Chapter

5.2

Television Antenna Principles

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5.2.1 Introduction

A wide variety of options are available for television station antenna system implementations. Classic designs, such as the turnstile, continue to be used while advanced systems, based on panel or waveguide techniques, are implemented to solve specific design and/or coverage issues. Regardless of its basic structure, any antenna design must focus on three key electrical considerations:

- Adequate power handling capability
- Adequate signal strength over the coverage area
- Distortion-free emissions characteristics

5.2.1a Power and Voltage Rating

Television antennas for conventional (NTSC, PAL, and SECAM) video transmissions are conservatively rated assuming a continuous black level. The nomenclature typically used in rating the antenna is "peak of sync TV power + 20 percent (or 10 percent) aural." The equivalent heating (average) power is 0.8 of the power rating if 20 percent aural power is used and 0.7 if 10 percent aural power is used. The equivalent heating power value is arrived at as given in Table 5.2.1.

As shown in the table, an antenna power rating increases by 14 percent when the aural output power is reduced from 20 to 10 percent.

In the design of feed systems, the transmission lines must be derated from the manufacturer's catalog values (based on VSWR = 1.0) to allow for the expected VSWR under extraordinary circumstances, such as ice and mechanical damage. The derating factor is

$$\left(\frac{1}{1+|\Gamma|}\right)^2 = \left(\frac{\mathrm{VSWR}+1}{2\,\mathrm{VSWR}}\right)^2 \tag{5.2.1}$$

Table 5.2.1 Television Antenna Equivalent Heating Power

Parameter	Carrier Level (%)		Fraction of Time (%)	Average Power (%)
	Voltage	Power		
Sync	100	100	8	8
Blanking	75	56	92	52
Visual black-signal power				60
Aural power (percent of sync power)				20 (or 10)
Total transmitted power (percent peak-of-sync)				80 (or 70)

where Γ = the expected reflection coefficient resulting from ice or a similar error condition. This *derating factor* is in addition to the derating required because of the normally existing VSWR in the antenna system feed line.

The manufacturer's power rating for feed system components is based on a fixed ambient temperature. This temperature is typically 40°C (104ºF). If the expected ambient temperature is higher than the quoted value, a good rule of thumb is to lower the rating by the same percentage. Hence, the television power rating (including 20 percent aural) of the feed system is given by

$$P_{TV} \approx \frac{1}{0.8} P_{T/L} \left(\frac{T_{T/L}}{T} \right) \left(\frac{\text{VSWR}+1}{2\,\text{VSWR}} \right)^2 \tag{5.2.2}$$

Where:
$P_{T/V}$ = quoted average power for transmission line components with VSWR = 1.0
$T/T_{T/L}$ = ratio of expected to quoted ambient temperature
VSWR = worst-possible expected VSWR

Television antennas must also be designed to withstand voltage breakdown resulting from high instantaneous peak power both inside the feed system and on the external surface of the antenna. Improper air gaps or sharp edges on the antenna structure and insufficient safety factors can lead to arcing and blooming. The potential problem resulting from instantaneous peak power is aggravated when multiplexing two or more stations on the same antenna. In this latter case, if all stations have the same input power, the maximum possible instantaneous peak power is proportional to the number of the stations squared as derived below.

For a single channel, the maximum instantaneous voltage can occur when the visual and aural peak voltages are in phase. Thus, with 20 percent aural, the worst-case peak voltage is

$$V_{\text{peak}} = \sqrt{2\,Z_0\,P_{PS}} + \sqrt{0.4\,Z_0\,P_{PS}} = 2.047\sqrt{Z_0\,P_{PS}} \tag{5.2.3}$$

Where:
P_{PS} = peak-of-sync input power
Z_0 = characteristic impedance

and the equivalent peak power is

$$P_{\text{peak}} = \frac{V_{\text{peak}}^2}{Z_0} = 4.189\, P_{PS} \tag{5.2.4}$$

For N stations multiplexed on the same antenna, the equivalent peak voltage is

$$\frac{1}{\sqrt{Z_0}} V_{\text{peak}} = 2.047\sqrt{P_{PS}} + 2.047\sqrt{P_{PS}} + \ldots\ 2.047\, N\, \sqrt{P_{PS}} \tag{5.2.5}$$

and the equivalent peak power is

$$P_{\text{peak}} = 4.189 N^2\, P_{PS} \tag{5.2.6}$$

Experience has shown that the design peak power and the calculated peak power should be related by a certain *safety factor*. This safety factor is made of two multipliers. The first value, typically 3, is for the surfaces of pressurized components. This factor accounts for errors resulting from calculation and fabrication and/or design tolerances. The second value, typically 3, accounts for humidity, salt, and pollutants on the external surfaces. The required peak power capability, thus, is

$$P_s = 4.189 \times F_s \times N^2 \times P_{PS} \tag{5.2.7}$$

Where:
P_s = safe peak power
F_s = 3 for internal pressurized surfaces
F_s = 9 for internal external surfaces

5.2.1b Effective Radiated Power

The *effective radiated power* (ERP) of an antenna is defined as

$$P_{\text{ERP}} = P_{\text{input}} \times G_{\text{antenna}}$$

The input power to the antenna (P_{input}) is the transmitter output power minus the losses in the interconnection hardware between the transmitter output and the antenna input. This hardware consists of the transmission lines and the filtering, switching, and combining complex.

The *gain* of an antenna (G_{antenna}) denotes its ability to concentrate the radiated energy toward the desired direction rather than dispersing it uniformly in all directions. It is important to note that higher gain does not necessarily imply a more effective antenna. It does mean a lower transmitter power output to achieve the licensed ERP.

The visual ERP, which must not exceed the FCC specifications, depends on the television channel frequency, the geographical zone, and the height of the antenna-radiation center above average terrain. The FCC emission rules relate to *either* horizontal or vertical polarization of the transmitted field. Thus, the total permissible ERP for *circularly polarized* transmission is doubled.

The FCC-licensed ERP is based on average-gain calculations for omnidirectional antennas and peak-gain calculations for antennas designed to emit a directional pattern.

5.2.1c Directional Antennas

As defined by the FCC rules, an antenna that is *intentionally* designed or altered to produce a noncircular azimuthal radiation pattern is a *directional antenna*. There are a variety of reasons for designing directional antennas. In some instances, such designs are necessary to meet interference protection requirements. In other instances, the broadcaster may desire to improve service by diverting useful energy from an unpopulated area toward population centers. Generally speaking, directional antennas are more expensive than omnidirectional antennas.

5.2.2 Polarization

The *polarization* of an antenna is the orientation of the electric field as radiated from the device. When the orientation is parallel to the ground in the radiation direction-of-interest, it is defined as *horizontal polarization.* When the direction of the radiated electric field is perpendicular to the ground, it is defined as *vertical polarization.* These two states are shown in Figure 5.2.1. Therefore, a simple dipole arbitrarily can be oriented for either horizontal or vertical polarization, or any tilted polarization between these two states.

If a simple dipole is rotated at the picture carrier frequency, it will produce *circular polarization* (CP), since the orientation of the radiated electric field will be rotating either clockwise or counterclockwise during propagation. This is shown in Figure 5.2.1. Instead of rotating the antenna, the excitation of equal longitudinal and circumferential currents in phase quadrature will also produce circular polarization. Because any state of polarization can be achieved by judicious choice of vertical currents, horizontal currents, and their phase difference, it follows that the reverse is also true. That is, any state of polarization can be described in terms of its vertical and horizontal phase and amplitude components.

Perfectly uniform and symmetrical circular polarization in every direction is not possible in practice. Circular polarization is a special case of the general *elliptical polarization*, which characterizes practical antennas. Other special cases occur when the polarization ellipse degenerates into linear polarization of arbitrary orientation.

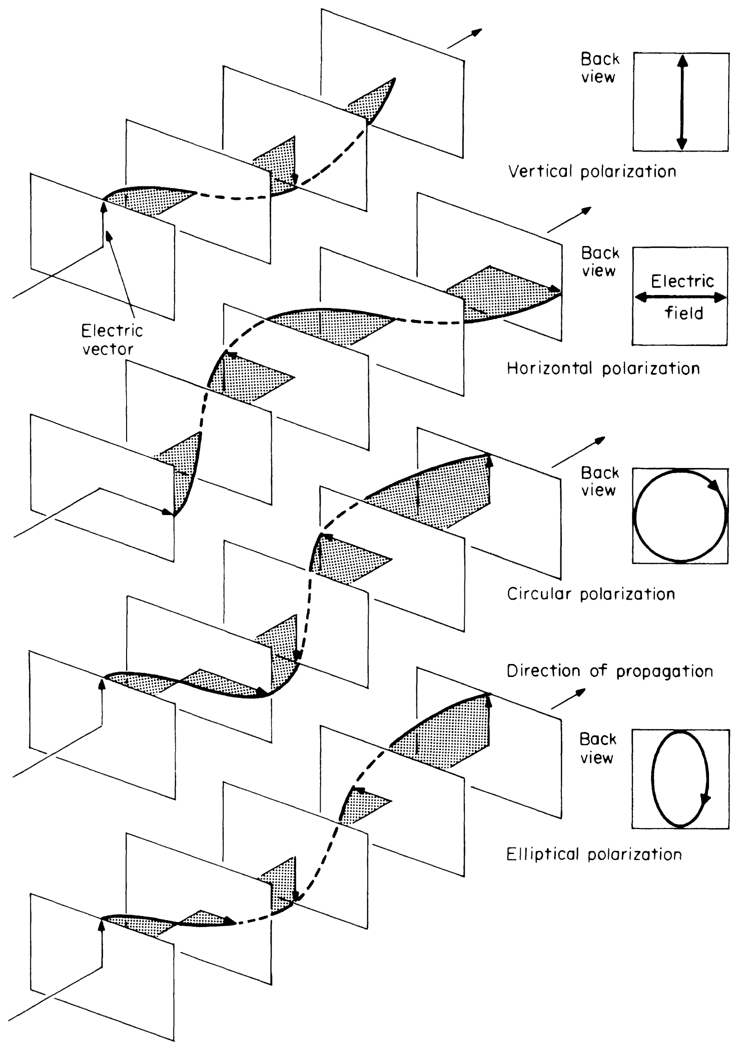


Figure 5.2.1 Polarizations of the electric field of the transmitted wave.

5.2.2a Practical Application

The polarization of the electric field of television antennas was limited in the U.S. to horizontal polarization during the first 30 years of broadcasting. But in other parts of the world, both vertical and horizontal polarizations were allowed, primarily to reduce co-channel and adjacent channel interference [1]. The FCC modified the rules in the early 1970s to include circularly polarized transmission for television broadcasting.

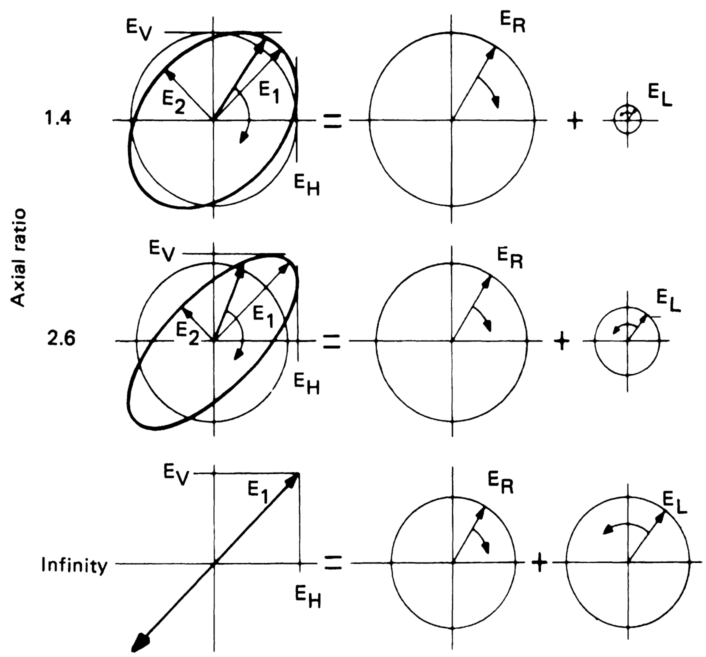


Figure 5.2.2 Elliptical polarization as a combination of two circularly polarized signals. As shown, the resultant ellipse equals the right-hand component plus the left-hand component.

It should be pointed out that the investment required in a circularly polarized transmission facility is considerably greater than that required for horizontal polarization, mostly because of the doubling of transmitter power. While doubling of antenna gain instead of transmitter power is possible, the coverage of high-gain antennas with narrow beam-width may not be adequate within a 2- to 3-mi (3- to 5-km) radius of the support tower unless a proper shaping of the elevation pattern is specified and achievable.

Practical antennas do not transmit ideally perfect circular polarization in all directions. A common figure of merit of CP antennas is the *axial ratio.* The axial ratio is not the ratio of the vertical to horizontal polarization field strength. The latter is called the *polarization ratio.* Practical antennas produce elliptical polarization; that is, the magnitude of the propagating electric field prescribes an ellipse when viewed from either behind or in front of the wave. Every elliptically polarized wave can be broken into two circularly polarized waves of different magnitudes and sense of rotation, as shown in Figure 5.2.2. For television broadcasting, usually a right-hand (clockwise) rotation is specified when viewed from behind the outgoing wave, in the direction of propagation.

Referring to Figure 5.2.2, the axial ratio of the elliptically polarized wave can be defined in terms of the axes of the polarization ellipse or in terms of the right-hand and left-hand components. Denoting the axial ratio as *R,* then

$$R = \frac{E_1}{E_2} = \frac{E_R + E_L}{E_R - E_L} \tag{5.2.8}$$

When evaluating the transfer of energy between two CP antennas, the important performance factors are the power-transfer coefficient and the rejection ratio of the unwanted signals (echoes) to the desired signal. Both factors can be analyzed using the *coupling-coefficient factor* between two antennas arbitrarily polarized. For two antennas whose axial ratios are R_1 and R_2, the coupling coefficient is

$$f = \frac{1}{2}\left[1 \pm \frac{4 R_1 R_2}{\left(1+R_1^2\right)\left(1+R_2^2\right)} + \frac{\left(1-R_1^2\right)\left(1-R_2^2\right)}{\left(1+R_1^2\right)\left(1+R_2^2\right)}\cos(2\alpha)\right] \tag{5.2.9}$$

where α = the angle between the major axes of the individual ellipses of the antennas.

The plus sign in Equation (5.2.9) is used if the two antennas have the same sense of rotation (either both right hand or left hand). The minus sign is used if the antennas have opposite senses of polarization.

Two special cases are of importance when coupling between two elliptically polarized antennas is considered. The first is when the major axes of the two ellipses are aligned ($\alpha = 0$). The second case is when the major axes are perpendicular to each other ($\alpha = \pm\pi / 2$).

For case 1, where the major axes of the polarization ellipses are aligned, the maximum power transfer is

$$f = \frac{\left(1 \pm R_1 R_2\right)^2}{\left(1+R_1^2\right)\left(1+R_2^2\right)} \tag{5.2.10}$$

and the minimum power rejection ratio is

$$\frac{f_-}{f_+} = \frac{\left(1 - R_1 R_2\right)^2}{\left(1 + R_1 R_2\right)^2} \tag{5.2.11}$$

For case 2, where the major axes of the two polarization ellipses are perpendicular, the maximum power transfer is

$$f = \frac{\left(R_1 \pm R_2\right)^2}{\left(1+R_1^2\right)\left(1+R_2^2\right)} \tag{5.2.12}$$

and the minimum power rejection ratio is

$$\frac{f_-}{f_+} = \frac{\left(R_1 - R_2\right)^2}{\left(R_1 + R_2\right)^2} \tag{5.2.13}$$

The ability to reject unwanted reflections is of particular importance in television transmission. Because in many cases the first-order reflections have undergone a reversal of the sense of rotation of the polarization ellipse, the minimum rejection ratio is given by f_- / f_+.

5.2.3 Gain

Antenna gain is a figure of merit that describes the antenna's ability to radiate the input power within specified sectors in the directions of interest. Broadcast antenna gains are defined relative to the peak gain of a half-wavelength-long dipole. Gain is one of the most critical figures of merit of the television broadcast antenna, as it determines the transmitter power required to achieve a given ERP. Gain is related to the beamwidth of the elevation pattern, which in turn affects the coverage and sets limits on the allowable *windsway*. It is related to height (windload) of the antenna and to the noncircularity of the azimuthal pattern.

The gain of any antenna can be estimated quickly from its height and knowledge of its azimuthal pattern. It can be calculated precisely from measurements of the radiation patterns. It can also be measured directly, although this is rarely done for a variety of practical reasons. The gain of television antennas is always specified relative to a half-wavelength dipole. This practice differs from that used in nonbroadcast antennas.

Broadcast antenna gains are specified by elevation (vertical) gain, azimuthal (horizontal) gain, and total gain. The total gain is specified at either its peak or average (rms) value. In the U.S., the FCC allows average values for omnidirectional antennas but requires the peak-gain specification for directional antennas. For circularly polarized antennas, the aforementioned terms also are specified separately for the vertically and horizontally polarized fields.

For an explanation of *elevation gain*, consider the superimposed elevation patterns in Figure 5.2.3. The elevation pattern with the narrower beamwidth is obtained by distributing the total input power equally among 10 vertical dipoles stacked vertically 1 wavelength apart. The wider-beamwidth, lower peak-amplitude elevation pattern is obtained when the same input power is fed into a single vertical dipole. Note that at depression angles below 5°, the lower-gain antenna transmits a stronger signal. In the direction of the peak of the elevation patterns, the gain of the 10 dipoles relative to the single dipole is

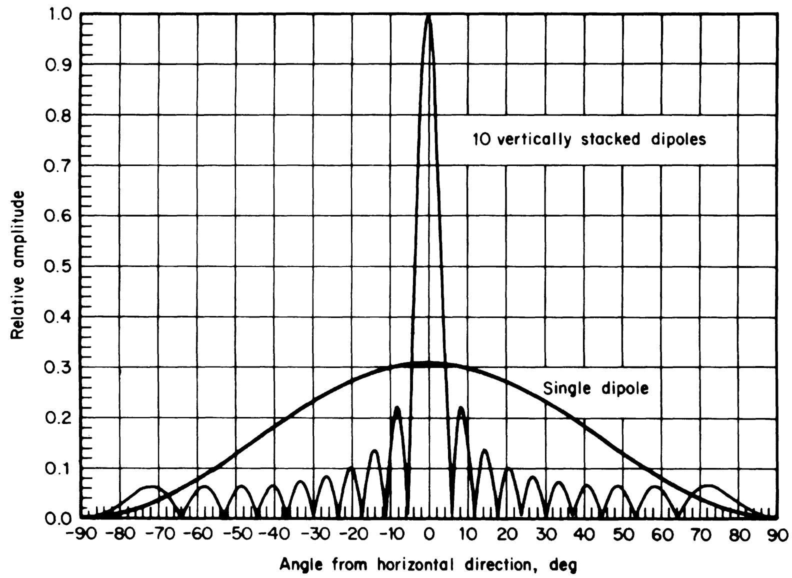


Figure 5.2.3 Elevation pattern gain of two antennas of different aperture.

$$g_e = \left(\frac{1.0}{0.316}\right)^2 = 10 \tag{5.2.14}$$

It can be seen from Figure 5.2.3 that the elevation gain is proportional to the vertical aperture of the antenna. The theoretical upper limit of the elevation gain for practical antennas is given by

$$G_E = 1.22\eta\frac{A}{\lambda} \tag{5.2.15}$$

Where:
η = feed system efficiency
A/λ = the vertical aperture of the antenna in wavelengths of the operating television channel

In practice, the elevation gain varies from $\eta \times 0.85\, A/\lambda$ to $\eta \times 1.1\, A/\lambda$.

To completely describe the gain performance of an antenna, it is necessary to also consider the azimuth radiation pattern. An example pattern is shown in Figure 5.2.4.

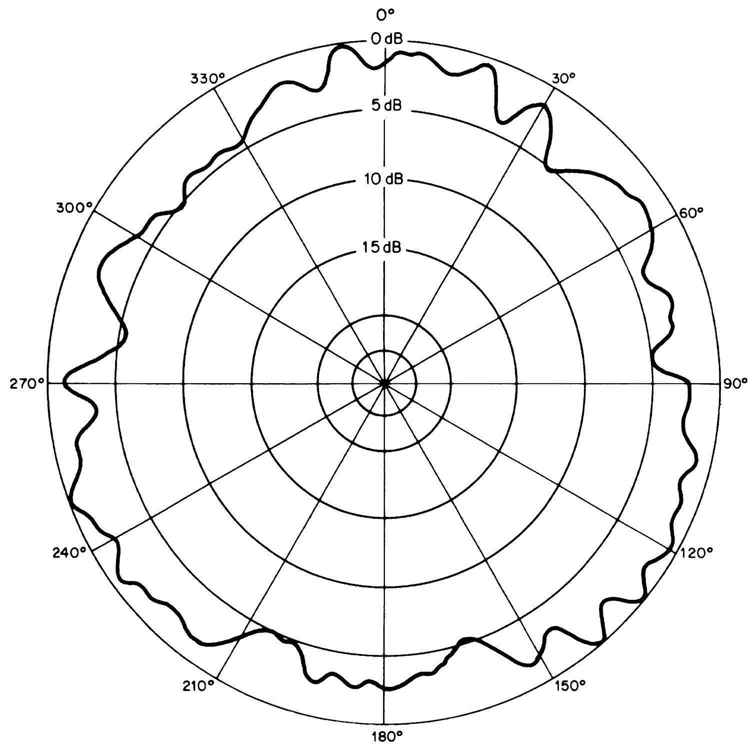


Figure 5.2.4 Measured azimuthal pattern of a three panel array.

5.2.3a Circular Polarization

To clarify the factors contributing to the gain figure for circular polarized antennas, the derivation of the applicable expressions for the gain of each polarization and the total gain follow.

The total gain of a mathematical model of an antenna can be described as the sum of the individual gains of the field polarized in the vertical plane and the field polarized in the horizontal plane regardless of their ratio.

Starting with the standard definition of antenna gain G

$$G = 4\pi\eta \frac{|E_v|^2 + |E_h|^2}{1.64 \int\int |E_v|^2 + |E_h|^2 \sin\theta \, d\theta \, d\phi} \tag{5.2.16}$$

Where E_v and E_h equal the magnitudes of the electric fields of the vertical polarization and the horizontal polarization, respectively, in the direction of interest. This direction usually is the peak of the main beam.

Next, it is necessary to define

$$G_h = 4\pi\eta \frac{|E_h|^2}{1.64 \int\int |E_h|^2 \sin\theta \, d\theta \, d\phi} \tag{5.2.17}$$

as the total (azimuthal and elevation) gain for the horizontal polarization component in the absence of vertical polarization, and then let

$$G_v = 4\pi\eta \frac{|E_h|^2}{1.64 \int\int |E_h|^2 \sin\theta \, d\theta \, d\phi} \tag{5.2.18}$$

be the total gain for the vertical polarization component in the absence of horizontal polarization. Then

$$\frac{G}{G_h} = \frac{1+|E_v/E_h|^2}{1+(G_h/G_v)\,|E_v/E_h|^2} = \frac{1+|P|^2}{1+(G_h/G_v)\,|P|^2} \tag{5.2.19}$$

and

$$\frac{G}{G_v} = \frac{1+|E_h/E_v|^2}{1+(G_v/G_h)\,|E_h/E_v|^2} = \frac{1+|P|^2}{|P|^2+(G_v/G_h)} \tag{5.2.20}$$

where $|P|$ is the magnitude of the polarization ratio. When the last two expressions are added and rearranged, the total gain G of the antenna is obtained as

$$G = \left[1+|P|^2\right]\left[\frac{1}{(1/G_h)+|P|^2/G_v}\right] \tag{5.2.21}$$

The total gain can be broken into two components whose ratio is $|P|^2$. For horizontal polarization

$$G = \frac{G_h}{1+(G_h/G_v)/|P|^2} \tag{5.2.22}$$

and for vertical polarization

$$G = \frac{G_v}{1+(G_v/G_h)/|P|^2} \tag{5.2.23}$$

The last three expressions specify completely any antenna provided G_h, G_v, and $|P|$ are known. From the definitions it can be seen that the first two can be obtained from measured-pattern integration, and the magnitude of the polarization ratio is either known or can be measured.

When the antenna is designed for horizontal polarization, $|P| = 0$ and $G = G_h$. For circular polarization, $|P| = 1$ in all directions, $G_h = G_v$ and the gain of each polarization is half of the total antenna gain.

5.2.3b Elevation Pattern Shaping

The elevation pattern of a vertically stacked array of radiators can be computed from the *illumination* or *input currents* to each radiator of the array and the elevation pattern of the single radiator [2–5]. Mutual coupling effects generally can be ignored when the spacing between the adjacent radiators is approximately a wavelength, a standard practice in most broadcast antenna designs. The elevation pattern $E(\theta)$ of an antenna consisting of N vertically stacked radiators, as a function of the depression angle θ, is given by

$$E(\theta) = \sum_{i=1}^{N} A_i P_i(\theta) \exp(j\phi) \exp\left(j\frac{2\pi}{\lambda} d_i \sin\theta\right) \tag{5.2.24}$$

Where:
$P_i(\theta)$ = vertical pattern of ith panel
A_i = amplitude of current in ith panel
θi = phase of current in ith panel
d_i = location of ith panel

In television applications, the normalized magnitude of the pattern is of primary interest. For an array consisting of N identical radiators, spaced uniformly apart (d), and carrying identical currents, the magnitude of the elevation, or vertical, radiation pattern, is given by

$$|E(\theta)| = \left| \frac{\sin\left[(N\pi/\lambda)\, d \sin\theta\right]}{\sin\left[(\pi d/\lambda)\sin\theta\right]} \right| |p(\theta)| \tag{5.2.25}$$

where the first part of the expression on the right is commonly termed the *array factor*. The elevation pattern of a panel antenna comprising six radiators, each 6 wavelengths long, is given in Figure 5.2.5. The elevation-pattern power gain g_e of such an antenna can be determined by integrating the power pattern, and is given by the expression

$$g_e \cong \frac{Nd}{\lambda} \tag{5.2.26}$$

Thus, for an antenna with N half-wave dipoles spaced 1 wavelength apart, the gain is essentially equal to the number of radiators N. In practice, slightly higher gain can be achieved by the use of radiators which have a gain greater than that of a half-wave dipole.

The *array factor* becomes zero whenever the numerator becomes zero, except at $\theta = 0$ when its value equals 1. The nulls of the pattern can be easily determined from the equation

$$\frac{N\pi d}{\lambda}\sin\theta_m = m \tag{5.2.27}$$

or

$$\theta_m = \sin^{-1}\frac{m}{g_e} \tag{5.2.28}$$

where m = 1, 2, 3 ... refers to the null number and θ_m = depression angle at which a null is expected in radians.

The approximate beamwidth corresponding to 70.7 percent of the field (50 percent of power), or 3 dB below the maximum, can be determined from the array factor. The minimum beamwidth is given by the expression

$$BW_{\min} = \frac{50.8}{N(d/\lambda)} = \frac{50.8}{g_e}\ \text{deg} \tag{5.2.29}$$

It is interesting to note that the gain-beamwidth product is essentially a constant. The gain-beamwidth product of practical antennas varies from 50.8 to 68, depending on the final shaping of the elevation pattern.

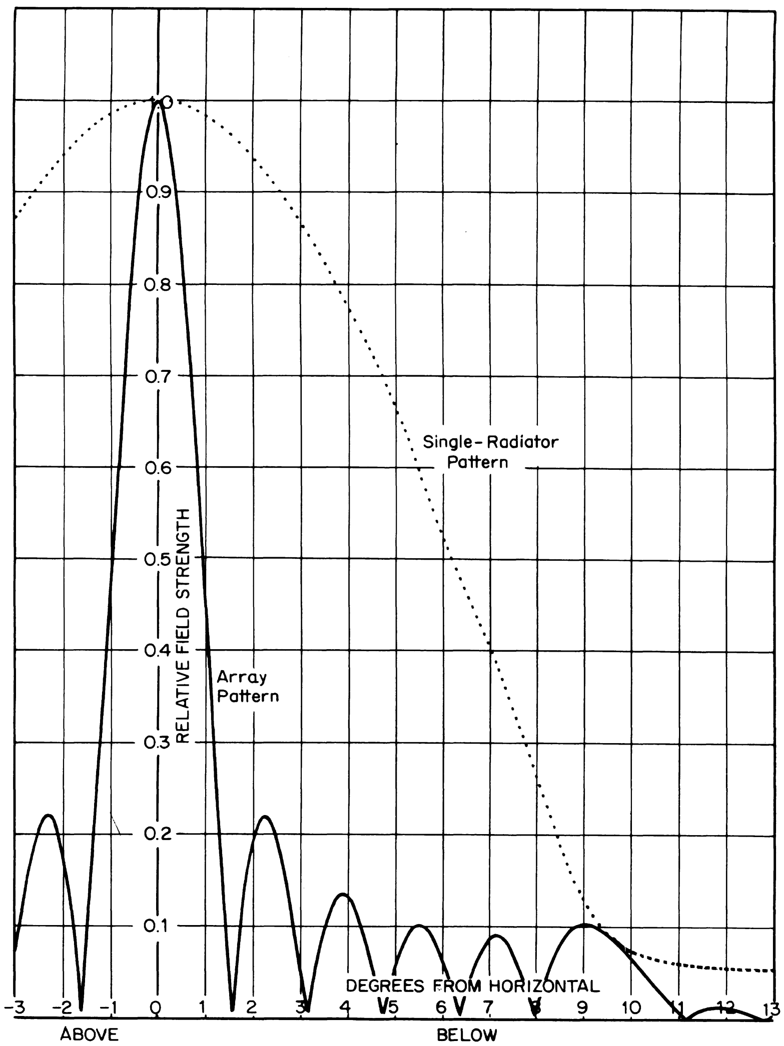


Figure 5.2.5 Elevation pattern of an antenna array of six radiators, each six wavelengths long. All radiators feed equally and in-phase.

In television broadcasting, the desired gain of an omnidirectional antenna generally is determined by the maximum-allowable effective radiated power and the transmitter power output to the antenna. Provision for adequate signal strength in the coverage area of interest requires synthesis of the antenna pattern to ensure that the nulls of the pattern are filled to an acceptable level. In addition, in order to improve the transmission efficiency, the main beam is tilted down to reduce the amount of unusable radiated power directed above the horizontal.

Although the previous discussion has been concerned with arrays of discrete elements, the concept can be generalized to include antennas that are many wavelengths long in aperture and have a continuous illumination. In such cases, the classic techniques of null filling by judicious antenna aperture current distribution, such as cosine-shaped or exponential illuminations, are employed.

Elevation-Pattern Derivation

The signal strength at any distance from an antenna is directly related to the maximum ERP of the antenna and the value of the antenna elevation pattern toward that depression angle. For a signal strength of 100 mV/m, which is considered adequate for analog television applications, and assuming the FCC (50,50) propagation curves, the desired elevation pattern of an antenna can be derived. Such curves provide an important basis for antenna selection.

Beam Tilting

Any specified tilting of the beam below the horizontal is easily achieved by progressive phase shifting of the currents (I_t) in each panel in an amount equal to the following

$$I_t = -2\left(\pi d_i / \lambda\right) \sin \theta_T \tag{5.2.30}$$

where θ_T is the required amount of beam tilt in degrees. Minor corrections, necessary to account for the panel pattern, can be determined easily, by iteration.

In some cases, a progressive phase shifting of individual radiators may not be cost effective, and several sections of the array can have the illuminating current of the same phase, thus reducing the number of different phasing lengths. In this case, the correct value of the phase angle for each section can be computed.

When the specified beam tilt is comparable with the beam width of the elevation pattern, the steering of the array reduces the gain from the equivalent array without any beam tilt. To improve the antenna gain, mechanical tilt of the individual panels, as well as the entire antenna, is resorted to in some cases. However, mechanically tilting the entire antenna results in variable beam tilt around the azimuth.

Null-Fill

Another important antenna criterion is the null-fill requirement. If the antenna is near the center of the coverage area, depending on the minimum gain, the nulls in the coverage area must be filled in to provide a pattern that lies above the 100-mV/m curve for that particular height. For low-gain antennas, this problem is not severe, especially when the antenna height is lower than 2000 ft (610 m) and only the first null has to be filled. But in the case of UHF antennas, with gains greater than 20, the nulls usually occur close to the main beam and at least two nulls must be filled.

When the nulls of a pattern are filled, the gain of the antenna is reduced. A typical gain loss of 1 to 2 dB generally is encountered.

The variables for pattern null-filling are the spacing of the radiators and the amplitudes and phases of the feed currents. The spacings generally are chosen to provide the minimum number of radiators necessary to achieve the required gain. Hence, the only variables are the $2(N-1)$ relative amplitudes and phases.

The distance from the antenna to the null can be approximated if the gain and the height of the antenna above average terrain are known. Because the distance at any depression angle θ can be approximated as

$$D = 0.0109\frac{H}{\theta} \tag{5.2.31}$$

with H equal to the antenna height in feet, and the depression angle of the mth null equal to

$$\theta_m = 57.3\sin^{-1}\left(\frac{m}{g_e}\right) \quad g_e = \text{elevation power gain of antenna} \tag{5.2.32}$$

then

$$D_m = 0.00019\frac{H\,g_e}{m} \text{ miles for } \sin\frac{m}{g_e} \approx \frac{m}{g_e} \tag{5.2.33}$$

is the distance from the antenna to the mth null.

A simple method of null-filling is by power division among the vertically stacked radiators. For example, a 70:30 power division between each half of an array produces a 13 percent fill of the first null. Power division usually is employed where only the first null is to be filled.

Another approach to null-filling by changing only the phases of the currents is useful because the input power rating of the antenna is maximized when the magnitude of the current to each radiator in the array is adjusted to its maximum value. For example, if the bottom and the top layers of an N-layer array differ in phase by θ from the rest, the first $(N/2) - 1$ nulls are filled.

In practice, the elevation pattern is synthesized, taking into consideration all the design constraints, such as power-rating of the individual radiators and the restrictions imposed on the feed system because of space, access, and other parameters. Beam tilting is achieved by progressive or discrete phasing of sections of the antenna. The pattern shown in Figure 5.2.6 illustrates the final design of the array pattern of a high-gain antenna, determined by a computer-aided iteration technique.

5.2.3c Azimuthal-Pattern Shaping

For omnidirectional antennas, a circular azimuthal pattern is desired. However, in practice, the typical circularity may differ from the ideal by ±2 dB. The omnidirectional pattern is formed by the use of several radiators arranged within a circle having the smallest-possible diameter. If a single radiator pattern can be idealized for a sector, several such radiators can produce truly cir-

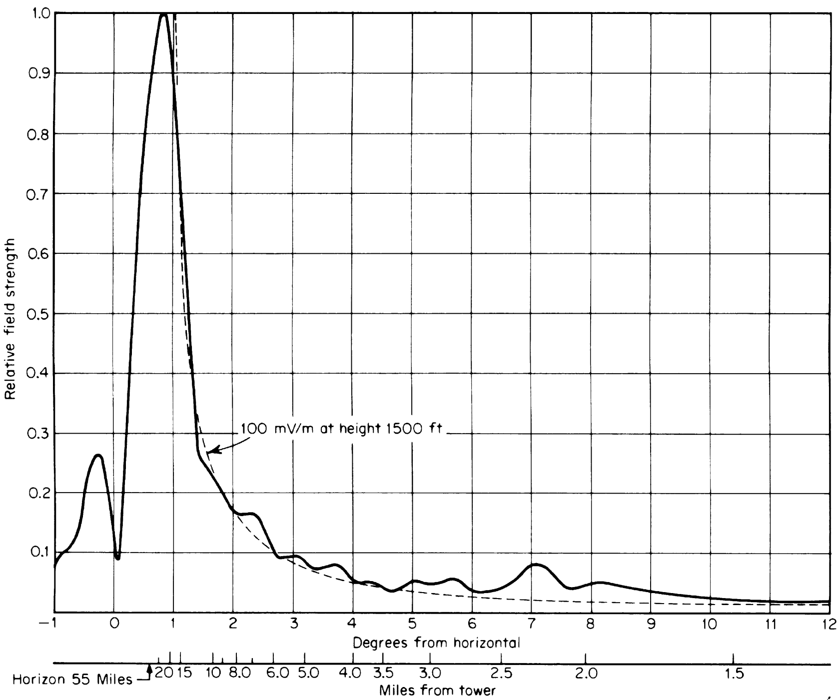


Figure 5.2.6 High-gain UHF antenna (ERP = 5 MW, gain = 60, beam tilt = 0.75°).

cular patterns (see Figure 5.2.7). Practical single-radiator-element patterns do not have sharp transitions, and the resultant azimuthal pattern is not a perfect circle. Furthermore, the interradiator spacing becomes important, because for a given azimuth, the signals from all the radiators add vectorially. The resultant vector, which depends on the space-phase difference of the individual vectors, varies with azimuth, and the circularity deteriorates with increased spacing.

In the foregoing discussion, it is assumed that the radiators around the circular periphery are fed in-phase. Similar omnidirectional patterns can be obtained with radial-firing panel antennas when the panels differ in phase uniformly around the azimuth wherein the total phase change is a multiple of 360°. The panels then are offset mechanically from the center lines as shown in Figure 5.2.8. The offset is approximately 0.19 wavelength for triangular-support towers and 0.18 wavelength for square-support towers. The essential advantage of such a phase rotation is that, when the feedlines from all the radiators are combined into a common junction box, the first-order reflections from the panels tend to cancel at the input to the junction box, resulting in a considerable improvement in the input impedance.

The azimuthal pattern of a panel antenna is a cosine function of the azimuthal angle in the front of the radiator, and its back lobe is small. The half-voltage width of the frontal main lobe ranges from 90° for square-tower applications to 120° for triangular towers. The panels are affixed on the tower faces. Generally, a 4-ft-wide tower face is small enough for U. S. channels 7

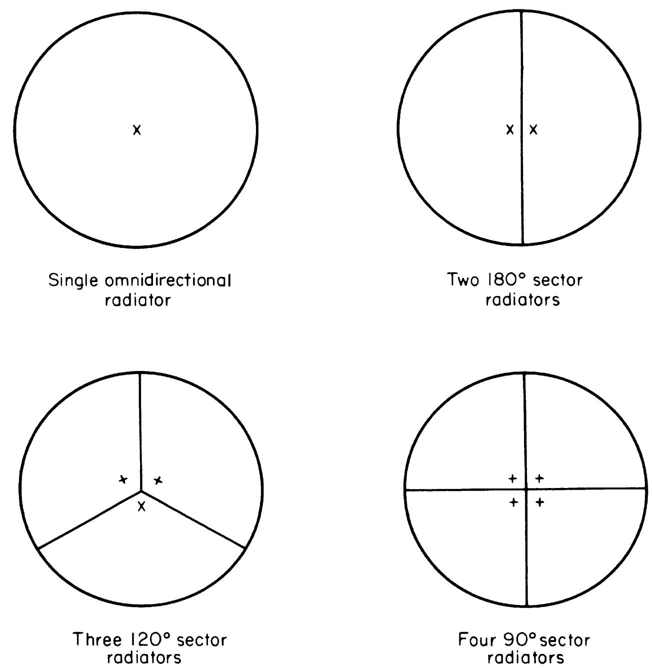


Figure 5.2.7 Horizontal pattern formation, ideal case.

to 13. For channels 2 to 6, the tower-face size could be as large as 10 ft (3 m). Table 5.2.2 lists typical circularity values.

In all the previous cases, the circular omnidirectional pattern of the panel antenna is achieved by aligning the main beam of the panels along the radials. This is the *radial-fire* mode. Another technique utilized in the case of towers with a large cross section (in wavelengths) is the *tangential-fire* mode. The panels are mounted in a skewed fashion around a triangular or square tower, as shown in Figure 5.2.9. The main beam of the panel is directed along the tangent of the circumscribed circle as indicated in the figure. The optimum interpanel spacing is an integer number of wavelengths when the panels are fed in-phase. When a rotating-phase feed is employed, correction is introduced by modifying the offset—for example, by adding 1/3 wavelength when the rotating phase is at 120°. The table of Figure 5.2.9 provides the theoretical circularities for ideal elements. Optimization is achieved in practice by model measurements to account for the back lobes and the effect of the tower members.

A measured pattern of such a tangential-fire array is shown in Figure 5.2.10.

In the case of directional antennas, the desired pattern is obtained by choosing the proper input-power division to the panels of each layer, adjusting the phase of the input signal, and/or mechanically tilting the panels. In practice, the azimuthal-pattern synthesis of panel antennas is done by superposition of the azimuthal phase and amplitude patterns of each radiator, while adjusting the amplitudes and phases of the feed currents until a suitable configuration of the panels on the tower yields the desired azimuthal pattern.

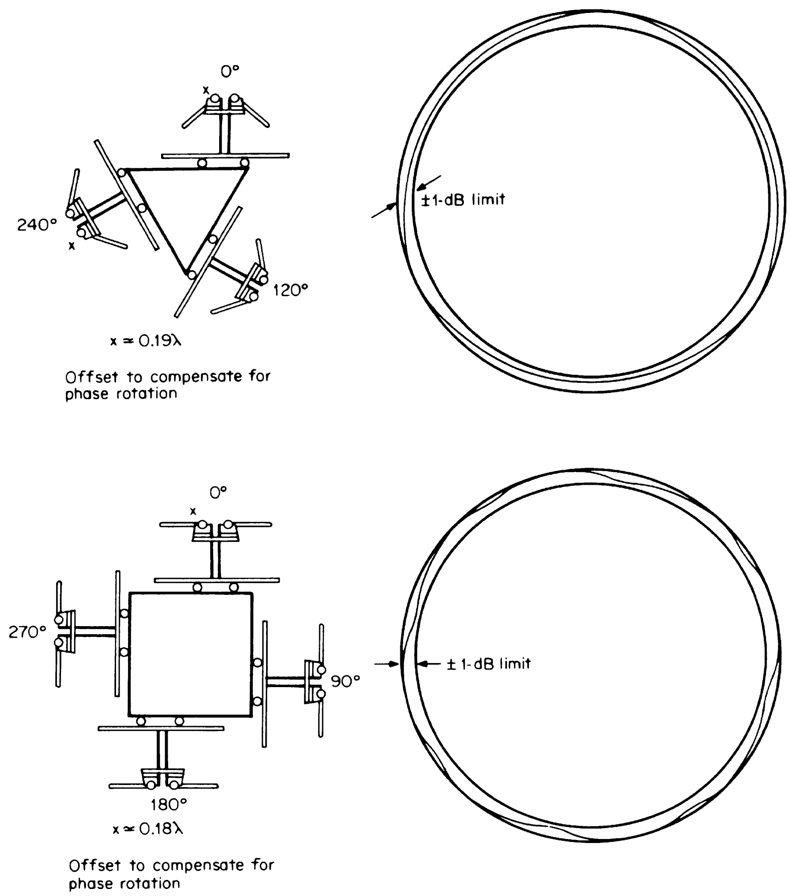


Figure 5.2.8 Offset radial firing panels.

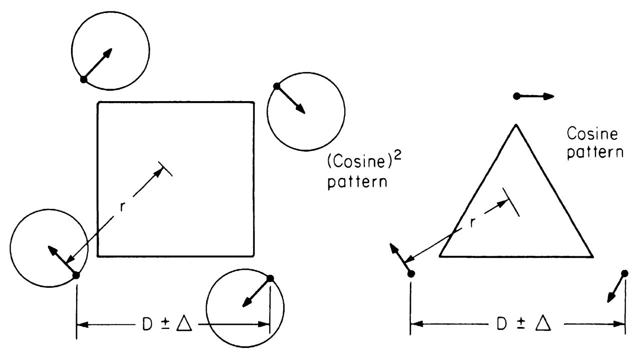
The *turnstile* antenna is a top-mounted omnidirectional pole antenna. Utilizing a phase rotation of four 90° steps, the crossed pairs of radiators act as two dipoles in quadrature, resulting in a fairly smooth pattern. The circularity improves with decreasing diameter of the turnstile support pole.

The turnstile antenna can be directionalized. As an example, a peanut-shaped azimuthal pattern can be synthesized, either by power division between the pairs of radiators or by introducing proper phasing between the pairs. The pattern obtained by phasing the pairs of radiators by 70° instead of the 90° used for an omnidirectional pattern is shown in Figure 5.2.11.

A directional pattern of a panel antenna with unequal power division is shown in Figure 5.2.12. The panels are offset to compensate for the rotating phase employed to improve the input impedance of the antenna.

Table 5.2.2 Typical Circularities of Panel Antennas

Shape	Tower-face Size, ft (m)	Circularity, ± dB	
		Channels 2–6	**Channels 7–13**
Triangular	5 (1.5)	0.9	1.8
	6 (1.8)	1.0	2.0
	7 (2.1)	1.1	2.3
	10 (3.0)	1.3	3.0
	4 (1.2)	0.5	1.6
Square	5 (1.5)	0.6	1.9
	6 (1.8)	0.7	2.4
	7 (2.1)	0.8	2.7
	10 (3.0)	1.2	3.2



$r = 0.577D$

$$\Delta = \begin{cases} 0 & \text{for in-phase feed} \\ \frac{\lambda}{4} & \text{for rotating-phase feed} \end{cases}$$

$r = 0.707D$

$$\Delta = \begin{cases} 0 & \text{for in-phase feed} \\ \frac{\lambda}{3} & \text{for rotating-phase feed} \end{cases}$$

Square configuration		Triangular configuration	
D/λ	Circularity, ± dB	*D*/λ	Circularity, ± dB
1	0.09	1	0.61
2	0.33	2	0.70
3	0.63	3	0.98
4	0.93	4	1.23
5	1.24	5	1.53
6	1.50	6	1.83

Figure 5.2.9 Tangential-fire mode. Note that with back lobes and tower reflections, the circularities tend to be worse by about 2 dB than those given here, especially for large tower sizes.

5.2.4 Voltage Standing-Wave Ratio and Impedance

The transmission line connecting the transmitter to the antenna is never fully transparent to the incoming or *incident wave*. Because of imperfections in manufacture and installation, some of

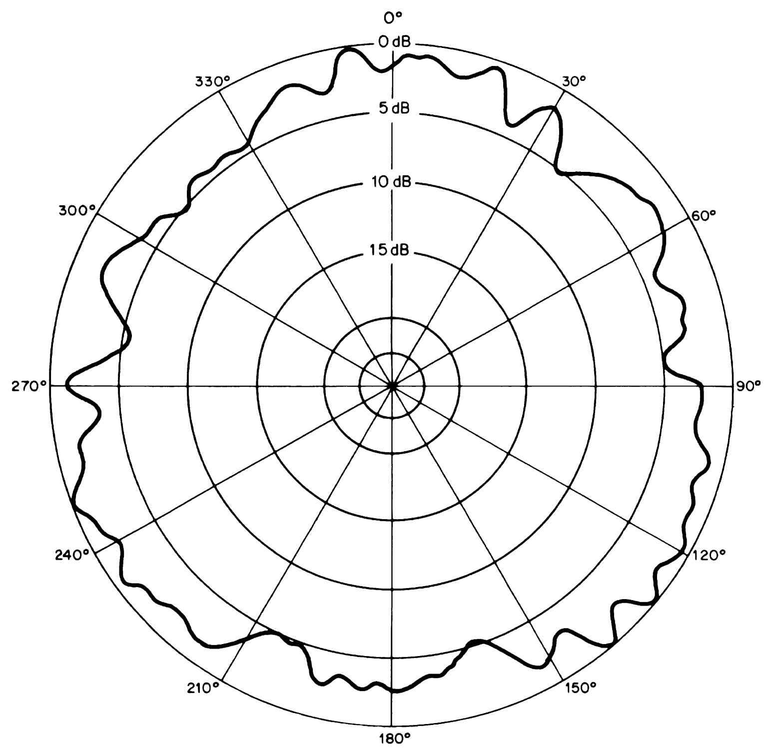


Figure 5.2.10 Measured azimuthal pattern of a "tangential-fire" array of three panels fed in-phase around a triangular tower with D = 7.13 wavelengths.

the power in the incident wave can be reflected at a number of points in the line. Additional reflection occurs at the line-to-antenna interface, because the antenna per se presents an imperfect match to the incident wave. These reflections set up a *reflected wave* that combines with the incident wave to form a *standing wave* inside the line. The characteristic of the standing-wave pattern is periodic maximums and minimums of the voltage and current along the line. The ratio of the maximum to minimum at any plane is called the *voltage standing-wave ratio* (VSWR). Because the VSWR is varying along the transmission line, the reference plane for the VSWR measurement must be defined. When the reference plane is at the gas stop input in the transmitter room, the measured value is *system VSWR.* When the reference plane is at the input to the antenna on the tower, the measured value is the *antenna VSWR.* The system VSWR differs from the antenna VSWR owing to the introduction of standing waves by the transmission line. When two sources of standing waves S_1 and S_2 exist, then the maximum VSWR is

$$\mathrm{VSWR}_{max} = S_1 S_2 \tag{5.2.34}$$

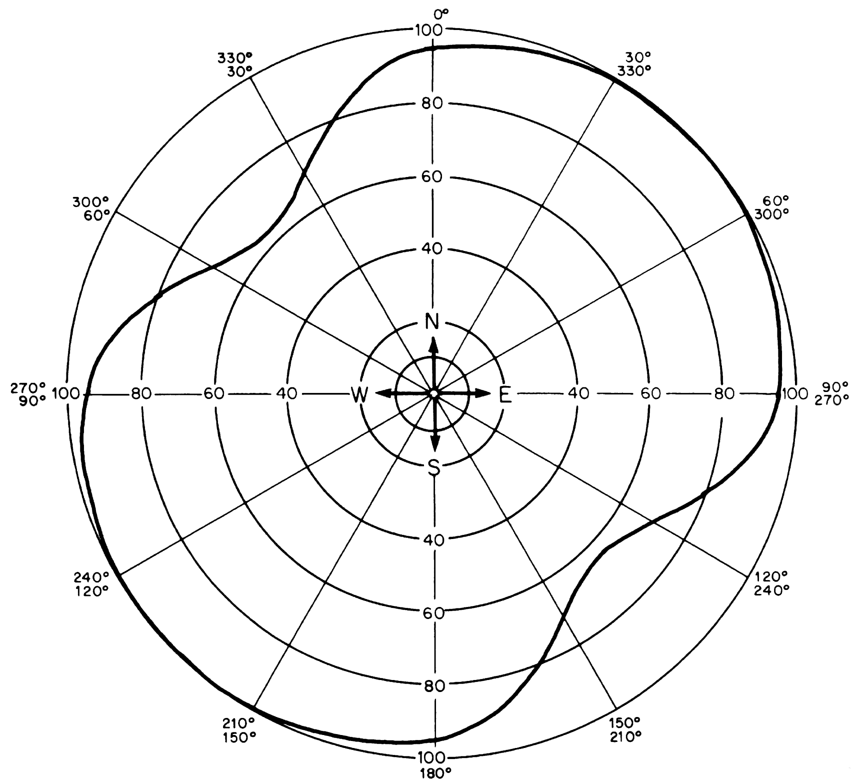


Figure 5.2.11 Directionalizing the superturnstile antenna by phasing.

and the minimum VSWR is

$$\text{VSWR}_{\text{min}} = \frac{S_2}{S_1} \quad \text{for } S_1 < S_2 \tag{5.2.35}$$

More generally, the expected system VSWR for n such reflections is, for the maximum case

$$\text{VSWR}_{\text{max}} = S_1 S_2 S_3 \ldots S_n \tag{5.2.36}$$

and for the minimum case

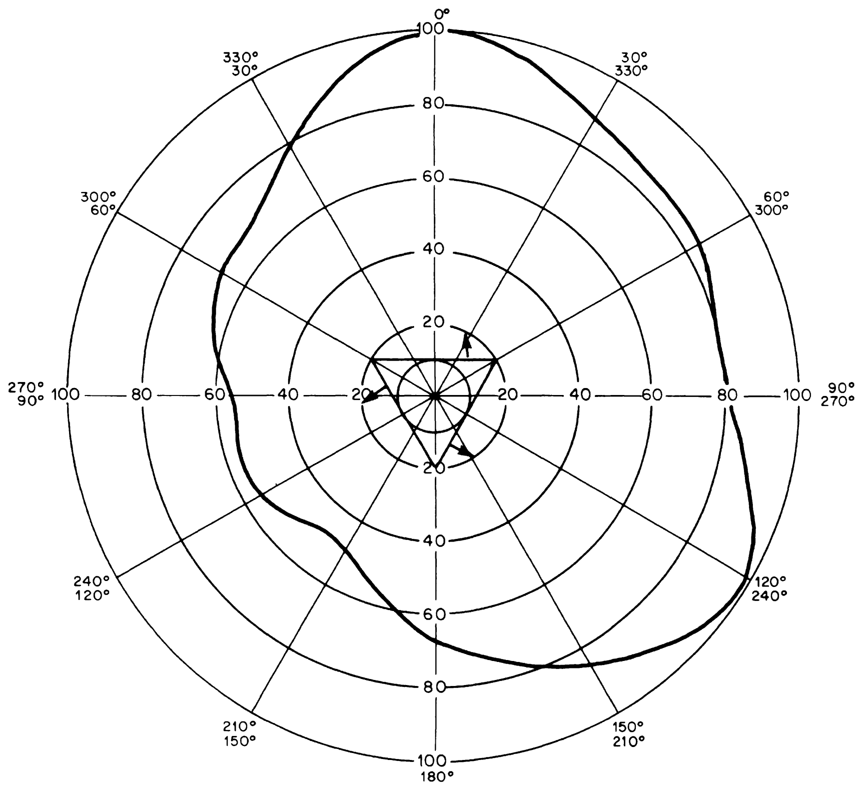


Figure 5.2.12 Directional panel antenna implemented using power division and offsetting.

$$\mathrm{VSWR}_{\min} = \frac{S_n}{S_1 S_2 S_3 \ldots S_{n-1}} \quad \text{for } S_1 < S_2 \ldots S_n \tag{5.2.37}$$

If the calculated minimum VSWR is less than 1.00, then the minimum VSWR = 1.00.

As an example, consider an antenna with an input VSWR of 1.05 at visual and 1.10 at aural carrier frequencies. If the transmission line per se has a VSWR of 1.05 at the visual and 1.02 at aural carriers, the *system* VSWR will be between

$$1.00 = \frac{1.05}{1.05} \le S_{\mathrm{vis}} \le 1.05 \times 1.05 = 1.103 \tag{5.2.38}$$

$$1.078 = \frac{1.10}{1.02} \leq S_{\text{aural}} \leq 1.10 \times 1.02 = 1.122 \tag{5.2.39}$$

The VSWR resulting from any reflection is defined as

$$S = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{5.2.40}$$

where $|\Gamma|$ is the magnitude of the reflection coefficient at that frequency. For example, if 2.5 percent of the incident voltage is reflected at the visual carrier frequency, the VSWR at that frequency is

$$S = \frac{1+0.025}{1-0.025} = 1.05 \tag{5.2.41}$$

A high value of VSWR is undesirable because it contributes to:

- Visible ghosts if the source of the VSWR is more than 250 ft (76 m) away from the transmitter
- Short-term echoes (<0.1-μs delay)
- Aural distortion
- Reduction of the transmission line efficiency

Of all the undesirable effects of the system VSWR, the first, a visible ghost resulting from input VSWR, is the most critical for conventional (analog) television applications. The further the antenna is from the transmitter, the higher the subjective impairment of the picture because of the reflection at the input of the antenna, will be.

Antenna input specification in terms of VSWR is not an effective figure of merit to obtain the best picture quality. For example, Figure 5.2.13 shows a comparative performance of two antennas. Antenna *A* has a maximum VSWR of 1.08 across the channel and a VSWR of 1.06 at picture (pix) carrier. Antenna *B* has a maximum VSWR of 1.13 and a VSWR of 1.01 at pix. It is hard to tell anything about the relative picture impairment of these two antennas by analyzing the VSWR alone. However, the reflection of a 2-*T* sine-squared pulse by each antenna is also shown in the figure. It can be seen that antenna *A*, with maximum VSWR of 1.08, produces a reflection of more than 3 percent. This reflection results in a ghost that could be perceptible if the transmission line to the antenna is at least 600 ft long. Antenna *B* with a maximum VSWR of 1.13 produces only 1 percent reflection for the same pulse.

The pulse response of an antenna mounted on top of a tower can be measured if the transmission line is sufficiently long and "clean" to resolve the incident from the reflected pulse. If the line is not sufficiently long or if knowledge of the antenna's pulse response is required prior to installation, a calculation is possible. Pulse response cannot be calculated from the VSWR data

(a)

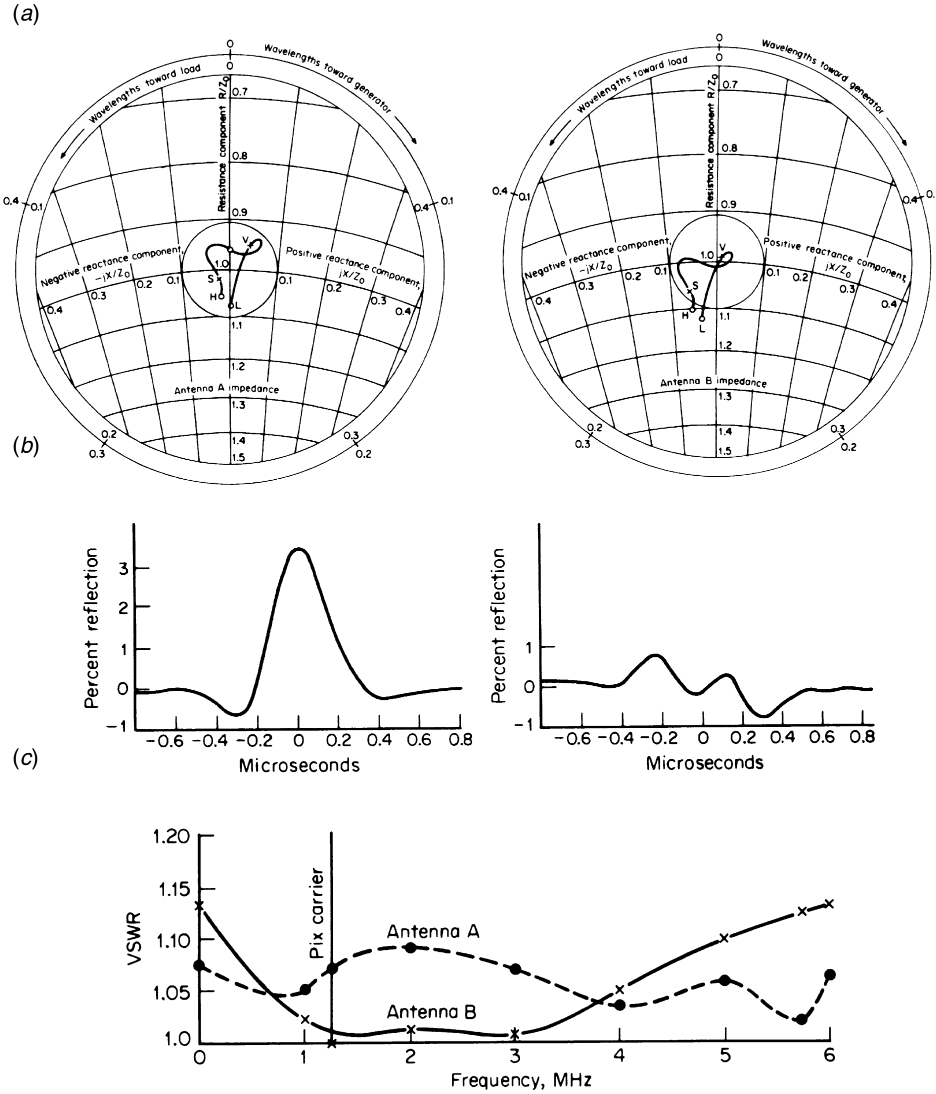


Figure 5.2.13 Example VSWR considerations for two antennas: (*a*) impedance, (*b*) reflected pulse, (*c*) measured VSWR.

alone because it contains no information with respect to the phase of the reflection at each frequency across the channel. Because the impedance representation contains the amplitude and phase of the reflection coefficient, the pulse response can be calculated if the impedance is known. The impedance representation is typically done on a Smith chart, which is shown in Figure 5.2.13 for antennas *A* and *B*. Some attempts at relating various shapes of VSWR curves to subjective picture quality have been made. A good rule of thumb is to minimize the VSWR in the region from –0.25 to + 0.75 MHz of the visual carrier frequencies to a level below 1.05 and not to exceed the level of 1.08 at color subcarrier.

5.2.4a VSWR Optimization Techniques

As noted in the previous section, the shape of the antenna VSWR across the channel spectrum must be optimized to minimize the subjective picture impairment. Frequently, it may be desirable to perform the same VSWR optimization on the transmission line, so that the entire system appears transparent to the incoming wave. The optimization of the transmission line VSWR is a relatively time-consuming and expensive task because it requires laying out the entire length of line on the ground and slugging it at various points. *Slugging* describes a technique of placing a metallic sleeve of a certain diameter and length that is soldered over the inner conductor of a coaxial transmission line. In some instances, it is more convenient to use a section of line with movable capacitive probes instead of a slug. This section is usually called variously a *variable transformer, fine tuner,* or *impedance matcher.*

The single-slug technique is the simplest approach to VSWR minimization. At any frequency, if the VSWR in the line is known, the relationship between the slug length in wavelengths and its characteristic impedance is given by

$$\frac{L}{\lambda}=\frac{1}{2\pi}\tan^{-1}\left[\frac{S-1}{\sqrt{\left(S-R^2\right)\left[\left(1/R^2\right)-S\right]}}\right] \tag{5.2.42}$$

Where:
S = existing VSWR
R = slug characteristic impedance ÷ line characteristic impedance
L/λ = length of slug

A graphic representation of this expression is given in Figure 5.2.14. The effect of the fringe capacitance, resulting from the ends of the slug, is not included in the design chart because it is negligible for all television channels. After the characteristic impedance of the slug is known, its diameter is determined from

$$Z_c = 138\log_{10}\frac{D}{d} \tag{5.2.43}$$

Where:
D = the outside diameter of the slug conductor
d = the outside diameter of the inner conductor

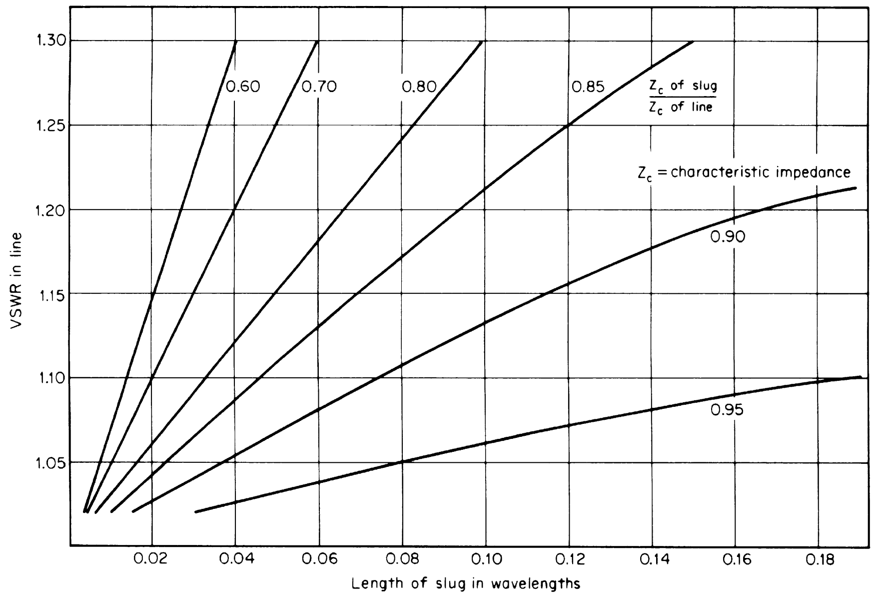


Figure 5.2.14 Single-slug matching of a coaxial line.

The slug thus constructed is slowly slid over the inner conductor until the VSWR disappears. This occurs within a line length of 1/2 wavelength.

There are two shortcomings in the single-slug technique:

- Access to the inner conductor is required
- The technique is not applicable if the VSWR at two frequencies must be minimized

The first shortcoming can be eliminated by using the variable transformer mentioned previously. While it is more expensive, slug machining and installation sliding adjustments are avoided. The second shortcoming can be overcome with the double-slug technique, or more conveniently, with two variable transformers.

The single- and double-slug techniques can have an undesirable effect if not properly applied. The slugs should be placed as near as possible to the source of the undesirable VSWR. Failure to do so can lead to higher VSWRs at other frequencies across the bandwidth of interest. Thus, if both the system and the antenna VSWRs are high at the visual carrier, slugging at the transmitter room will lower the system VSWR but will not eliminate the undesirable echo. Another effect of slugging is the potential alteration of the power and voltage rating. This is of particular importance if the undesirable VSWR is high. Generally, the slugging should be limited to situations where the VSWR does not exceed 1.25.

5.2.5 Azimuthal-Pattern Distortion in Multiple-Antenna Installations

In a stacked arrangement, the cross sections of the support structure of the antenna on the lower levels are large in order to support the antenna above. Hence, the circularity of the azimuthal pattern of the lower antennas will not be as uniform as for the upper antennas where the support structure is smaller.

In the case of a candelabra arrangement, the centers of radiation of most antennas are approximately equal. However, the radiated signal from each antenna is scattered by the other opposing antennas and, owing to the reflected signal, there results a deterioration of azimuthal-pattern circularity and video-signal performance criteria. When the proximity of one antenna to others is equal to its height or less, the shape of its elevation pattern at the interfering antennas is essentially the same as its aperture illumination. Consequently the reflections of significance are from the sections of the interfering structures parallel to the aperture of the radiating antenna. In this case, a two-dimensional analysis of the scatter pattern can be utilized to estimate the reflected signal and its effect on the free-space azimuthal pattern.

Owing to the physical separation between the transmitting antenna and the reflecting structure, the primary and reflected signals add in-phase in some azimuthal directions and out-of-phase in others. Thus, the overall azimuthal pattern is serrated. The minimum-to-maximum level of serrations in any azimuthal direction is a function of the cross section of the opposing structure. It also is directly proportional to the incident signal on the reflecting structure and inversely proportional to the square root of the spacing, expressed in wavelengths.

Furthermore, the reflections resulting from the vertical polarization component are higher than those resulting from the horizontal polarization component. Consequently, candelabras for circularly polarized antennas require larger spacing or fewer antennas. Figures 5.2.15 and 5.2.16 show the azimuthal pattern distortion of a channel-4 circularly polarized antenna 35 ft (11 m) away from a channel-10 circularly polarized antenna, for horizontal and vertical polarizations, respectively.

The calculated in-place pattern is based on ideal assumptions, and the exact locations of the nulls and peaks of the in-place pattern cannot always be determined accurately prior to installation. However, the outer and inner envelopes of the pattern provide a reasonable means for estimating the amount of deterioration that can result in the pattern circularity. For larger cross sections of the opposing cylinder, the scatter pattern can he approximated by a uniformly constant value around a major portion of the azimuth and a larger value over the shadow region. The former is very close to the rms value of the scatter serration. The maximum value occurs toward the shadow region except for the very small diameter of the opposing structure. The variation of the rms and peak values of $g(\phi)$, the reflection coefficient, is shown in Figure 5.2.17. The rms value of the reflection coefficient can be utilized to estimate the in-place circularity from an obstructing cylinder, over most of the periphery, and the peak value can be used to judge the signal toward the shadow region.

5.2.5a Echoes in Multiple-Tower Systems

In multiple-tower systems, at least two towers are utilized to mount the antennas for the same coverage area. The discussion relating to multiple-antenna systems in the previous section is applicable here when the towers are located within 100 ft of each other. The in-place azimuthal patterns can be determined and the echoes are not perceptible because the delay is less than 0.2 μs if the reradiation due to coupling into the feed system of the interfering antennas is negligible.

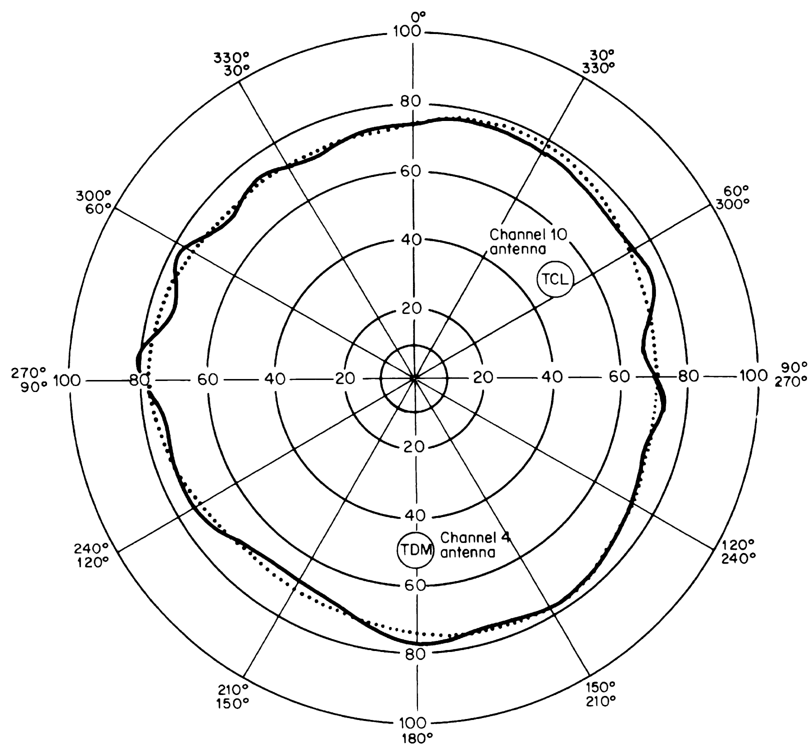


Figure 5.2.15 In-place azimuthal pattern of one antenna in the presence of another 35 ft away from it (horizontal polarization). The self pattern is the dotted curve.

When towers are located at a spacing greater than 100 ft (30 m), both the problem of azimuthal pattern deterioration and the magnitude of the ghost have to be considered. The magnitude of the reflection from an opposing structure decreases as the spacing increases, but not linearly. For example, if the spacing is quadrupled, the magnitude of the reflection is reduced by only one-half. When the antennas are located more than several hundred feet from each other, the magnitude of the reflection is usually small enough to be ignored, as far as pattern deterioration is concerned. However, a reflection of even 3 percent is noticeable to a critical viewer. Thus, large separations, usually more than a thousand feet, are necessary to reduce the echo visibility to an acceptably low level.

In the previous analysis for the illumination of the interfering structure by the antenna, it was assumed that only the portion of the interfering structure in the aperture of the antenna was of importance. This is true for separation distances comparable with the antenna aperture. However, as the separation distance from the antenna increases, the elevation pattern in any vertical plane changes its shape from a *near-field* to a *far-field* pattern. As the elevation pattern changes, more of the opposing structure is illuminated by the primary signal. This effect of distance from the antenna on the elevation pattern is illustrated in Figure 5.2.18. Note that the elevation pattern shown is plotted against the height of the opposing structure, rather than the elevation angle.

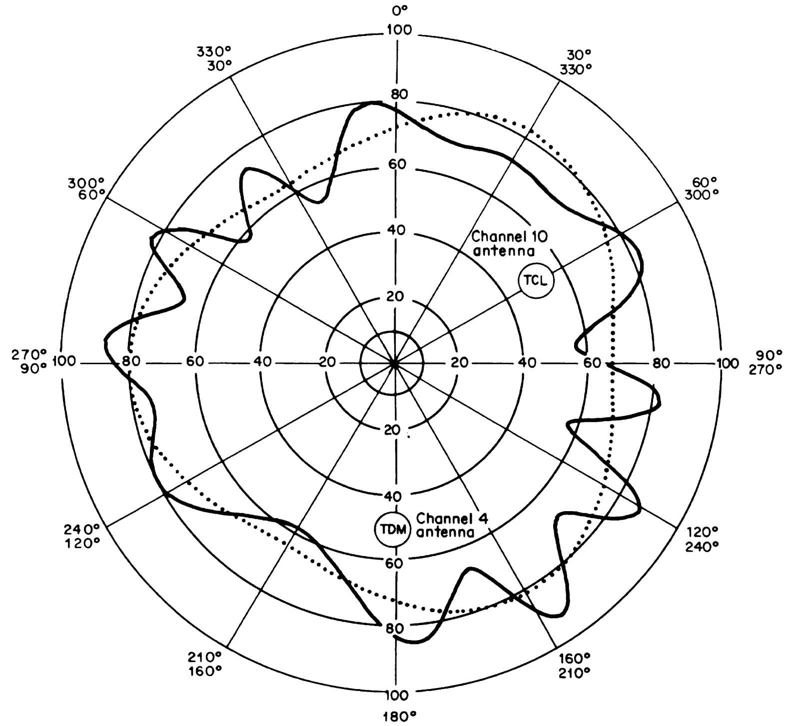


Figure 5.2.16 In-place azimuthal pattern of one antenna in the presence of another 35 ft away from it (vertical polarization). The self pattern is the dotted curve.

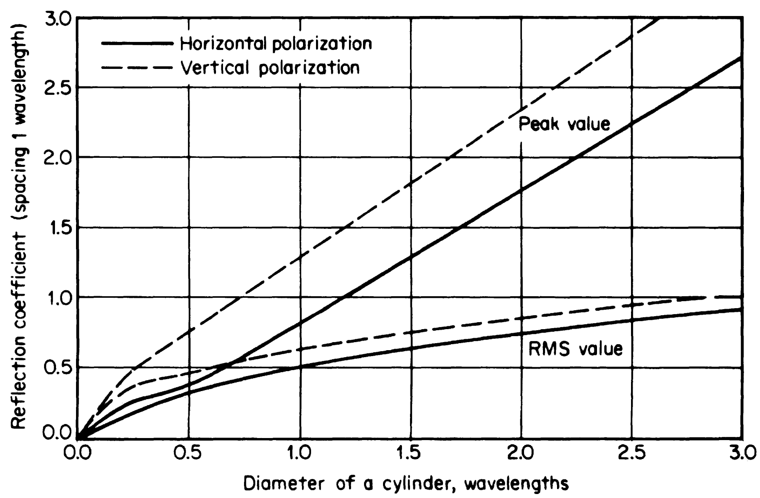


Figure 5.2.17 Reflection coefficient from a cylinder.

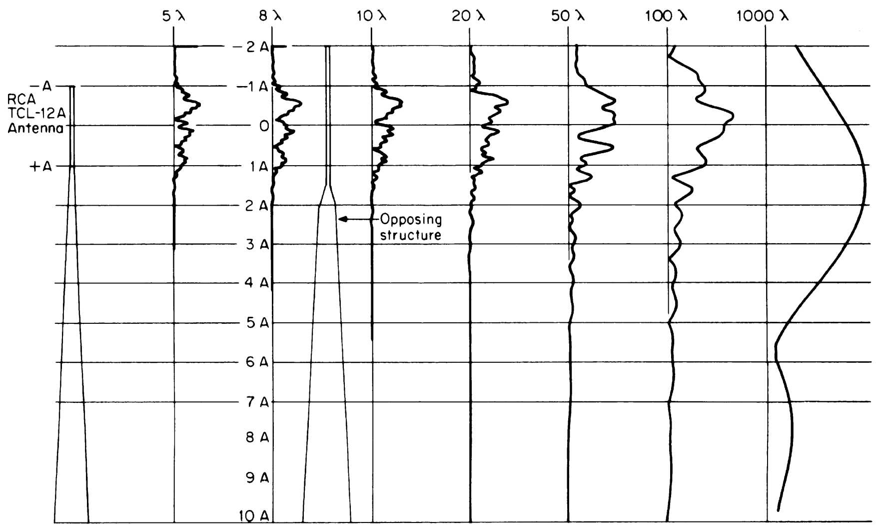


Figure 5.2.18 Illustration of opposing tower illumination for various spacings, given in wavelengths between the transmitting antenna and the opposing structure.

In practice, optimization of a multiple-tower system may require both a model study and computer simulation. The characteristics of the reflections of the particular tower in question can best be determined by model measurements and the effect of spacing determined by integration of the induced illumination on the interfering structure.

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Chapter

5.3

Television Transmitting Antennas

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Jerry C. Whitaker, Editor-in-Chief

5.3.1 Introduction

Broadcasting is accomplished by the emission of coherent electromagnetic waves in free space from a single or group of radiating-antenna elements, which are excited by modulated electric currents. Although, by definition, the radiated energy is composed of mutually dependent magnetic and electric vector fields, conventional practice in television engineering is to measure and specify radiation characteristics in terms of the electric field [1–3].

The field vectors may be polarized, or oriented, linearly, horizontally, vertically, or circularly. Linear polarization is used for some types of radio transmission. Television broadcasting has used horizontal polarization for the majority of the system standards in the world since its inception. More recently, the advantages of circular polarization have resulted in an increase in the use of this form of transmission, particularly for VHF channels.

Both horizontal and circular polarization designs are suitable for tower-top or tower-face installations. The latter option is dictated generally by the existence of previously installed tower-top antennas. On the other hand, in metropolitan areas where several antennas must be located on the same structure, either a *stacking* or a *candelabra-type* arrangement is feasible. Figure 5.3.1 shows an example of antenna stacking.

The use of stacked antennas provides a number of operational benefits, not the least of which is reduced cost. There are numerous examples of such installations, including the Sears Tower in Chicago (Figure 5.3.2) and Mt. Sutro in San Francisco, where antennas are mounted on a candelabra assembly (Figure 5.3.3). The implementation of DTV operation has generated considerable interest in such designs primarily because of their ability to accommodate a great number of antennas on a given structure.

Another solution to the multichannel location problem, where space or structural limitations prevail, is to diplex two stations on the same antenna. This approach, while economical from the installation aspect, can result in transmission degradation because of the diplexing circuitry, and antenna-pattern and impedance broadbanding usually is required.

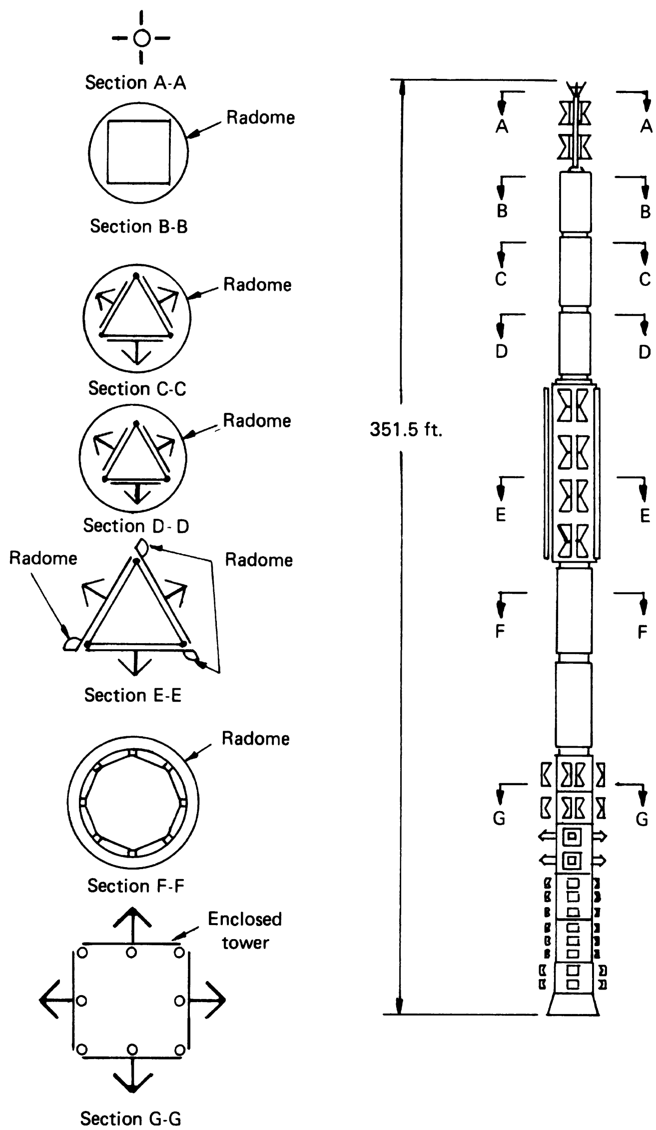

Figure 5.3.1 Stacked antenna array.

5.3.2 Common Antenna Designs

The typical television broadcast antenna is a broadband radiator operating over a bandwidth of several megahertz with an efficiency of over 95 percent. Reflections in the system between the transmitter and antenna must be small enough to introduce negligible picture degradation. Fur-

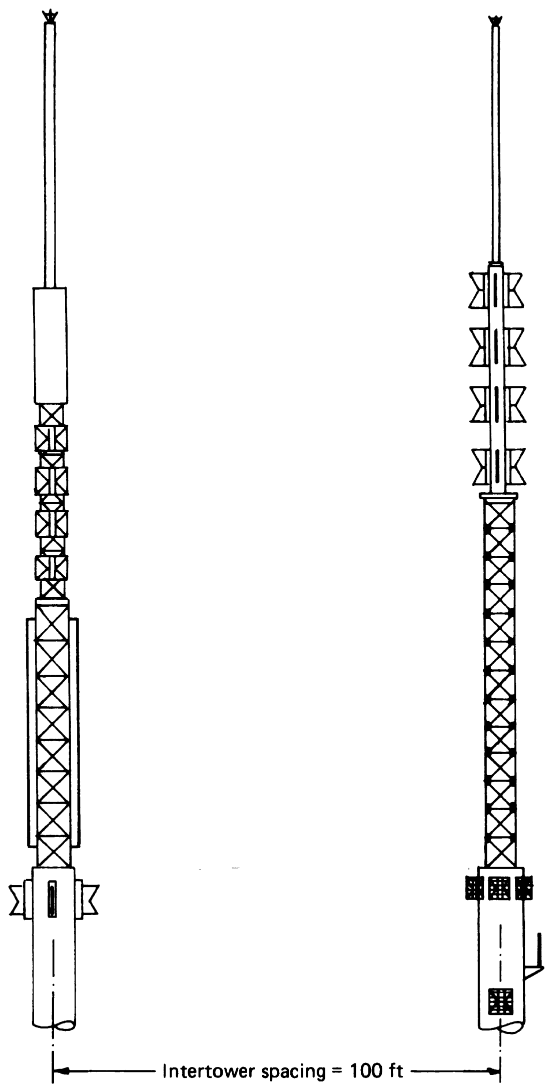

Figure 5.3.2 Twin tower antenna array atop the Sears Tower in Chicago.

thermore, the gain and pattern characteristics must be designed to achieve the desired coverage within acceptable tolerances, and operationally with a minimum of maintenance. Tower-top, pole-type antennas designed to meet these requirements can be classified into two broad categories:

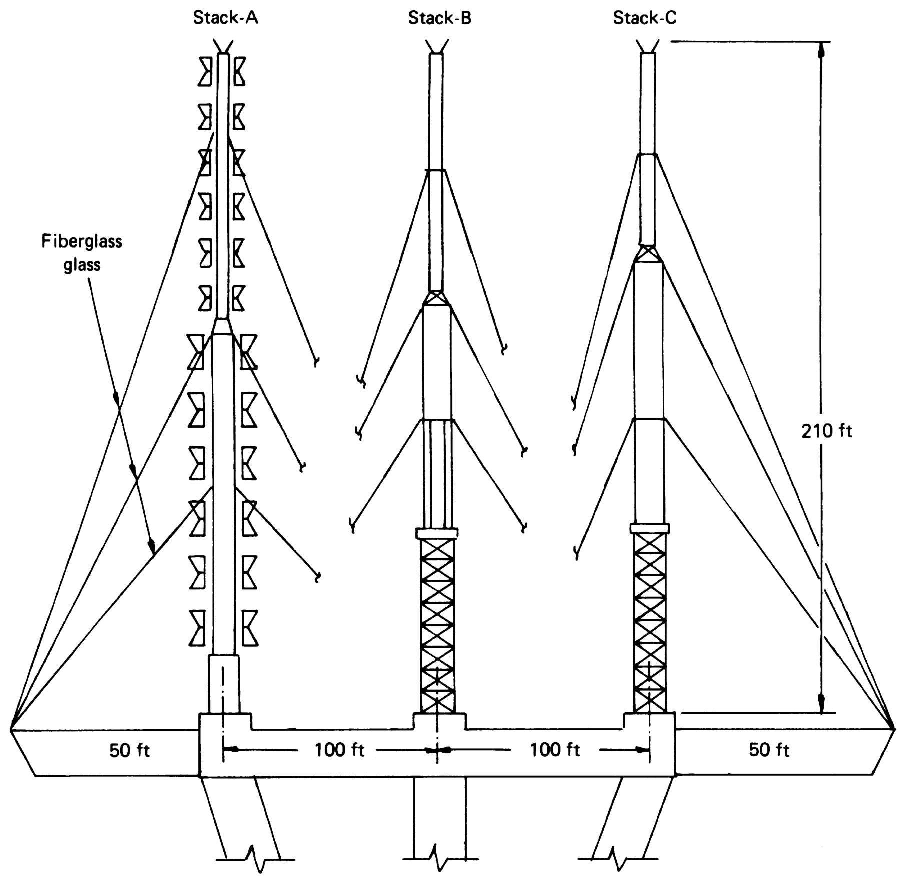

Figure 5.3.3 The triangular candelabra of antennas at Mt. Sutro in San Francisco.

- Resonant dipoles and slots
- Multiwavelength traveling-wave elements
- Turnstile configuration

The main consideration in top-mounted antennas is the achievement of excellent omnidirectional azimuthal fields with a minimum of windload. The earliest and most popular resonant antenna for VHF applications is the turnstile, which is made up of four batwing-shaped elements mounted on a vertical pole in a manner resembling a turnstile. The four "batwings" are, in effect, two dipoles that are fed in quadrature phase. The azimuthal-field pattern is a function of the diameter of the support mast and is within a range of 10 to 15 percent from the average value. The antenna is made up of several layers, usually six for channels 2 to 6 and twice that number for channels 7 to 13. This antenna is suitable for horizontal polarization only. It is unsuitable for side-mounting, except for standby applications where coverage degradation can be tolerated.

5.3.2a Multislot Radiator

A multislot antenna consists of an array of axial slots on the outer surface of a coaxial transmission line. The slots are excited by an exponentially decaying traveling wave inside the slotted pole. The omnidirectional azimuthal pattern deviation is less than 5 percent from the average circle. The antenna is generally about fifteen wavelengths long. A schematic of such an antenna is shown in Figure 5.3.4; the principle of slot excitation is illustrated in Figure 5.3.5.

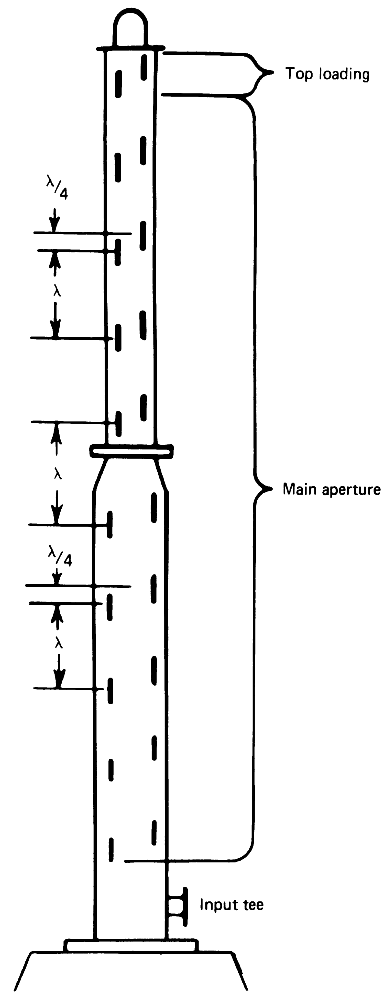

Figure 5.3.4 Schematic of a multislot traveling-wave antenna.

5.3.2b Circular Polarization

For circular polarization, both resonant and traveling-wave antennas are available. The traveling-wave antenna is essentially a side-fire helical antenna supported on a pole. A suitable number of such helices around the pole provide excellent azimuthal pattern circularity. This type of antenna is especially suited for application with channels 7 to 13 because only 3 percent pattern and impedance bandwidth are required. For channels 2 to 6 circular polarization applications where the bandwidth is approximately 10 percent, resonant dipoles around a support pole are a preferred configuration.

5.3.2c UHF Antennas for Tower-Top Installation

The slotted-cylinder antenna, commonly referred to as the *pylon* antenna, is a popular top-mounted antenna for UHF applications. Horizontally polarized radiation is achieved using axial resonant slots on a cylinder to generate circumferential current around the outer surface of the cylinder. An excellent omnidirectional azimuthal pattern is achieved by exciting four columns of slots around the circumference of the cylinder, which is a structurally rigid coaxial transmission line.

The slots along the pole are spaced approximately one wavelength per layer and a suitable number of layers are used to achieve the desired gain. Typical gains range from 20 to 40.

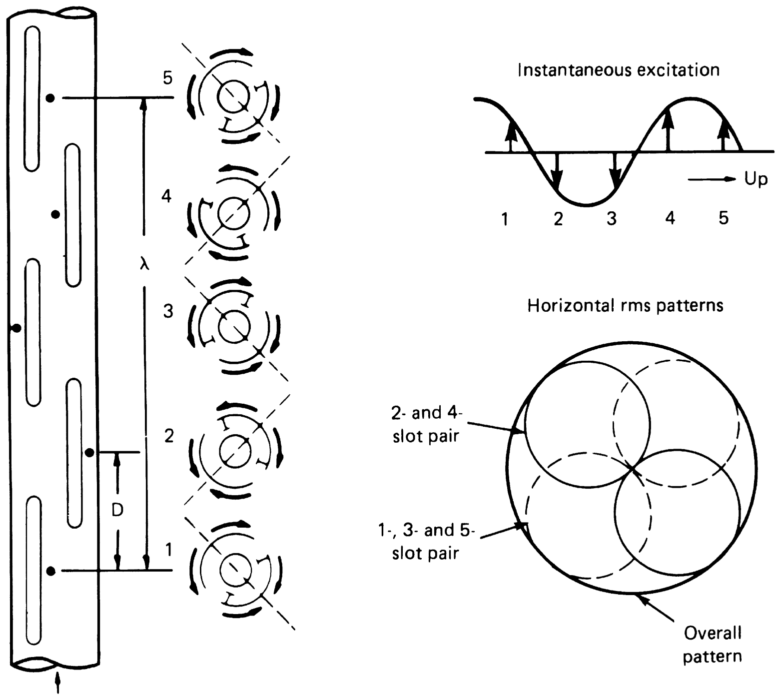

Figure 5.3.5 Principle of slot excitation to produce an omnidirectional pattern.

By varying the number of slots around the periphery of the cylinder, directional azimuthal patterns are achieved. It has been found that the use of fins along the edges of the slot provide some control over the horizontal pattern.

The ability to shape the azimuthal field of the slotted cylinder is somewhat restricted. Instead, arrays of panels have been utilized, such as the zigzag antenna [4]. In this antenna, the vertical component of the current along the zigzag wire is mostly cancelled out, and the antenna can be considered as an array of dipoles. Several such panels can be mounted around a polygonal periphery, and the azimuthal pattern can be shaped by the proper selection of the feed currents to the various panels.

5.3.2d VHF Antennas for Tower-Face Installation

There are a number of possible solutions to the tower-face mounting requirement. A common panel antenna used for tower face applications is the so-called *butterfly* [5] or batwing panel antenna developed from the turnstile radiator. This type of radiator is suitable for the entire range of VHF applications. Enhancements to the basic structure include modification of the shape of the turnstile-type wings to rhombus or diamond shape. Another version is the multiple dipole panel antenna used in many installations outside the U.S. For circularly polarized applications,

Table 5.3.1 Circularities of Panel Antennas for VHF Operation

Shape	Tower-face Size, ft (m)	Circularity, ±dB[1]	
		Channels 2–6	**Channels 7–13**
Triangular	5 (1.5)	0.9	1.8
	6 (1.8)	1.0	2.0
	7 (2.1)	1.1	2.3
	10 (3.0)	1.3	3.0
Square	4 (1.2)	0.5	1.6
	5 (1.5)	0.6	1.9
	6 (1.8)	0.7	2.4
	7 (2.1)	0.8	2.7
	10 (3.0)	1.2	3.2

[1] Add up to ±0.3 dB for horizontally polarized panels and ± 0.6 dB for circularly polarized panels. These values are required to account for tolerances and realizable phase patterns of practical hardware assemblies.

two crossed dipoles or a pair of horizontal and vertical dipoles are used [6]. A variety of cavity-backed crossed-dipole radiators are also utilized for circular polarization transmission.

The azimuthal pattern of each panel antenna is unidirectional, and three or four such panels are mounted on the sides of a triangular or square tower to achieve omnidirectional azimuthal patterns. The circularity of the azimuthal pattern is a function of the support tower size [7].

Calculated circularities of these antennas are shown in Table 5.3.1 for idealized panels. The panels can be fed in-phase, with each one centered on the face of the tower, or fed in rotating phase with proper mechanical offset on the tower face. In the latter case, the input impedance match is far better.

Directionalization of the azimuthal pattern is realized by proper distribution of the feed currents to the individual panels in the same layer. Stacking of the layers provides gains comparable with those of top-mounted antennas.

The main drawbacks of panel antennas are high wind-load, complex feed system inside the antenna, and the restriction on the size of the tower face in order to achieve smooth omnidirectional patterns. However, such devices provide an acceptable solution for vertical stacking of several antennas or where installation considerations are paramount.

5.3.2e UHF Antennas for Tower-Face Installation

Utilization of panel antennas in a manner similar to those for VHF applications is not always possible for the UHF channels. The high gains, which are in the range of 20 to 40 compared with those of 6 to 12 for VHF, require far more panels with the associated branch feed system. It is also difficult to mount a large number of panels on all the sides of a tower, the cross section of which must be restricted to achieve a good omnidirectional azimuthal pattern.

The zigzag panel described previously has been found to be applicable for special omnidirectional and directional situations. For special directional azimuthal patterns, such as a cardioid shape, the pylon antenna can be side-mounted on one of the tower legs.

The use of tangential-firing panels around the periphery of a large tower has resulted in practical antenna systems for UHF applications. Zigzag panels or dipole panels are stacked vertically

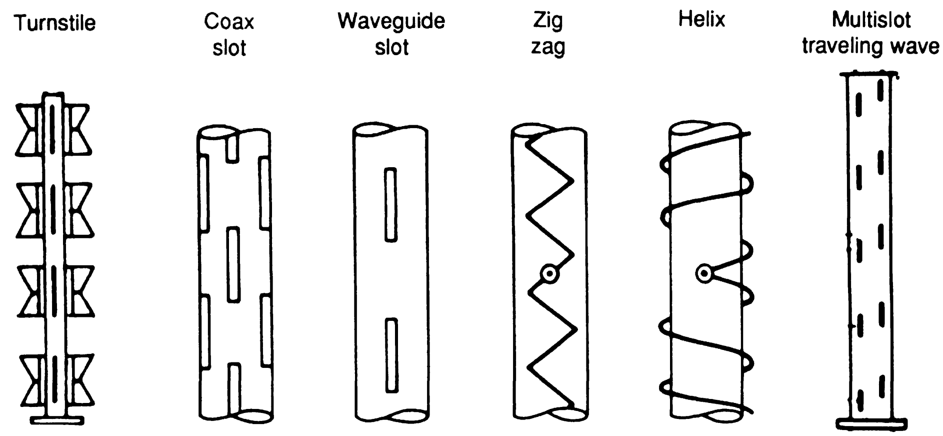

Figure 5.3.6 Various antenna designs for VHF and UHF broadcasting. Note that not all these designs have found commercial use.

at each of the corners of the tower and oriented such that the main beam is along the normal to the radius through the center of the tower. The resultant azimuthal pattern is usually acceptable for horizontal polarization transmission.

Figure 5.3.6 summarizes the most common TV antenna technologies for VHF and UHF applications.

5.3.2f Vertically Stacked Multiple Antennas

In metropolitan areas where there are several stations competing for the same audience, usually there may be only one preferred location for all the transmitting antennas [8, 9]. A straightforward approach to the problem is stacking the antennas one on top of the other. One of the earliest installations of stacked antennas was on the Empire State Building in New York City. Because the heights of the centers of radiation decrease from the antenna at the top to that at the lowest level, there is a preference to be at a higher level. Thus, the final arrangement depends on both technical and commercial constraints. For relatively uniform coverage, technical considerations usually dictate that the top of the mast be reserved for the higher channels and the bottom of the mast for the low channels. However, because of contractual stipulations, this is not always possible.

Vertical stacking provides the least amount of interference among the antennas. However, because the antennas in the lower levels are panels on the support tower faces, which tend to be larger because the level is lower, the azimuthal pattern characteristics can be less than optimum. Furthermore, the overall height constraint can compromise the desirable gain for each channel.

5.3.2g Candelabra Systems

In order to provide the same, as well as the highest, center of radiation to more than one station, antennas can be arranged on platform in a *candelabra* style. There are many *tee bar* arrangements in which there are two stacks of antennas. A triangular or even a square candelabra is utilized in some cases. When several antennas are located within the same aperture, the radiated signal from one antenna is partly reflected and partly reradiated by the opposing antenna or antennas. Because the interference signal is received with some time delay, with respect to the primary signal, it can introduce picture distortion and radiation-pattern deterioration. The choice of opposing antennas and the interantenna spacing and orientation of the antennas determine the trade-offs among the in-place performance characteristics, which include:

- Azimuthal pattern
- Video bandwidth response
- Echoes
- Differential windsway
- Isolation among channels

5.3.2h Multiple-Tower Installations

The *candelabra* multiple-antenna system requires cooperation of all the broadcasters in an area and considerable planning prior to construction [10]. In many cases, new channels are licensed after the first installation and addition of the antenna on an existing tower is not possible. Consequently, location on a nearby new tower is the only solution. In some cases, the sheer size of the candelabra may make it more expensive than multiple towers. The antenna farms around Philadelphia and Miami are good examples of several towers located in the same area.

In the case of multiple towers, the creation of long-delayed echoes is of major concern, if economically or practically towers cannot be located close enough to result in echoes that either (a) cannot be resolved by the television system, or (b) will not affect color subcarrier phase and amplitude (for analog systems). This would dictate an impractical spacing of under 100 ft (30 m). Circularly polarized antennas provide an advantage because the reflected signal sense of polarization rotation is usually reversed, and the effect of echoes can he reduced with a proper circularly polarized receiving antenna [11, 12]. The twin stack of antennas atop the Sears Tower in Chicago is illustrative of a multiple-tower system.

5.3.2i Multiplexing of Channels

Another technique of accommodating more than one channel in the same antenna location is by combining the signals from these stations and feeding them to the same antenna for radiation. Broadband antennas are designed for such applications. The antenna characteristics must be broadband in more terms than input impedance. Pattern bandwidth and, in the case of circularly polarized antennas, axial-ratio bandwidth are equally important. Generally, it is more difficult to broadband antennas if the required bandwidth will be in excess of 20 percent of the design-center frequency. Another of the problems of multiplexing is that the antenna must be designed for the peak voltage breakdown, which is proportional to the square of the number of channels. A third problem is the resolution of all technical, commercial, and legal responsibilities that arise from joint usage of the same antenna.

Multiplexed antennas typically are designed with integral redundancy. The antenna is split into two halves with two input feedlines. This provides protection from failure as a result of the potential reduction in the high-power breakdown safety margin.

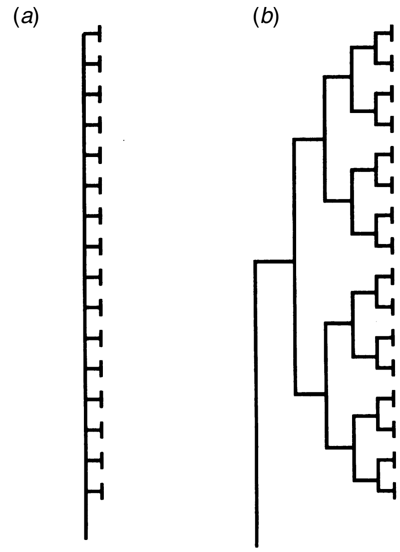

Figure 5.3.7 Antenna feed configurations: (*a*) series feed, (*b*) branch feed.

5.3.2j Broadband Television Antennas

As touched on in the previous section, the radiation of multiple channels from a single antenna requires the antenna to be broadband in both pattern and impedance (VSWR) characteristics. As a result, a broadband TV antenna represents a significant departure from the narrowband, single channel pole antennas commonly used for VHF and UHF. The typical single channel UHF antenna uses a series feed to the individual radiating elements, while a broadband antenna has a branch feed arrangement. The two feed configurations are shown in Figure 5.3.7.

At the designed operating center frequency, the series feed provides co-phased currents to its radiating elements. As the frequency varies, however, the electrical length of the series line feed changes such that the radiating elements are no longer in-phase outside of the designed channel. This electrical length change causes significant beam tilt out of band, and an input VSWR that varies widely with frequency.

In contrast, the branch feed configuration employs feed lines that are nominally of equal length. Therefore the phase relationships of the radiating elements are maintained over a wide span of frequencies. This provides vertical patterns with stable beam tilt, a requirement for multichannel applications.

The basic building block of the multi-channel antenna is the broadband panel radiator. The individual radiating elements within a panel are fed by a branch feeder system that provides the panel with a single input cable connection. These panels are then stacked vertically and arranged around a supporting spine or existing tower to produce the desired vertical and horizontal radiation patterns.

Bandwidth

The ability to combine multiple channels in a single transmission system depends upon the bandwidth capabilities of the antenna and waveguide or coax. The antenna must have the necessary bandwidth in both pattern and impedance (VSWR). It is possible to design an antenna system for low power applications using coaxial transmission line that provides whole-band capability. For high power systems, waveguide bandwidth sets the limits of channel separation.

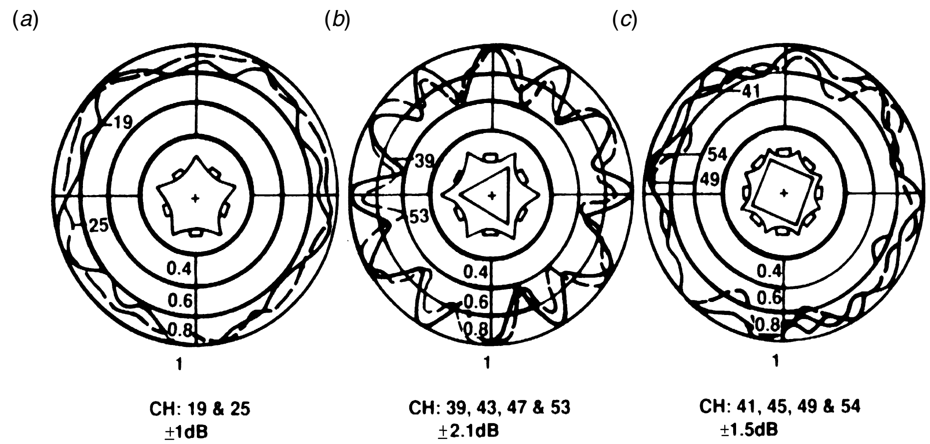

Figure 5.3.8 Measured antenna patterns for three types of panel configurations at various operating frequencies: (*a*) 5 panels per bay, (*b*) 6 panels per bay, (*c*) 8 panels per bay.

Antenna pattern performance is not a significant limiting factor. As frequency increases, the horizontal pattern circularity deteriorates, but this effect is generally acceptable, given the primary project objectives. Also, the electrical aperture increases with frequency, which narrows the vertical pattern beamwidth. If a high gain antenna were used over a wide bandwidth, the increase in electrical aperture might make the vertical pattern beamwidth unacceptably narrow. This is, however, usually not a problem because of the channel limits set by the waveguide.

Horizontal Pattern

Because of the physical design of a broadband panel antenna, the cross-section is larger than the typical narrowband pole antenna. Therefore, as the operating frequencies approach the high end of the UHF band, the *circularity* (average circle to minimum or maximum ratio) of an omnidirectional broadband antenna generally deteriorates.

Improved circularity is possible by arranging additional panels around the supporting structure. Previous installations have used 5, 6, and 8 panels per bay. These are illustrated in Figure 5.3.8 along with measured patterns at different operating channels. These approaches are often required for power handling considerations, especially when three or four transmitting channels are involved.

The flexibility of the panel antenna allows directional patterns of unlimited variety. Two of the more common applications are shown in Figure 5.3.9. The peanut and cardioid types are often constructed on square support spines (as indicated). A cardioid pattern can also be produced by side-mounting on a triangular tower. Different horizontal radiation patterns for each channel can also be provided, as indicated in Figure 5.3.10. This is accomplished by changing the power and/or phase to some of the panels in the antenna with frequency.

Most of these antenna configurations are also possible using a circularly-polarized panel. If desired, the panel can be adjusted for elliptical polarization, with the vertical elements receiving

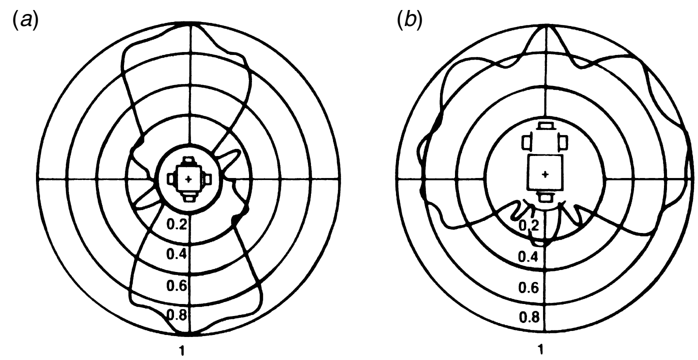

Figure 5.3.9 Common directional antenna patterns: (*a*) peanut, (*b*) cardioid.

less than 50 percent of the power. Using a circularly-polarized panel will reduce the horizontally-polarized ERP by half (assuming the same transmitter power).

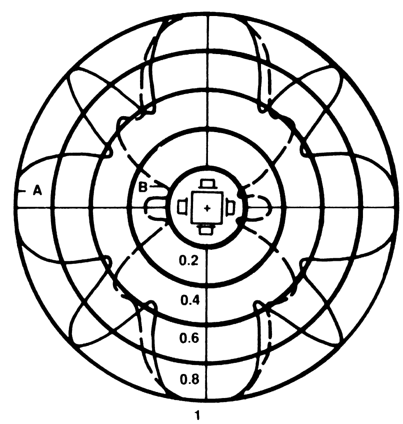

Figure 5.3.10 Use of a single antenna to produce two different radiation patterns, omnidirectional (trace A) and peanut (trace B).

5.3.3 DTV Implementation Issues

The design and installation of a transmitting antenna for DTV operation is a complicated process that must take into consideration a number of variables. Fortunately, new technologies and refinements to classic antenna designs have provided additional flexibility in this process.

5.3.3a Channel-Combining Considerations

A number of techniques are practical to utilize an existing tower for both NTSC and DTV transmissions. Combining RF signals allows broadcasters to use an existing structure to transmit NTSC and DTV from a common line and antenna or, in the case of a VHF and UHF combination, to utilize the same line to feed two separate antennas.

In the transition period from NTSC to DTV, many broadcasters have chosen to use their existing tower to transmit both NTSC and DTV channels. Some have chosen to add a new line and DTV antenna; others to combine their DTV with NTSC and transmit from a common antenna and line; and still others to consolidate to a new structure common to many local channels. For most stations, it is a matter of cost and feasibility.

Channel combiners, also known as *multiplexers* or *diplexers*, are designed for various applications. These systems can be generally classified as follows [13]:

- *Constant impedance*—designs that consist of two identical filters placed between two hybrids.
- *Starpoint*—designs that consist of single bandpass filters phased into a common output tee.
- *Resonant loop*—types that utilize two coaxial lines placed between two hybrids; the coaxial lines are of a calculated length.
- *Common line*—types that use a combination of band-stop filters matched into a common output tee.

The *dual-mode channel combiner* is a device that permits a single transmission line on a tower to feed two separate antennas. Dual-mode channel combining is the process by which two channels are combined within the same waveguide, but in separate orthogonal modes of propagation [14].

The device combines two different television channels from separate coaxial feedlines into a common circular waveguide. Within the circular waveguide, one channel propagates in the TE_{11} mode while the other channel propagates in the TM_{01} mode. The dual-mode channel combiner is reciprocal and, therefore, also may be used to efficiently separate two TE_{11}/TM_{01} mode-isolated channels that are propagating within the same circular waveguide into two separate coaxial lines. This provides a convenient method for combining at the transmitters and splitting at the antennas. The operating principles of the dual-mode channel combiner are described in [14].

5.3.3b Antenna Systems

The availability of suitable locations for new television transmission towers is diminishing, even in the secondary markets, and sites are practically nonexistent in major markets [15]. After the hurdles of zoning variance and suitable tower location are overcome, FAA restrictions and environmental concerns can delay the construction of a new tower for years. Not surprisingly, many broadcasters have looked at the pros and cons of using existing towers to support their new DTV antennas even though the prime tower-top spots are occupied.

For any given antenna, directional or omnidirectional, the tower will modify the as-designed antenna pattern. For optimum coverage, the as-installed pattern must be known—not just at the carrier frequency, but throughout the entire channel—before the relative position of the antenna and its azimuthal pattern orientation can be fixed. There is usually one position that will provide the optimum coverage without exceeding the structural limitations of the tower. This optimum position can be calculated (see [15]).

Coverage considerations are particularly important to DTV because undesired energies, such as reflections, translate into a loss of coverage, whereas the undesired energies in NTSC translate primarily into a loss of picture quality.

Another transmission-optimization technique that holds promise for DTV is circular polarization. The transmission of CP has obvious drawbacks in the form of a 2× increase in required transmitter power and transmission line, as well as a more complex antenna. Still, for the DTV signal, *polarization diversity* can be achieved if the vertically polarized signal is transmitted through CP. A polarization-diversity system at the receive antenna can provide missing signal level when one of the horizontal or vertical signal components experiences a deep fade. It follows that the inherent diversity attributes of CP operation could be put to good use in reducing the cliff-edge effect of the terrestrial DTV signal [16].

5.3.4 Key Considerations in System Design

Antenna system design is always an iterative process of configuration analysis, subject to some well-defined and many ill-defined constraints. Each iteration basically is a study with a sequence of basic technical and commercial decisions. The number of antennas at the same location increases the complexity of such a study, The main reason for this is that most constraints must be viewed from three angles: engineering, legal, and commercial. Following is a checklist of items that are key considerations in system design:

- Coverage and picture quality
- Transmitter power
- Antenna mechanical aperture
- Channel multiplexing desirability or necessity
- System maintenance requirements for the broadcaster and service organization
- Performance deterioration resulting from ice, winds, and earthquakes
- Initial investment
- Project implementation schedule
- Building code requirements
- Aesthetic desires of the broadcaster and the community
- Radiation hazards protection
- Environmental protection
- Beacon height
- Accessibility of beacon for maintenance

It is worth reemphasizing that these considerations are interrelated and cover more than isolated technical issues.

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