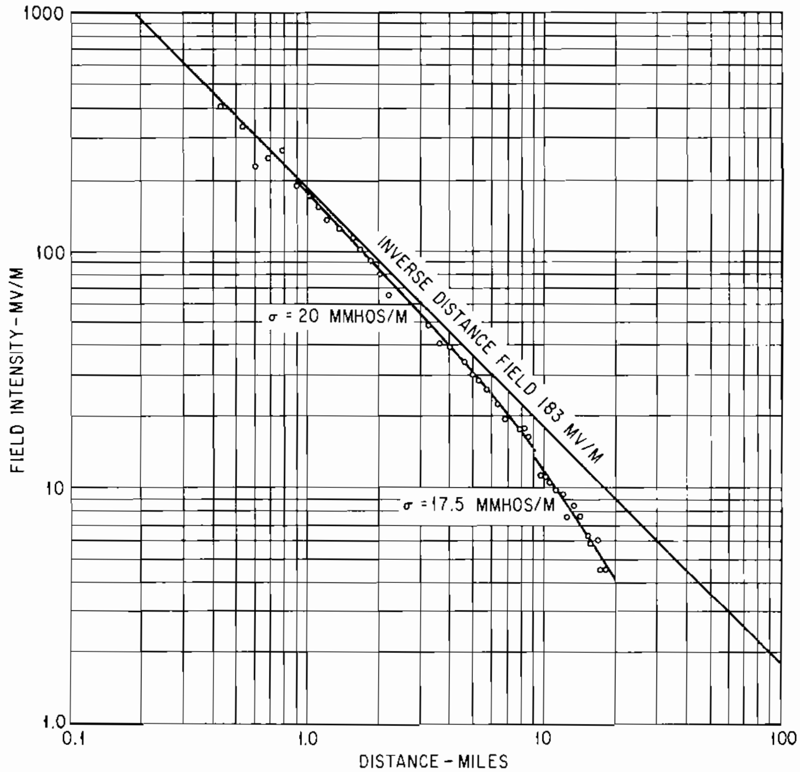

FIG. 9-3. Inverse distance and measured fields: nondirectional operation in direction of protected null, 223° true.

Plotting

Now, we return to the map, carefully measure the distance from the transmitting antenna to each of the measuring points, and tabulate these distances opposite the signal values. The values of field strength which we have measured can now be plotted as a function of distance, and for this plot we can use one of the following commercially available graph papers or its equivalent:

1. If we wish to employ the charts of ground-wave field strength found in Part 3, Radio Broadcast Services (January, 1956, edition), or "FCC Broadcast Engineering Charts" available from the Superintendent of Documents, the data can be plotted on K&E "Ground Wave Field Intensity," paper No. 61729. This paper has the same logarithmic scale as that employed in the above FCC documents, and the data which we have measured can be matched directly against the appropriate graph for the frequency involved. By matching the abscissa of our data with that of the FCC graph, we can then slide the ordinate information data up and down as described in Sec. 3.186, and when the "best fit" is obtained, we have determined both the un-

attenuated field at 1 mile and the conductivity along the radial path. On a light table or against a window, mark the inverse distance field and trace off the apparent conductivity.

2. For those who prefer a slightly higher order of accuracy, we should refer to Graph 20 of the above publications "Ground Wave Field Intensity Versus Numerical Distance over a Plane Earth." By use of this graph, we can construct a new family of attenuation curves for our exact frequency for any desired values of conductivity

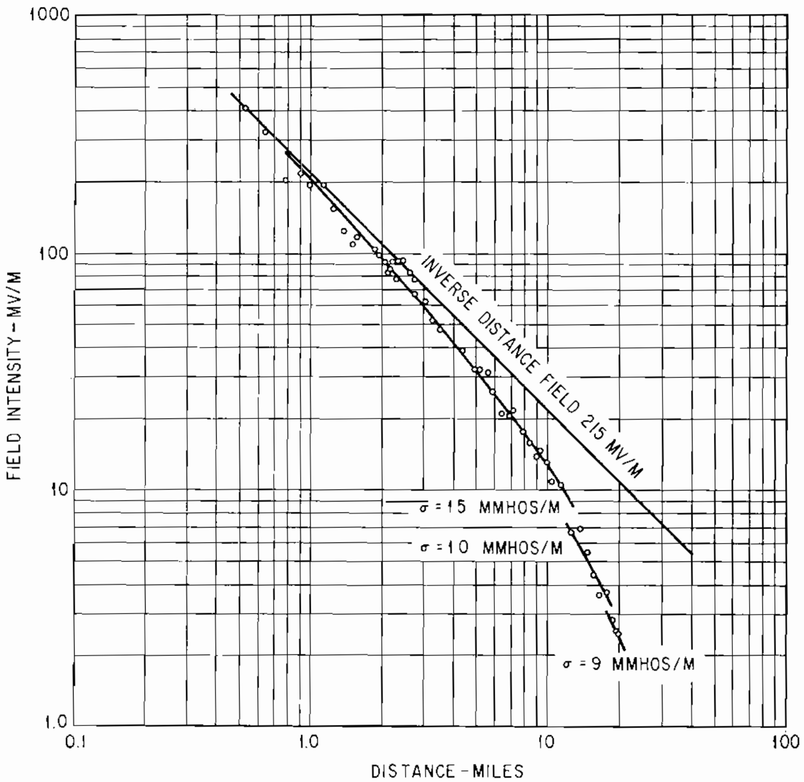

FIG. 9-4. Inverse distance and measured fields: nondirectional operation in the direction of the maximum, 6° true.

and also for several values of dielectric constant. For each value of conductivity and its associated value of dielectric constant we must compute the numerical distance in terms of R(1 mile) from the equations shown on Graph 20 for vertical polarization. After drawing the inverse distance line on our graph paper, we then simultaneously match this line with the equivalent line on Graph 20 while holding our 1-mile distauce line on the computed numerical distance value. We then draw the attenuation curve most closely approaching our calculated value of b, interpolating where necessary. This is repeated for each value of conductivity and dielectric constant chosen.

For convenience, it is most practical to assume one value of dielectric constant, compute the numerical distance for several values of conductivity, and plot this family on one graph sheet. If other values of dielectric constant are assumed, the same conductivities assumed before should be computed and a separate graph employed for this family. The plotted radial data can then be matched to these families.

3. If a still higher order of accuracy is desired, the curves shown on Graph 20 can be transferred to either Dietzgen 3- by 3-cycle logarithmic graph paper No. 340-L33 or K&E No. 359-120, which is equivalent. Using this paper and having our own Graph 20, we can construct our families of attenuation curves as outlined in the second method above. The principal advantage gained by the use of this latter method is that the data are well spread out and more precisely analyzed. Again we match measured data to theoretical graph.

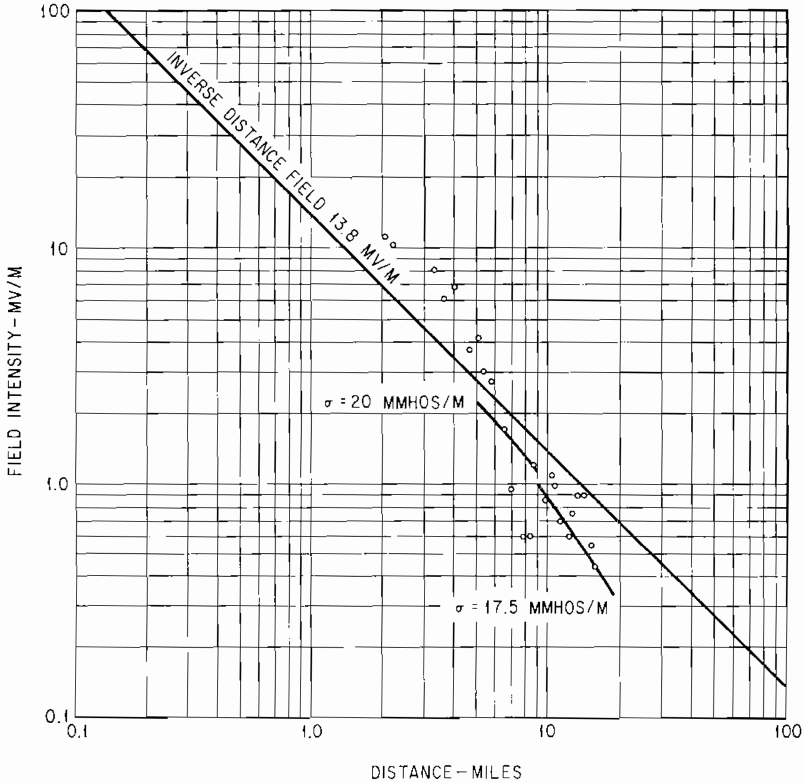

FIG. 9-5. Inverse distance and measured fields: directional operation on radial of protected null, showing increased scattering, 223° true.

If we have prepared the data by the third method above, we should have a radial plot similar to Figs. 9-3 and 9-4. Here we have more data than are needed for a nondirectional radial alone, but we are preparing for more difficult tasks ahead. When we have completed a sufficient number of such radials to determine the nondirectional pattern and have analyzed them, we are prepared to measure our directional pattern or patterns.

Directional Measurements

If we have taken our nondirectional data carefully and noted the exact location of each measuring point, the measurement of the directional data will be easy. If we have been careless in describing the measuring points, we are in for trouble, and the deeper the null in the directional pattern, the more trouble we are likely to encounter. Take heed! Do it right the first time.

The basic difference in the measurement of directional vs. nondirectional antennas is that the directional looks much less like a point source of radiation. Where we began our nondirectional measurements at five times the tower height, we now begin our directional measurements at about ten times the maximum separation between the extremities of the array. In some instances even this is too close, which will appear as wide scattering of the measured values at locations close to the transmitter. We must then depend on data at greater distances where the scatter has diminished to establish the unattenuated field of the array (see Fig. 9-6).

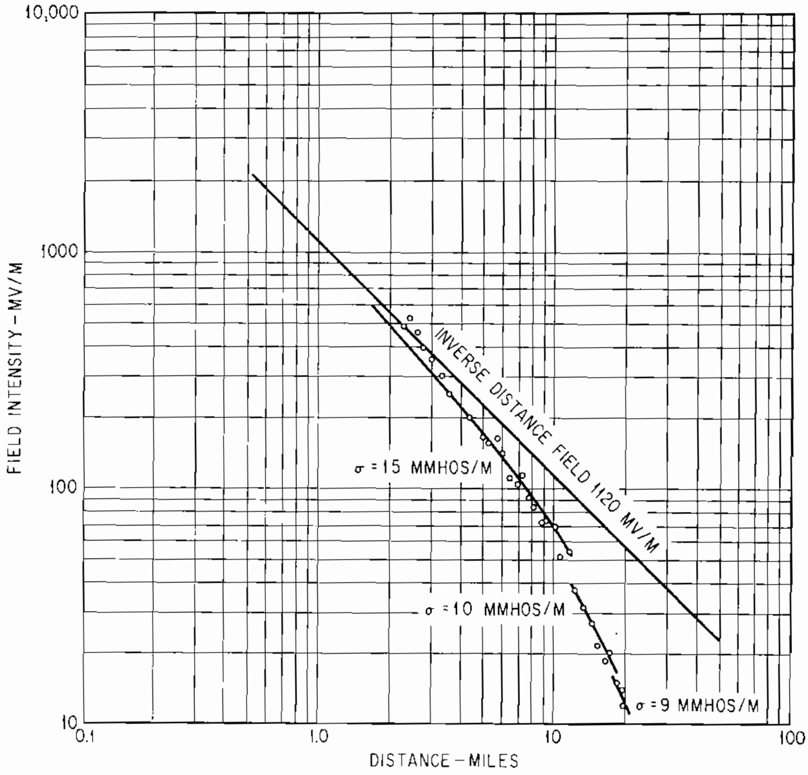

FIG. 9-6. Inverse distance and measured fields: directional operation in the direction of the maximum, 6° true.

It is of the utmost importance, in the directional case, to verify the direction of the approaching wavefront. If in doubt, refer to a good magnetic compass and be sure to correct for the earth's magnetic variation.

After the radial has been run in the directional case, we again plot our data as before but this time we try to match it with the previously analyzed nondirectional data. Now you can appreciate the importance of adequate data carefully taken in the nondirectional case! In most cases, there will be more scatter to the directional data, and the scatter is usually emphasized where we have one or more of the following conditions prevailing:

1. Widely spaced arrays in terms of frequency
2. Deep nulls
3. Poor soil conductivity or rugged terrain
4. Metallic obstacles near the path

5. Reradiation from obstacles near the antenna
6. Buried pipelines running near the path

Under such circumstances it is necessary that we obtain as many data as possible and depend upon the most probable grouping of measurements to determine the directional field. Most often we find that the points at the greater distances give the best comparison with the nondirectional field values. Refer to Fig. 9-5. This is the same radial that is shown nondirectionally in Fig. 9-3. Note that we started our data at a greater distance from the antenna and we still encounter severe scattering. In this particular case, the scattering is attributable to conditions 1 and 2 above. Note also that some of the points measured and plotted in Fig. 9-3 are omitted from the plot in Fig. 9-5. Either these points produced poor nulls on the field-strength meter or the wavefront arrived from some direction other than that of the transmitter or both.

In contrast, see Figs. 9-4 and 9-6 taken on the same array but in the direction of maximum directional radiation. Here, we observe that there is little or no scatter in the directional data in spite of the fact that condition 1 above still applies. These data are typical.

Monitoring Points

The next order of business is to locate the "monitoring points" required on the protected radials. At least one such point and preferably one or two alternate points must be established on each such radial. They must be easily accessible. The locations should be clear of obstacles and likely to remain so. The measured values at the point should lie reasonably close to the attenuation curve shown on the graph of the measured data, and there should be some readily identifiable object near by that will show in the photograph of the point. The description of the point itself should be clear, and the route from the transmitter to the point should be specified along main highways or well-traveled and marked roads. Figure 9-7 illustrates a good monitoring point.

FIG. 9-7. Typical monitoring point location. Note freedom from overhead wires, etc., at point of measurement.

Requirements for Satisfactory Results

Now for a few tips—
1. Read the rules of the FCC and understand them before you begin.
2. Obtain accurate and up-to-date maps and check them.

3. Use a recently calibrated meter or check it against another meter which has been recently calibrated.
4. Start out with fresh batteries and have a spare set available.
5. Stay on the radial.
6. Dont' skimp on the amount of data even at the larger distances.
7. Accurately describe each point so you can find it again.
8. You don't need headphones if you have a car radio receiver. Listen to the station and then to the heterodyne when you turn the calibration oscillator on.
9. Treat your meter with care—it's expensive and is a precise instrument.

Establishing Coverage

Everything that has been written so far has dealt with the signal intensities relatively close to the transmitter. If we wish to extend our data further for the purpose of establishing our coverage, we merely continue along our radials until the desired signal level has been reached and passed by a reasonable margin. Fairly abrupt changes in conductivity can extend the average contour distance beyond that anticipated on the basis of just passing the desired signal value. Besides, if this does occur and the boss wants the data for sales purposes, he may be happy enough to "cough up" a raise.

For extended measurements, to establish the degree of electrical interference which may be expected, and where these data are to be submitted to the Commission either by petition or in hearing, strict adherence to the rules in principle as well as in fact is demanded. Furthermore, it is of the utmost importance that measurements taken at the larger distances be made several hours after sunrise and be completed several hours before sunset. During these hours, propagation via the ionosphere is at a minimum and more realistic values of the ground wave obtain.

So far we have limited the discussion to those techniques required to cover the originally stated usual reasons for making field-strength measurements in the broadcast band with the exception of items 5, 6, and 7. Actually, we have covered 5 because a site survey is in most cases just a nondirectional survey with low effective power. In the few instances where this statement doesn't hold, we may be required to make a directional survey at low power. In either case, the procedures previously outlined apply.

Harmonic Radiation

In measuring the performance of a broadcast transmitter to satisfy the annual and prelicense renewal requirements of Rule 3.47(a)(5), we are told by FCC that field-strength measurements are preferred to observations made with a communications receiver although the latter will be accepted. *Actually, either method yields nothing more than the field strength in either absolute or relative values at the point or points at which a measurement was taken.* Neither method defines the harmonic content of the transmitted signal. Only in the case of the relatively short (compared with a wavelength at the fundamental frequency) nondirectional antenna do field-strength measurements of the harmonic have any meaning. Here they do give a fair approximation of the harmonic content of the *system*. In the case of a directional antenna, we know energy distribution of neither the horizontal plane nor the vertical plane; hence, emphasis on the italicized sentence above.

This doesn't mean that harmonic radiation from a broadcast antenna system can't cause serious interference to other services. The author has experienced too many instances of such interference to deny it. It does mean, however, that when operating directionally, a few field-strength measurements of the harmonic signal near by won't prove a thing.

The best solution to the problem is to locate some point where the harmonic signal is audible and using a Communications receiver with an S meter, insert between the transmitter and the common point a trap or low-pass filter, then adjust it for minimum S-meter reading. Thereafter, once the harmonic signal is sufficiently reduced, comparative checks of the harmonic intensity can be made using the same receiver and antenna.

If absolute values of the harmonic signal are required, alas the Clarke 120-D is of no use. Start looking for an old RCA TMV-75B, 308-B, a Federal 101 with high-frequency loops, or resort to one of the newer products of Stoddart, Empire Devices, Polarad, or equal.

Sky-wave Signals

The measurement of sky-wave signals from distant stations by individuals has passed into limbo in recent years. The Commission has consistently held that snch data will not be admitted in contested hearings and that these data are admissible ouly in "rule-making" procedures. Since there have been no such procedures recently—no sky-wave data! Besides that, FCC and the Central Radio Propagation Laboratory of the Bureau of Standards have miles of recordings for every inch an individual could assemble, and they've been collecting it for years. Hence, there is little incentive to go to the trouble to set up the equipemnt and then analyze the recorded data.