SECTION 2: ANTENNAS AND TOWERS

2.1

Design, Erection, and Maintenance of Antenna Structures

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INTRODUCTION

The purpose of this section is to provide broadcast engineers and managers information concerning the design, erection and maintenance of antenna structures. While fundamental principles of the design and behavior of these structures will be discussed, it is not intended to enable the reader to design and build his own tower, but rather to provide him with a basic understanding of these unique structures that will enable him to better plan, modify and maintain his facilities.

TOWER CHARACTERISTICS

Types

All towers may be classified in one of the two basic groups—guyed or self-supporting. As their names imply, guyed towers are those which depend upon cables running to anchors located some distances from the tower base for their structural integrity, while self-supporting towers rely solely on their own construction as a cantilivered space truss.

With only a few exceptions, the cost of the actual tower structure and foundations is considerably less for a guyed tower than for one that is self-supporting. The advantage of the self-supporting tower is the relatively small land area required. Therefore, the choice between guyed or self-supporting depends to a large degree on the availability and cost of real estate.

A self-supporting tower requires a nearly square plot of land with sides equal to 8 to 20 percent of its height.

The amount of land required for a guyed tower depends on the distance between the tower base and the guy anchors. This distance is preferably between 70 and 80 percent of the height which would require a rectangular plot having sides equal to 125 and 145 percent of the height.

Because of the great flexibility in guyed tower design, it is possible to reduce the anchor distance to as little as 35 percent of height thereby requiring a much smaller land area. However, the cost of the tower increases as the anchor distance decreases. The approximate relationship of cost to anchor distance for a representative 1200 feet television broadcast tower is shown in Fig. 1.

It is often possible to position a guyed tower on an irregularly shaped plot or to obtain long-term lease agreements or easements for guy paths and anchor locations in order to minimize the tower cost without obtaining large, rectangular land areas.

Configurations

1. ***Self-supporting Towers*** may be either square or triangular in cross section. While it is usually more economical to use a triangular cross

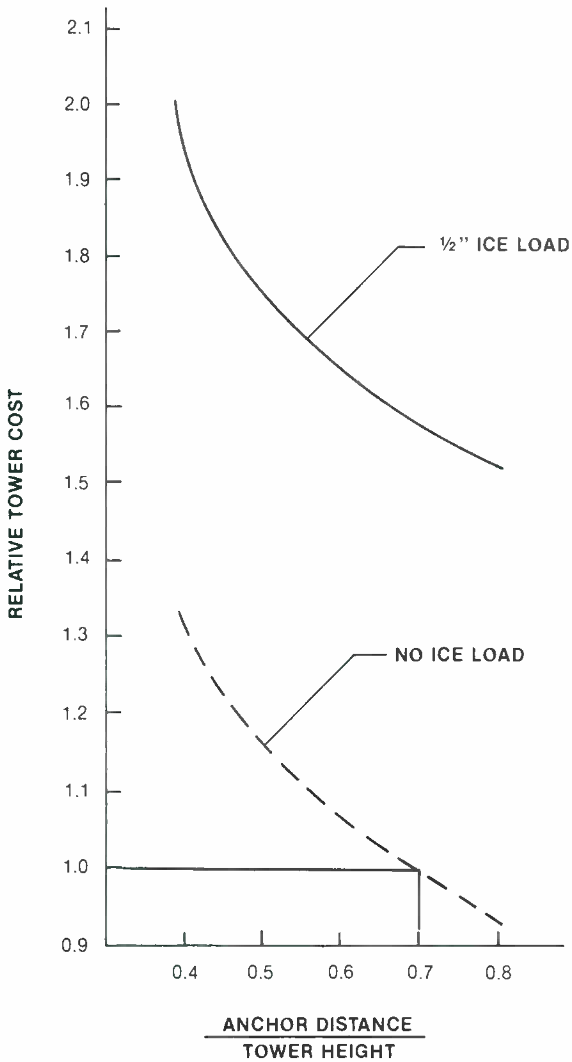


Fig. 1. Effects of anchor distance on cost of a 1200 ft. guyed TV broadcast tower.

section, there are situations where a square cross section is a better choice. The principal structural elements are the legs, the web bracing in each face, and if required for stability, horizontal diaphragm bracing. The legs are usually sloped (tapered) to provide adequate strength and stability as the height increases. The degree of slope is an option of the designer to suit the equipment supported, the required rigidity and the available land area. The slope is sometimes varied within a tower to maintain a desirable balance between the costs of leg members and bracing, or to reduce the foundation loads. Frequently the legs in the top section of the tower will be parallel to simplify the mounting of equipment.

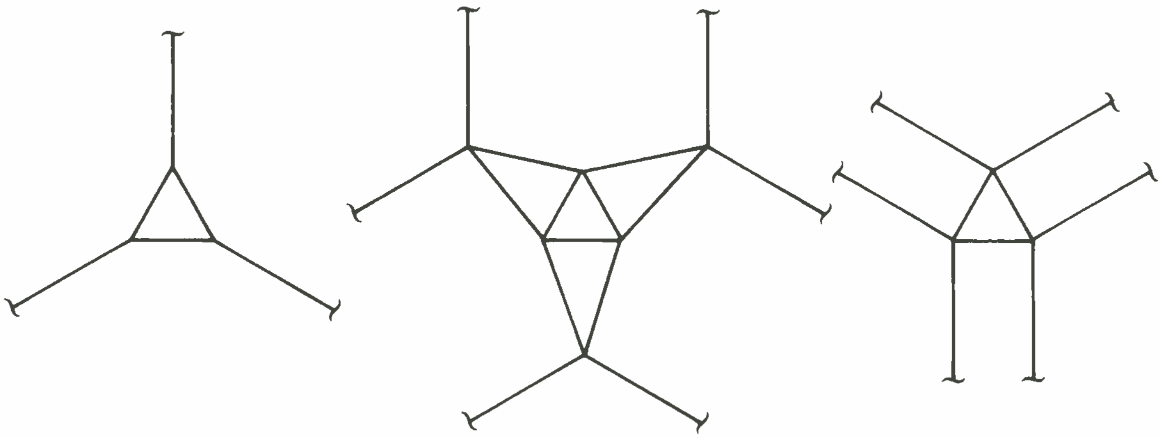
There are several different configurations of bracing members for the individual truss panels. The choice is influenced by the width of the panel, the magnitude of the wind and ice loads imposed, the location of equipment and the required stability. Continuity in transferring the applied loads through the structure without significant eccentricity is essential regardless of the configuration used.

2. *Guyed towers* are almost always of triangular cross section although there are a few unique conditions for microwave antenna supports where a square cross section is advantageous. The principal structural elements are the legs, the web bracing in each face, and the guy support systems. Except for sections at the tower base and locations where the width changes, the legs are parallel. The width of the tower is usually constant throughout the height of the tower with the exception of sections supporting antennas requiring a specific width of support structure. The base section is often tapered to a single point to provide a pivot support to eliminate large bending and torsional moments.

Theoretically there are an infinite number of arrangements of guy cables to support a tower. The most common arrangement is three cables spaced at 120 degrees with one attached to each leg. This is the minimum number of cables that can be used. When the tower supports equipment which imposes large twisting moments (torques), it is necessary to provide six cables at a level to maintain torsional stability. If the torque is localized, the guys at that location may be attached to triangular frames as shown in Fig. 2b. If the torques occur throughout the height, it may be desirable to double guy the tower at every level as shown in Fig. 2c.

The number of levels of guy cables to support the tower is dependent on a number of factors including the height of the tower, width, location of equipment, and the environmental loading conditions. Because the tower is an axially compressed column, its strength is a function of its slenderness. While design codes permit slenderness ratios resulting in triangular towers having a span-to-width ratio as great as 49, it is usually economical to limit the ratio to a maximum of 30. While there is no upper limit to the number of guy levels imposed by any code, a practical limit for economical design is 10.

The position of equipment on the tower is an important factor in determining the location of guy levels. Preferably, guy attachments should not be located within the apertures of side mounted TV and FM broadcast antennas. Equipment producing large localized wind loads, such as microwave antennas or clusters of two-way radio cabinets and antennas,



(a) (b) (c)

Fig. 2. Typical guy arrangements.

should not be positioned near the center of spans between guys.

If the tower will be subjected to ice loading, it is desirable to reduce the number of guy levels to minimize loads imposed on the tower by ice accumulation on the guy cables.

The number of anchors in each guy direction is dependent on several factors including the number of guy levels, the soil conditions, topography, and obstacles. As a general guideline, it is desirable to limit the number of guy levels attached to a single anchor to five. However, there is nothing absolute about this number, and other conditions may dictate using an anchor for a greater number. There are some soil conditions where it may be economical to provide two or more smaller anchors while in another instance the use of one large anchor might be desirable. If minimizing the area within which the tower would fall in the event of a collapse is a consideration, a minimum of two anchors should be used in each direction.

Where the elevations of the anchors differ from the tower base, it is desirable to vary the distance of the anchors from the tower base to maintain nearly equal initial tensions in the guy cables. Anchors higher than the tower base should be moved toward the tower; and anchors that are lower, away from the tower. The amount of movement should be specified by the designer.

Materials

1. *Tower Structures*

Nearly all broadcast towers are made from steel because it provides the most economical structure. The selection of the grade and shape of steel is obviously an important design consideration.

Steels used for towers commonly have low carbon content with yield strengths in the range of 36,000 to 60,000 psi. These materials have good ductility and are suitable for welding. Some towers have been built using higher grade materials with yield strengths up to 100,000 psi, but the savings in weight are more than offset by higher base prices and increased fabrication costs. Regardless of the grade of material, its physical and chemical properties should be certified by the producing mill to ensure that it conforms to the design requirements.

The shape of the material as well as its size and strength affects its load carrying capacity. The shape also has a significant effect on the magnitude of loads produced by wind. Design standards permit a reduced wind load on round members between 60 to 70 percent of that for flat or angular members of the same width. For this reason, solid round bars, round structural tubes and pipe are used extensively. This advantage in wind load is offset somewhat by increased fabrication costs, due to the necessity of welding plates onto them for connecting the various members.

There is no one grade or shape of material that is "best". The choice depends to a large degree on the preference of the designer and the type of fabricating facilities available.

A factor equally as important as the selection of the grade and shape of the structural steel is the design of the connections. For shop welded connections, the compatibility of the base and filler metals and required preheat temperatures must be considered. The procedures used must be qualified and the welders certified for them. Inspection procedures should be compatible with the weld design.

Bolts for field assembly may be of various types. Usually those for the main load carrying members are high strength. If positive resistance to slippage of the connections is required, interference body, ribbed ("drive") bolts may be used.

2. *Guys*

The most common material for tower guys is galvanized steel strand. This material has excellent strength and durability. Its "structural" elongation due to the seating of the individual wires in the strand is small and can be almost entirely eliminated by prestressing the strand to 50 percent of its breaking strength at the factory. This should be done for guys on tall towers with factory connected end fittings.

For guys on AM towers, and those close to FM and TV antenna appertures, a nonconductive material is sometimes desirable. Two such materials that have been used are Kevlar rope and fiberglass rods. When using these materials, careful attention must be given to protection against corona effects, fatigue and deterioration from exposure to ultraviolet light. Also, their elongation characteristics under load must be evaluated. They require delicate handling at all times.

Just as for the tower structure, the connections for the guys are as important as the guy material itself. Some of the more common connections are as follows:

a. ***Sockets*** of forged or cast steel attached with molten zinc or epoxy resins develop the full strength of the guy. They are normally installed at the factory and proof loaded to 50 percent of the guy breaking strength. This type of fitting is most common for the larger guys used on tall towers.

b. ***Dead end grips*** are preformed wire loops in the shape of a large hairpin. The two legs of the hairpin are wrapped around the guy with its closed end forming an eye. These grips are used for guys up to one inch in diameter and usually develop their full strength. They are easily installed in the field, but the ends must be completely snapped into place and a protective device installed to prevent ice from sliding down the guy and loosening the grip.

c. ***Clips*** used to clamp the ends of guys develop 85 percent of the guys's strength when properly applied and tightened. To install them it is necessary to bend the strand back on itself to form a loop; thus their use is difficult on large cables. The saddle of U-bolt type clips must be on the load side and not the dead end which provides another potential error in their installation.

d. ***Swaged Sleeves*** develop between 85 and 100 percent of a guy's strength depending on its size and equipment used to squeeze the sleeve. These fittings are usually installed at the factory and can be proof loaded. They are advantageous for connecting closely spaced insulators where the length of dead end grips is unacceptable.

e. ***Serving*** is a connection made by rolling the individual wires of a strand back on the strand itself. This method has for the most part been replaced with dead end grips, but it is advantageous for small guys with closely spaced insulators.

3. *Insulators*

a. ***Base insulators*** for AM towers are made from porcelain with appropriate galvanized steel end fittings. For a guyed tower, one end is fitted with a rocker plate or spherical bearing joint to prevent uneven loading on the porcelain and subsequent cracking. For self-supporting towers the fittings must be designed so that the assembly can sustain either upward or downward forces while keeping the porcelain loaded in compression.

b. ***Sectionalizing insulators*** to isolate portions of a guyed tower have been made from both porcelain and fiberglass. If these insulators are designed only for the compression loads they are subjected to after installation, temporary connections, or fittings to prevent their failure under tension loads imposed during construction, must be provided.

c. ***Guy insulators*** are available in several types. To break up a cable into segments and prevent re-radiation, porcelain insulators are normally used. These insulators are a single piece of porcelain placed between interlocking loops of the guy. In this manner, the porcelain is loaded in compression, and even if it should fail, the loops remain connected providing a "fail-safe" connection. For larger size guys, the same concept is achieved by placing the porcelain within an interlocking steel frame which is in turn connected to the guy segments.

Strings of the insulators may be used to provide insulation between the guy and an AM tower. Strain insulators made of fiberglass rods or porcelain cylinders have also been used next to the tower where a higher degree of insulation is required. These insulators are loaded in tension and do not have the "fail-safe" characteristics of the porcelain break-up insulators.

Finishes

1. *Corrosion Protection*

Steel is susceptible to deterioration from atmospheric corrosion. To prevent this, the tower members and hardware must be given a protective coating. This coating is usually zinc which has excellent resistance to corrosion, and because it is higher in the electrochemical series, it provides cathodic protection to exposed steel surfaces adjacent to it. Even though the zinc coating may be scraped or otherwise damaged, it continues to inhibit corrosion of these exposed areas, and rust will not develop beneath the zinc coat adjacent to them.

There are several methods of applying the zinc including hot dip galvanizing, flame spraying electroplating and painting. All must be applied to clean surfaces.

a. ***Hot-dip galvanizing*** consists of dipping the steel into a bath of molten zinc. A metallurgical bond develops between the steel and the zinc which adheres to it. When galvanizing tubular members, it is necessary to provide holes in both ends to ensure that the inside surfaces are coated. Careful attention must be given to the type of base and weld metals used, as well as to the welding and forming procedures used in fabrication to safeguard against possible embrittlement of the steel when galvanized. When properly applied, this process provides the most durable coating.

b. ***Flame spraying*** consists of spraying molten zinc at high pressure onto the steel surfaces. The bond in this process is mechanical rather than metallurgical. The coating produced is more porous and has less resistance to abrasion than the hot-dip galvanized coating. It cannot be used for the inside of hollow sections or other cavities where access is difficult.

c. ***Electroplating***, while suitable for small objects, does not produce a coating thick enough to withstand an aggressive environment. It is not recommended for tower parts or hardware.

d. ***Zinc Rich Paint*** consists of extremely finely divided zinc in an inorganic or organic vehicle. It is not a metal coating method, but rather a painting procedure. Its resistance to abrasion and durability are less than hot-dip galvanizing. It is, however, useful for maintenance.

2. *Aircraft Marking*

When required by the FCC construction permit, towers must be marked as a hazard to air traffic. To comply with this requirement, a tower is painted with contrasting colors of white and international orange in alternate bands. Selection of the paint materials must be compatible with surfaces to which they will be applied. There are several manufacturers who have one-coat paint systems that can be applied directly to galvanized surfaces. Like all paint procedures, clean, dry surfaces and suitable temperatures are essential to obtaining satisfactory adherence.

3. *Ice Prevention*

Recently, a coating has been developed that is intended to reduce the adherence of water to surfaces and subsequently the formation of ice on them. There is not sufficient data as yet to evaluate its effectiveness and life expectancy.

Access Facilities

A tower must have some access facilities in order to maintain it and the equipment it supports. For small towers, the bracing members of the tower itself often serve as steps or step bolts are attached to one leg or face.

1. *Ladders*

For taller broadcast towers, a fixed ladder inside the tower is desirable. OSHA Standards for these ladders require a minimum clear width between side rails of 16 inches and a maximum rung spacing of 12 inches. They also require that any continuous ladder more than 20 feet in height be equipped with a safety device. This device consists of a continuous rail, either rigid or cable, running up the center of the ladder. A clamping device attached to the climber's safety belt rides along this rail. As long as the climber is in a normal position, the clamp slides freely; if he begins to fall, a cam actuated mechanism freezes the clamp to the rail and prevents his falling.

2. *Elevators*

For tall towers supporting multiple antennas, it is often desirable to install an elevator. Most tower elevators are of the power, cable-driven type with a capacity of 500 to 750 pounds and a speed between 80 and 100 feet per minute. They consist of a driving mechanism, car, guide rails, hoist cable with supporting sheaves, tension weights, electronic controls, and a two-way communications system.

Considerable attention must be given to safety features. These should include limit switches to prevent travel beyond the upper and lower landings on the tower, an automatic brake on the driving mechanism that is activated by any interruption in power, a mechanism to automatically clamp the car to the rails in the event of a broken hoist cable, and interlocks to prevent operation with the car gate open. It is advisable to determine what state or municipal government regulations apply and what permits, tests, and inspections are required before the tower and elevator system are designed.

The added wind and dead loads from an elevator system are substantial and must be considered in the tower design. Also, careful attention must be given to the positioning of the ladder, RF transmission lines and electrical conduits in relationship to the elevator. The ladder must be positioned so it is accessible from the elevator car and can be used for emergency descent. While the elevator hoist cables can be restrained in guides on the return side, they are free to move about under wind load on the lifting side. Therefore, the conduits and transmission lines must be protected from hoist cables striking and damaging them. If a side mounted TV or FM antenna produces a high RF field within the hoistway, protection must be provided to prevent arcing between the hoist cables, the tower structure, and other appurtenances.

3. *Transmission Line Bridges*

   To allow for thermal expansion and contraction, it is necessary to locate broadcast towers some distance from the transmitter building. Unless the transmission line is going to be placed underground, it is necessary to provide a structural support for it at a height compatible with the transmitter location in the building. The top of the support can be covered with steel grating or plate to protect the lines from falling ice. The details of this structure can become quite involved for sites with multiple antennas, uneven terrain and roadways, or obstacles between the tower and building.

4. *Stairways*

   The lower landing for a tall, guyed broadcast tower with an elevator is often 30 feet or more above ground level. A stairway may be desirable to permit easier access to the landing. This structure can be combined with the transmission lines support bridge. It may also be desirable to install a small capacity boom above the lower landing to lift radio cabinets or other equipment onto the landing.

ELECTRICAL SYSTEMS FOR TOWERS

Tower Lighting

Since a tower is a hazard to air navigation, the government prescribes certain warning lights to be installed on broadcast towers. In general, the lighting requirements are spelled out in a pamphlet put out by the Federal Aviation Administration (FAA) called "Standards for Marking and Lighting Obstructions to Air Navigation" (AC 70/7460-1). Prior to submission of your application for construction to the FCC, the various options for tower lighting should be carefully considered, and any preferance for an option should be requested with the application.

The various methods for marking and lighting towers are as follows:

Red Lights With Orange and White Paint

When considering red lights and paint, the height of the tower determines the number of flashing beacons and steady burning side light levels. (See FAA AC 70/7460-1). Other factors to be considered are:

1. Due to color fading, repainting may have to be done every 4 to 5 years to meet the FAA color specifications. On galvanized towers, paint peeling can become a severe problem after several years. Depending on the tower location, the cost of insurance during the repainting may become a very significant economic consideration.
2. In view of the high cost of electricity and the low efficiency of incandescent lighting, the long-term cost of power should also be considered.
3. Lamp life is dependent on many factors but is particularly sensitive to vibrations and high line voltage. The FAA recommends changing lamps when they have reached 50% of their rated life, which in a practical sense usually amounts to changing all of the lamps every 6 months.
4. The requirement of ±3% of nominal voltage at the lamp socket must be met by the system design. If the voltage is too low the light output falls below specifications, and if too high the lamp life is shortened. For instance, a 3% low voltage results in a 10% drop in light output, and a 3% high voltage results in a 30% reduction of the rated lamp life.
5. Although the FCC no longer requires the daily logging of tower light operation, the logging of a tower light failure is required along with notification to the FAA of the failure and the

proposed schedule for resumption of normal operation. Automatic monitoring is available in accordance with FAA requirements to alert station personnel of a flashing beacon failure as well as a side light failure. Computer compatible monitoring systems are available for use with logging systems.

Medium Intensity Electronic Lights With Orange and White Paint

FAA AC 70/7460-1 currently permits the use of medium intensity electronic lights during twilight and nighttime on painted towers over 250 feet. This type of lighting is energy efficient; power costs will typically be less than 10% of comparable red lighting systems. Although this type of lighting is especially suitable for remote locations, it has also proven economical for lighting systems on towers that use paint for daytime marking.

Refer to the previous marking method for paint considerations, and to the following marking method for the electronic light considerations.

High Intensity Electronic Lights

High intensity electronic lights may be used effectively to mark towers and eliminate the requirements for the orange and white paint. These lighting systems have three intensities for marking the structure during the day, twilight, and night. Again, the height of the tower will determine the number of high intensity light levels needed to mark the tower. (See FAA AC/70/7460-1). Effective intensity is probably the least understood term when it comes to the practical use of electronic flash equipment. The term *candella* is used as the unit of measurement, and *effective candella* is specified if the Blondel-Ray relationship has been taken into account.

The eye is able to integrate a light pulse with virtually no reciprocity failure for pulse lengths much shorter than the decay time constant for the eye which is approximately 0.2 seconds. Therefore, the eye is sensitive to the integrated value of the light pulse and not to the peak value, which for short pulses can be stated in impressively high but meaningless figures, as far as the eye is concerned.

The effective intensity can be determined from the Blondel-Ray relationship

$$I_E = \frac{I_M \times t}{0.2 + t} \text{ candella}$$

Where:

I_E = Effective Intensity
I_M = Measured Intensity in candle-seconds
t = Pulse width of the light pulse (Usually between the ⅓ amplitude points)
0.2 = the decay time constant for the eye.

For short light pulses, the effective intensity can approach 5 times that of a steady light source with the same candle-second intensity.

Other factors to be considered when using high intensity electronic lights for marking towers are:

1. With the higher efficiency optics and power converters of the electronic lights that are currently available, the 24 hour per day operating power cost can be reduced to at least one-half that of the red light nighttime operating cost.

2. The economics of electronic light operation is governed by many design factors. FAA approved systems are required to meet specific operational requirements but must only guarantee a minimum of one year life. Economical operation demands the careful consideration of the following life-determining factors:

   a. Even the best quality UV-inhibiting quartz flash tubes will have a life that will vary widely depending on the flash tube's bore size, length, operating voltage, current pulse shape, and electrode, operating temperatures. Generally speaking, larger bore flash tubes using lower voltages between 500 and 1000 volts and a power loading of less than 5 watts per square centimeter of flash tube surface area, along with good electrode cooling, should give a lamp life in excess of 5 year providing that the flash tube current wave shape has been optimized.

   b. The energy storage capacitors should be properly derated for the operational voltage to provide long life. Operational deratings for capacitors in common use during the past 10 to 20 years have shown deratings to 60% as being safe and long-lived. New technology capacitors using state of the art dielectric materials have shown derating to 80% as being safe and long-lived. Because of the significant energy levels used in these lights, energy storage capacitors using minimal derating should have built-in protection devices to minimize the possibility of overheating, rupturing and causing damage not only to themselves but to beacon interiors as well.

   c. The power transformers used in electronic lights today are typically of the constant current/voltage regulating type. This type of transformer is very efficient when used to charge capacitors and is capable of supplying a near constant current from 0 volts to full flash operating voltage on the capacitor. This type of transformer is not harmed if a flash capacitor shorts out, and is less likely to catastrophically destroy the capacitor. Another feature of this type of transformer is its inherent immunity to voltage transients and spikes on the power line. Since the flash energy is proportional to the square of the flash voltage, capacitor safety margins are maintained and light output can be kept within the FAA specifications over the normal input power voltage fluctuations. To guard against lightning induced voltages on the tower, the breakdown voltage from the primary to case and to other windings should be designed for at least 5 kV with insulation of high enough heat rating to hold up for the desired useful life of the beacon.

d. Using up-to-date technology with properly engineered designs and low flash voltages in the 500 to 1000 volt range, recent beacon designs have been able to virtually eliminate the corrosion problems that have plagued many of the older style, high voltage designs operating in the 1.5 to 3.1 kV flash voltage range.

e. For enviromental considerations, the optical design is very important. These lights are specifically designed to alert pilots, on a collision course, of the tower's existence. Stray light reaching inhabited areas on the ground may be minimized by using louvers to block the direct radiation from the flash tube. Special optical designs using polyfocal parabolas, which provide a very sharp cut off on the bottom of the beam, may also be used to further reduce the undesirable light reaching the ground. Within ranges where the eye is able to resolve the light aperture size, a larger aperture will provide a less intense looking light, while at the same time, providing the proper far-field intensity.

f. Although the FCC no longer requires daily logging of tower light operation, the logging of a tower light failure is required along with notification to the FAA of the failure and the proposed schedule for resumption of normal operation. Automatic monitoring is available in accordance with FAA requirements to alert station personnel of a tower lighting failure. Computer compatible monitoring systems are available for use with remote logging systems.

Other Electrical Circuits

Other electrical considerations when planning a tower installation are:

a. Antenna deicing circuits should be designed to be installed in the main electrical power conduit. If a choice of deicer operating voltage is available, consider choosing the highest voltage under 600 volts in order to minimize wire size. In many cases a 208/240 volt deicer system is fed with 480 volts using a step down transformer to reduce the I^2R losses incurred in the long run feeding systems on tall towers. Deicing systems should be designed to provide no more than 5 to 10 percent voltage drop to insure the proper operation of the deicer since the available heating power is proportional to the square of the voltage. Most deicer control circuits require a shielded triplet which may also be installed in the power conduit.

b. An ac utility circuit to provide access to 120 volt power at several elevations on the tower will often save time during maintenance and repair work on the tower and associated systems.

c. Wiring for the elevator control circuits, if needed, may also be installed in the power conduit.

d. A sound-powered telephone system in a separate ½" conduit to provide communications with ground personnel from the various working platforms can likewise save time during maintenance and repairs.

e. With the recent increase in two-way communications activity, many tall tower installations have found it advantageous to provide several platforms with up to 150 amp, 120 volt service which will accomodate the full spectrum of two-way communication systems.

A separate conduit with 20 to 100 pair telephone cable is normally used to provide audio input for these systems.

DESIGN STANDARDS

Industry

The vast majority of towers in the United States have been designed in accordance with the Electronic Industries Association (EIA) Standard RS-222, *Structural Standards for Steel Antenna Towers and Antenna Supporting Structures*. This standard has been used since 1959 when it replaced the Radio-Electronic-Television Manufacturers Association (RETMA) Standard TR-116. The current revision "C" of RS-222 was issued in 1976, and a new edition is contemplated toward the end of 1985.

This standard is intended to provide *minimum* criteria for specifying and designing steel antenna towers and antenna supporting structures. Unlike general specifications and building codes it is applicable only to antenna towers and supporting structures. As such it contains criteria peculiar to these structures that are not readily available elsewhere. Therefore it is always advisable to specify that your tower must conform to this standard.

Statutory

Most municipal and state governments have statutory codes regulating the design of structures. Many of these are patterned after or include one of several model codes. The most common of these are the Building Officials and Code Administrators International (BOCA) *Basic Building Code,* The International Conference of Building Officials (ICBO) *Uniform Building Code*, and the Southern Building Code Congress (SBC) *Standard Building Code.*

These codes cover all types of structures and are directed primarily toward conventional types of buildings. As such, they do not contain all the criteria necessary to design broadcast towers. For example, none of them includes a recommended safety factor for guy cables.

Of particular concern to tower designers is their provisions for calculating wind load.

> The *BOCA Code* specifies that radio and television towers be designed for wind loads in accordance with the American National Standards Institute (ANSI) Standard A.58.1, *Minimum Design Loads for Buildings and Other Structures,* which contains specific criteria for wind loads on towers.
>
> *The Uniform Building Code* gives specific, but incomplete criteria for towers up to 400 feet tall, and states that taller structures be designed in accordance with "approved national standards." No further definition is given, leaving that determination to the judgement of the local building official.

Since it is necessary to comply with the applicable statutory requirements, it is important to determine what they are and include them in the specification for the tower. They can have a significant effect on the cost.

LOADS, ANALYSIS AND SAFETY FACTORS

Loads

In addition to its own dead weight and the dead weight of the appurtenances and equipment it supports, the tower must withstand the forces of nature: wind, ice, temperature changes, and earthquakes.

1. *Wind Load*

   Wind produces a principal load on tower structures. For design purposes it is represented as a horizontal static force proportional to the square of the wind velocity and the size and shape of the structure and its attachments.

   While all of the design standards use the same statistical data for the maximum probable wind velocity at a specific location, they use different procedures for relating the design load to that velocity. These differences are in the shape coefficients applied to the projected area of the members and in amplification factors used to account for the dynamic effects of wind gusts and the tower's response to them.

   The design standards also differ in their methods of accounting for the variation of wind velocity with respect to height above ground. This relationship has been empirically determined to be exponential based on records obtained during severe storms. In this area the EIA Standard differs significantly from the others for towers greater than 650 feet in that its recommended design wind pressures are based on a constant velocity over the entire height.

   Graphic examples of the differences in wind loads when using various design standards are shown in Fig. 3.

   Since the wind may act from any direction, it is necessary to apply the wind loads in any horizontal direction to determine the maximum stresses produced in the structure. For a triangular tower three directions must be considered, while for a square tower two are sufficient. These are shown in Fig. 4.

   In addition to this direct load in the direction of the wind (drag), there may also be a component of load perpendicular to the wind direction (lift). These lift components are calculated in a manner similar to that for drag forces using different shape coefficients that vary with respect to the angle of attack between the member's geometric axis and the wind direction. They are most significant for wind acting on guy cables, microwave antennas and rectangular waveguides.

2. *Ice Load*

   Ice accumulations have two effects on a tower. The weight of the ice acts directly on the structure in the same manner as the dead weight. The ice accumulation also increases the area exposed to the wind and consequently the load produced by the wind. This increase is substantial on small components such as guy cables, tension rods, ladders, small diameter transmission lines and reflector screens for antennas. It is also possible for the ice accumulation to alter the aerodynamic shape of members thereby requiring the use of a different coefficient in calculating the wind load. An example of this would be a set of closely spaced parallel coaxial lines. Without ice they would each be considered a round cylindrical member. With accumulated ice they would

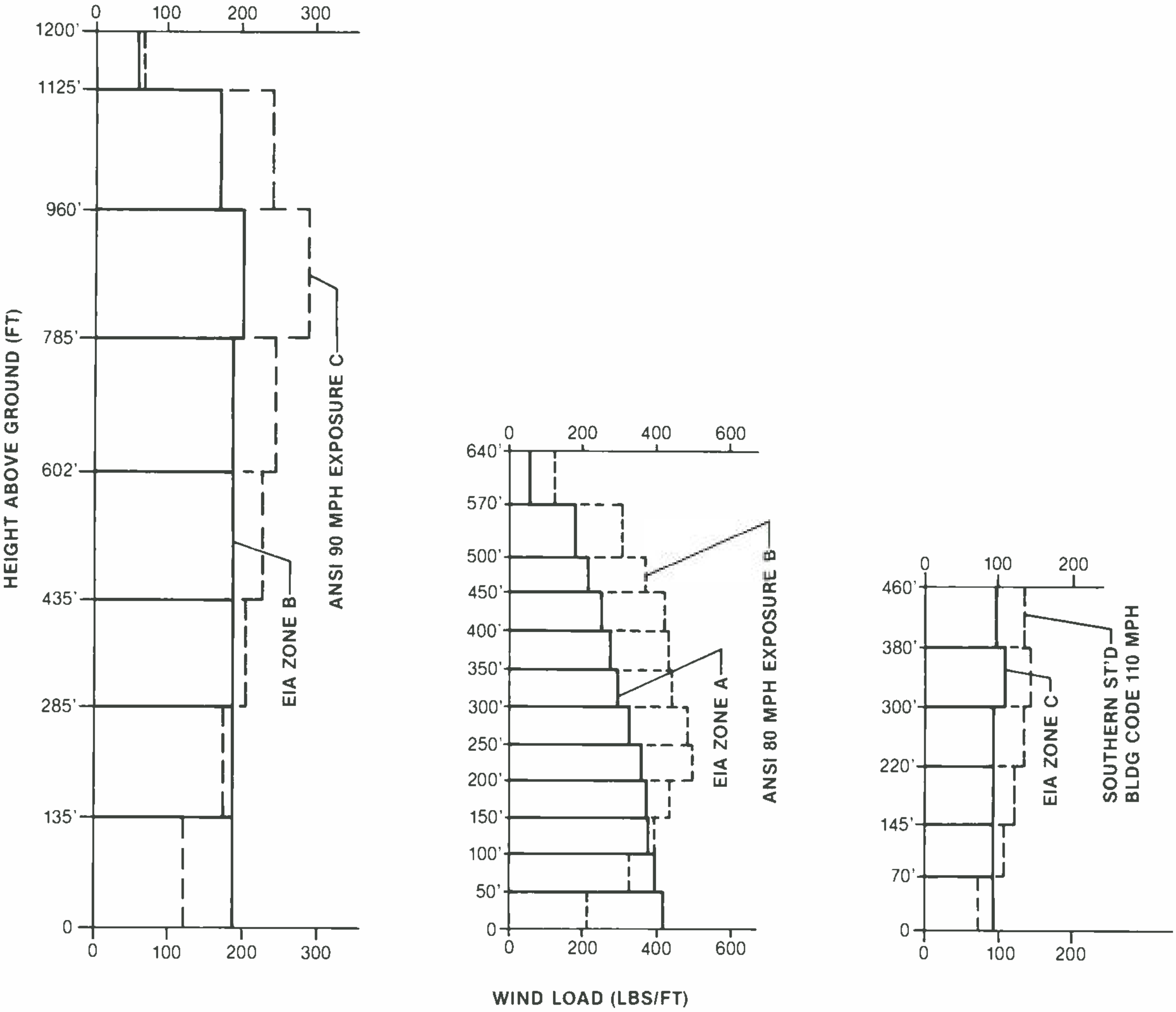


Fig. 3. Examples of wind load differences using various design standards.

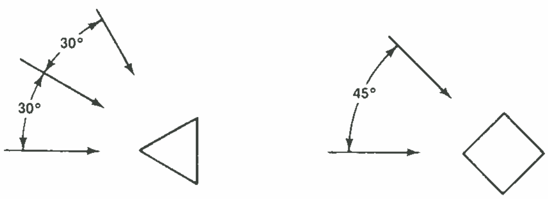


Fig. 4. Wind directions to be considered.

present a large flat area to the wind requiring a much larger coefficient.

Ice produces an entirely different stress distribution in a tower than wind so it is not reasonable to merely increase the design wind load to provide for ice accumulations. It is also a misconception that ice will break up and blow off the tower, and therefore, ice and wind need not be considered simultaneously. In areas where ice may form, it is advisable to specify an ice accumulation and a wind load to act concurrently.

While all of the design standards say that ice accumulations should be considered, none of them gives specific recommendations for the magnitude of accumulation or the wind load with which it should be considered. This is unfortunate because ice is a significant load on a tower and has been the direct cause of a number of collapses in recent years.

3. *Temperature Changes*

Changes in temperature have no significant load producing effects on self-supporting towers, but they can on guyed towers. Because of their differences in length, the guy cables expand and contract different amounts than the tower itself and thereby require elastic deformations from stress changes. The effects are greatest for those cables having the flattest angle with the ground. While the stresses produced are considerably less than those produced by wind and ice loads, they should be considered in the design of guyed towers.

4. *Seismic Loads*
Loads due to earthquakes are considered to act horizontally and are dependent on the mass and stiffness of the tower. They are usually less than those produced by wind but are distributed in a different manner. Procedures for calculating these loads are given in some of the design standards including ANSI A58.1, but not in EIA RS222C. While a tower properly designed for wind load is usually adequate for seismic forces, they cannot be neglected in areas with frequent and intense earthquake occurrences.

Structural Models and Analysis

A self-supporting tower may be described structurally as a cantilevered space frame or truss. Although it may have many different members, it is a relatively simple structure, and the determination of the forces in the individual members due to the applied static loads is easily done using fundamental principles of structural mechanics. The potential modes of failure are buckling of individual leg or bracing members under compressive loads, and shear or tension failures of the connections.

A guyed tower is a much more complex structure than a self-supporting tower. Whereas there is only one basic path through a self-supporting tower for the loads to be transferred to the ground, there are several for a guyed tower. The distribution of the loads among these paths is dependent upon the relative stiffnesses of guy systems and the tower shaft.

Each span of the tower has a stiffness with respect to axial and shear forces and bending and torsional moments. These stiffnesses are a function of several variables including the geometric configuration, the mechanical properties and size of the individual guy cables, the amount of initial tension, the magnitude of ice load, and the magnitude and direction of wind load on the cables.

By evaluating all of these it is possible to simulate all the guys at a given level as a spring having a specific stiffness. Because of the nonlinearity of some of the relationships involved, the spring constant derived is only valid for a specific set of conditions and for a finite range of translation. Similarly a torsional spring constant can be derived. It is interdependent with the translation stiffness and is also valid for only a finite range of translation.

Another difference between a guyed and self-supporting tower is the magnitude and significance of the axial load. For a self-supporting tower this is composed only of the gravity loads from the tower, its appurtenances and any ice load. It is independent of wind load and its effects on individual member loads are relatively small. The axial load for a guyed tower includes in addition to the gravity loads, the vertical components of the tensions in the various guys. Since these tensions are directly affected by the wind loads, the axial load is now dependent upon wind load, and its effects on the individual leg members are relatively large. It also produces an additional bending moment on the tower equal to the product of the axial load and the deflection of the tower.

Despite the complexity of the relationship involved, the availability and wide spread use of digital computers permits accurate structural analysis of guyed towers. There are several different structural models that may be used.

One of the most commonly used is to idealize the tower shaft as a continuous beam-column on non-linear elastic supports (the guys) subjected to simultaneous transverse (wind and/or seismic) and axial (dead, ice and vertical components of guy tensions) loads.

The modes of failure are buckling of individual leg or bracing member under compressive loads, rupture of bracing members, guys or guy anchor arms under tensile loading, and shear or tension failures of the connections.

Dynamic Considerations

As previously mentioned, even though wind and earthquakes involve kinetic energy, their effects are simulated by equivalent static loads determined in accordance with the design standards. In recent years there have been more sophisticated efforts to investigate the actual response of tower structures to the dynamic aspects of wind gusts. A conclusion drawn from these studies is that the bending moments in the upper portions of tall guyed towers are considerably higher than those determined by the usual static analysis. Consequently the loads imposed on the vertical legs and their splice connections would be amplified beyond safe limits indicating a potential failure condition. Considering the usual fundamental periods of tall guyed towers, it appears that towers taller than 1200 to 1300 feet should be investigated dynamically as well as statically.

There are two other phenomena related to the dynamics of wind that are important in guyed

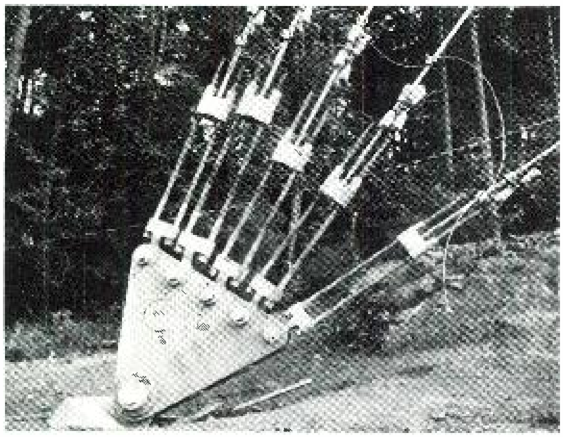


Fig. 5. Typical anchor connection with dampers to prevent aeolian vibrations.

tower design. These are aeolian vibrations and "galloping", both of which involve periodic loading.

Aeolian vibrations are low amplitude, high frequency movements which occur in the tower guy cables due to a phenomenon known as vortex shedding. If they are not suppressed through the use of dampers, they can result in destruction of the filaments in the tower lights at the least, or fatigue failure of a guy cable and collapse of the tower at the worst. Stockbridge dampers attached at one or both ends of the guy cables have proven effective in controlling these vibrations and should be considered for all tall guyed towers.

Galloping is a condition of instability involving large amplitude, low frequency movements. It is caused by the perpetual amplifications of periodic load due to the motion of the body itself. The most dramatic and well-known example of galloping is the collapse of the Tacoma Narrows suspension bridge in 1940.

For tower structures, galloping is usually associated with the guy cables on tall towers, but in at least one instance it was related to a large rectangular waveguide. There have been several different methods involving detuning and energy dissipation used for preventing galloping in guy cables that appear to be successful. In the case of the rectangular waveguide, galloping was controlled by moving the waveguide inside the tower along the centroidal axis from its original position on the outside of one face. This reduced the torsional rotation of the structure which was the source of the perpetuating force. Based on this experience it would appear prudent to always install this type of waveguide inside the tower unless adequate torsional rigidity is provided throughout the height of the tower.

Allowable Stresses and Safety Factors

Towers, like all other structures, are designed so that the maximum anticipated stresses that occur in them are less than those which would cause failure. This ratio of failure stress to maximum allowable stress is known as the safety factor. It is intended to provide for several variations from the ideal conditions assumed for design including loads greater than anticipated, imperfections in materials and tolerances in fabrication and construction.

The design standards refer to the American Institute of Steel Construction (AISC) "Specification for the Design, Fabrication and Erection of Structural Steel for Buildings," and the American Concrete Institute (ACI) "Building Code Requirements for Reinforced Concrete Structures," for the allowable stresses and safety factors to be used. Both of these specifications permit an increase in allowable stresses (or a reduction in safety factor) for stresses due to wind and seismic loads acting alone or in combination with dead and live loads above those values normally permitted for dead and live loads only. The reason for this is that maximum wind and seismic forces are infrequent and of brief duration. EIA Standard RS-222 has always prohibited use of this increase for stresses due to wind load on tower structures. Thus, while wind loads calculated according to other design standards are greater than

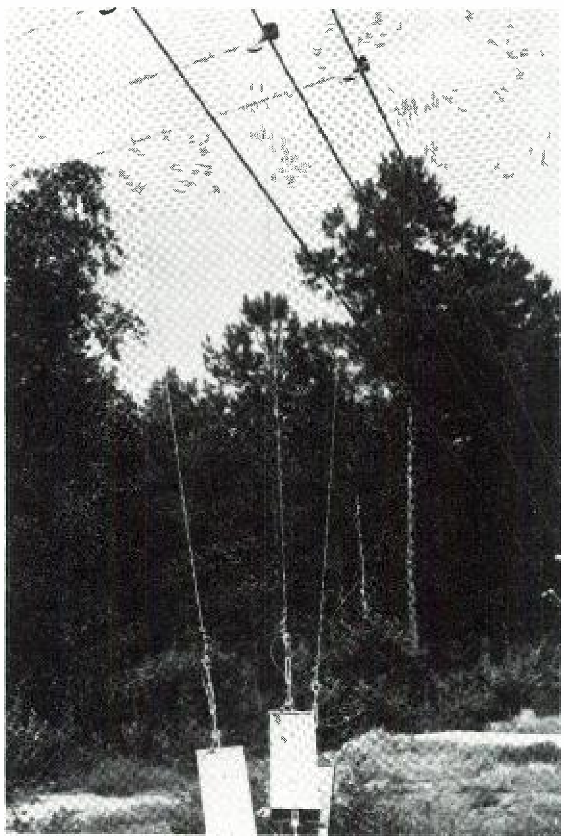


Fig. 6. Anchor connection with snubber system to prevent galloping.

those calculated according to EIA RS-222, their effects are offset by consideration of the increase in allowable stresses. This demonstrates the importance of not extracting portions of different design standards and combining them into a single specification.

EFFECTS OF ANTENNAS AND TRANSMISSION LINES

Except for AM radiators, the tower is the "necessary evil" to support the broadcast antennas and transmission lines at a suitable height above ground. Thus the effects of this equipment are of paramount importance.

Loads

Every antenna imposes a wind load and a dead load on the tower. If the antenna is mounted atop the tower, it also imposes an overturning moment, and if it is mounted off one side of the tower, it imposes a torsional moment. For TV and FM broadcast antennas and microwave antennas, these loads are relatively large, and their location has a significant effect on the placement of guy cables.

Transmission lines feeding the various antennas also impose wind and dead loads on the tower. These loads are distributed uniformly between the antenna and their entry point near the base of the tower. The total load produced by a coaxial line or a waveguide is frequently greater than that produced by the antenna itself. The shape of the transmission line influences the magnitude of the wind load, with circular or elliptical lines having loads two-thirds of those for rectangular lines with the same projected area.

It is important not to overlook the support system required for transmission lines. Some large waveguides have support systems that require nearly continuous vertical structural members that add substantial wind and dead loads. Small, flexible lines require supports at a maximum interval of three to four feet which is often less than the vertical spacing of horizontal members in the tower. Thus it may be necessary to provide an additional support structure for these lines, again adding to the total load.

Width Restrictions

Some antennas impose restrictions on the width of the supporting tower. One common example is a side mounted FM antenna requiring a maximum width of 18 to 24 inches. For antennas with more than 8 bays, this results in a very slender structure. When placed at the top of a tall guyed tower, the design of the guy system for this structure becomes extremely critical. Use of a cantilevered pole structure above the top of the main tower should be considered for these cases.

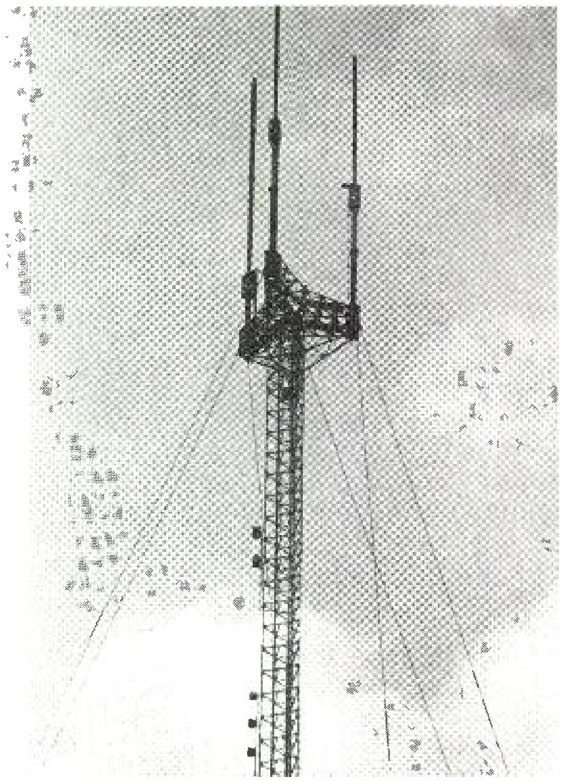


Fig. 7. Triangular multiple TV antenna support with FM antennas side mounted below.

Another example of width restriction is a panel type TV or FM antenna mounted on the faces of the tower. Here, too, it is often better to support these antennas on a cantilevered structure above the main tower rather than placing guys within the aperture of the antenna.

As previously mentioned, it is desirable to place large waveguides inside the tower near the vertical centroidal axis to prevent large torsional loads. This requires a tower having a minimum face width in the range of 7 to 8 feet to accommodate the waveguide and its supports.

Initial and Future Considerations

Because the antennas and transmission lines have such a significant effect on the tower design, it is important to consider all possible uses for a tower before it is designed. It is better to have unused capacity than to undergo expensive modifications or replacement in several years to obtain additional height or accomodate another antenna. This has become apparent in recent years with the proliferation of microwave, two-way communication, and cellular radio systems.

When providing for multiple antennas, it is important to determine not only the number and type of antennas and lines, but also their location on the tower. The distribution of load is equally important as magnitude.

Triangular top platforms ("candelabras") to support broadcast antennas on each corner have been successfully used for many years. They have the advantage of placing all antennas at the same height. A variation of this platform to support only two antennas ("tee-bars") has also been used. Both of these systems require multiple guy cables at the top platform to provide adequate torsional stability. It is possible to design the tower for a multiple antenna support platform, but not install it until some later date.

Another arrangement of multiple antennas is "stacking", i.e., installing one antenna atop the tower and arranging others along the tower, one below the other. This arrangement can also be combined with a multiple antenna support platform.

If capacity for microwave antennas is required, it should be provided near guy levels and preferably above to minimize interference with the guy cables. The guy system and web bracing at these levels must be designed to provide adequate torsional rigidity.

Capacity for small antennas may be provided at various locations throughout the height of the tower. One arrangement for a large number of antennas is to provide a platform around the outside of the tower large enough to support the radio equipment for these antennas. The antennas can be mounted on the outside railing of the platform, thereby requiring only a short run of coax. Electrical power must be provided to the platform. This arrangement imposes a large concentrated load at the platform location with a relatively small uniform load between the tower base and the platform. If the same number of antennas were mounted along the tower and each fed by an individual coax line from the base, there would be only small concentrated loads at the antenna locations, but a relatively large uniform load due to the lines. This is an entirely different distribution of load and would have a pronounced effect on the design.

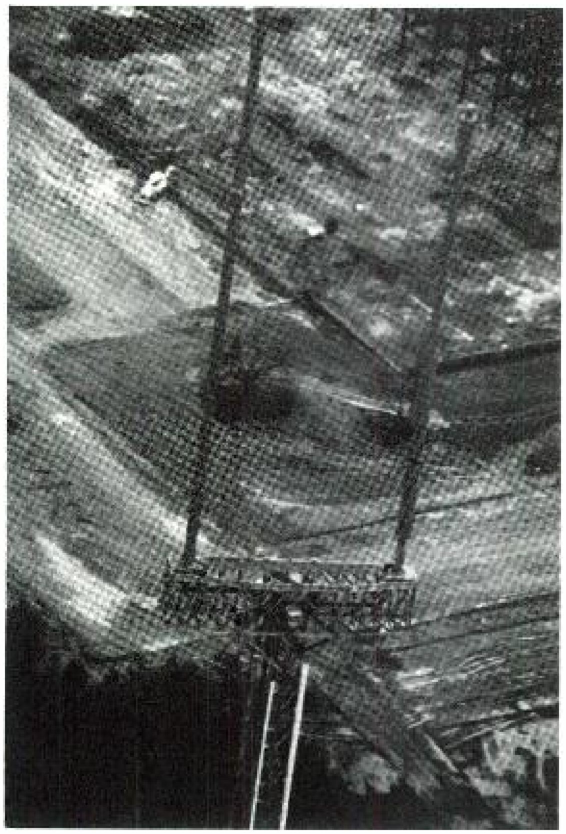


Fig. 8. Tee bar antenna support platform for two TV antennas.

Another important consideration for future antennas or height extensions is the electrical system. If an extension in height is planned, the wiring for the aircraft warning light system should be designed so that any additional lights can be connected to the system without adding or replacing wires in the existing conduit. The same holds true for any circuits required for future antennas. If the necessary wiring cannot be provided during the initial installations, capacity should be provided for additional conduits to hold the future circuits.

Replacement, Relocation or Additions to Existing Towers

Since every tower has been designed for a specified arrangement of equipment, changes should not be made without considering their effects on the structural adequacy of the tower.

Two common misconceptions related to changes in equipment are: "lower is better", and "smaller is better". Neither is necessarily correct, especially for guyed towers. Decisions based on these premises can have serious consequences.

It is much better to have a structural analysis of the tower made by a structural engineer experienced in tower design. This analysis will determine if any overstresses would occur in the tower or its foundations and what modifications and reinforcing would be required to retain the structural integrity. To make this analysis, it is necessary for the engineer to have complete data on the tower and its foundations including configuration, member sizes and material strengths. The use of presumptive values can result in an analysis with little value.

FOUNDATIONS AND ANCHORS

The component of a tower installation for which it is most difficult to predict the cost is the foundation system. This is due to the nonhomogeneous nature of soils and the uncertainty of what conditions exist below grade. Therefore, it is necessary to have an investigation made of the sub-surface soil conditions.

It is important to note that the soil design parameters given in EIA Standard RS-222-C are intended to serve only as a basis for preliminary design and estimating of foundation costs prior to obtaining specific soil data. They should not be used for the final design without verification by subsurface investigation.

Soil Investigation

The soil investigation should be made by an engineering firm which specializes in soil investigations and evaluations and is familiar with the general area of the tower site. It should consist of making a test boring at each foundation and guy anchor location, analysis of soil samples taken from the borings, determination of the structural properties of the soils, determination of ground water levels, recommendations of parameters for designing the foundations, identification of any special construction procedures required, and recommended backfill specifications. If piles or rock anchors are necessary, recommendations related to these should be provided. It should also address requirements for frost protection and bouyancy effects.

Because the loads imposed on foundations for towers are unique from those for conventional buildings in that they include large uplift and horizontal components, it is important to provide the soils engineer with the loading conditions before he makes his investigation. This will enable him to plan his work in a manner suitable for obtaining and reporting those characteristics relevant to designing for these loads.

Self-Supporting Tower Foundations

Except for relatively small towers with narrow base spreads isolated foundations at each leg are usually more economical than a single mat for all legs. These foundations may be spread footings, drilled caissons or driven piles. If sound rock is present at shallow depths it is often economical to anchor the footing to the rock. These anchors should be proof loaded to ensure their holding capacity in uplift.

Since these foundations are subjected to large uplift forces, it is important to consider bouyancy effects if ground water is present. Also, if driven or cast-in-place piles are used, they must be adequately anchored to the reinforced concrete cap.

Guyed Tower Base Foundations

These foundations may be spread footings, drilled caissons, or driven piles. Since they are subject only to downloads with relatively small horizontal forces, they require no special anchorage details for uplift unless they are placed above expansive soils. Bouyancy is usually not a problem.

Guy Anchors

Deadmen (buried reinforced concrete blocks), drilled caissons or driven piles may be used for these foundations. If sound rock is present at shallow depths it is often economical to anchor the foundation to the rock.

These foundations are subject to large horizontal forces as well as vertical uplift. Therefore, deadmen must have a large enough frontal area bearing against the soil to resist sliding; drilled caissons must have sufficient diameter and depth to prevent excessive lateral deflection; and driven piles must be sloped to prevent large lateral loads being imposed on them. Rock anchors may be installed along the slope of the resultant of the horizontal and vertical loads, or they may be installed vertically and post tensioned to clamp the concrete cap to the rock to prevent sliding. Because of the uplift forces, it is important to consider buoyancy due to ground water and to provide adequate anchorage for driven or cast-in-place piles.

Construction

Since nearly the entire foundation system will be below finished grade and not subject to later inspection, it is important to carefully monitor its construction. The following items should be verified:

1. Location and alignment of anchors in plan and elevation.
2. Condition of excavation surfaces on which concrete will be placed.
3. Position, size and grade of reinforcement steel.
4. Placement of concrete to prevent voids and air pockets.
5. Strength of concrete using test cylinders for 7 and 28 day break tests.
6. Protection of concrete against freezing during the curing period.
7. Placement and compaction of backfill.
8. Driving records and/or load tests of piles.
9. Proof loading and post-tensioning of rock anchors.

For towers with extensive foundation systems, it is advisable to retain an independent inspections service for this work. Often the firm making the subsurface soil investigation can also provide this service.

ERECTION

The erection of towers is a highly specialized field and should be done only by firms having the proper equipment and experienced rigging personnel. It is also important that the erector have adequate insurance coverage including workmen's compensation, general and automobile liability and all risk for direct damage to the tower and antennas being erected.

Owners Preparation

Prior to the arrival on site of the erection crew, the site should be made ready for work to begin. These preparations include:

1. *Access*

   Suitable access from public roads for delivery of the tower materials and erection equipment is required. While a paved roadway is not necessary, the access must be able to handle heavy trucks and construction equipment.

2. *Permits*

   All necessary building and construction permits should be obtained and posted as required. Any inspections required during construction should be noted.

3. *Clearing*

   A work area must be cleared to permit unloading, sorting, and assembling the tower. Paths from the tower base to the guy anchors must be cleared for a width adequate to permit hauling the guy cables to the anchors and pulling them to the tower. Paths must also be cleared for the hoist line from the tower base to the hoist location and for the tag line used to stabilize the loads as they are uplifted. The sizes and locations of these cleared areas should be agreed upon beforehand with the erector. A typical layout is shown in Fig. 9.

4. *Electrical Power*

   Power for operating the temporary aircraft warning lights must be available before erection begins.

Assembly

The usual procedure for erecting a guyed tower is to assemble the individual sections on the ground and then lift them one at a time as an assembled unit. For a self-supporting tower, the wider sections near the bottom of the tower are often assembled in the air as the tower is constructed.

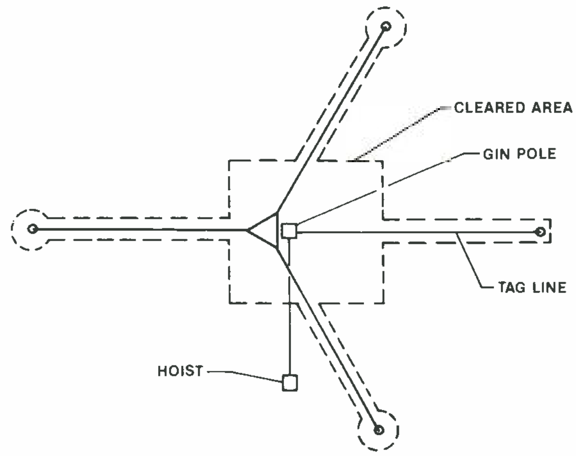


Fig. 9. Typical layout for guyed tower.

Assembly of the tower sections should be done on a level bed to ensure that they will be straight and not racked or twisted. Bolts must be properly tightened and have a locking device. For high strength galvanized bolts, tightening by the "turn-of-the-nut" method is preferable to using a calibrated torque wrench.

Stacking

For a guyed tower, the first group of three to six sections are often joined together on the ground and then lifted into place using a crane. This portion of the tower is then guyed with temporary cables, and the remaining sections are erected one at a time using a vertical boom or "gin pole". This boom is moved or "jumped," up the tower as each section is installed. This arrangement is shown in Fig. 10. Temporary guys to stabilize the tower should be used as instructed by the designer.

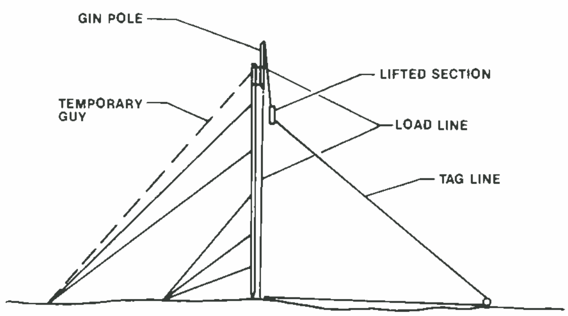


Fig. 10. Typical erection setup for guyed tower.

For a self-supporting tower, a crane is often used to lift as many of the tower sections as possible after which a gin pole is installed and used for the upper sections beyond the crane's reach.

Temporary aircraft warning lights must be installed at the top of the construction at the end of each day.

The tower should be grounded as soon as the first section is in place.

Guy Installation

When the tower reaches a guy attachment level, the cables at that level are installed. The guys in all three directions should be pulled out simultaneously to prevent any large unbalanced loads on the tower.

The tower should be checked for plumbness as each set of guys is installed and tensioned. Maintaining a plumb tower during erection eliminates the need for time-consuming adjustments later. Final tensioning of the guy cables and a plumbness check are done after the entire tower is erected.

INSPECTION AND MAINTENANCE PROCEDURES

To ensure trouble-free performance of a tower and its appurtenances, it is desirable to have a regular inspection and maintenance program. Portions of the program can be done by station personnel while others require experienced tower personnel.

Safety precautions should be observed at all times when working on or around the tower. If the tower itself is energized or if a high intensity RF field exists from antennas mounted on it, no work should be done on the tower without clearing it with the station engineer. When climbing the tower, safety belts and climbing devices should always be used. Automatic safety features on elevators should never be by-passed to save time. It is a good idea to never work alone. Failure to observe proper safety measures can result in serious injury or death.

Tower Structure

1. *Damage or Deformed Member*

   A visual inspection should be made of the entire tower structure to determine if any of the members have been deformed or damaged. Any bowed or kinked member should be noted as to type, location in tower, and nature and magnitude of deformation or damage. This information should be reported to the tower designer for evaluation and recommended action.

2. *Condition of Paint*

   A visual inspection should be made of the entire tower structure to determine the condition of the paint. If the painting of the tower is for aircraft observation marking only, and not for corrosion protection, it is necessary only to note any general deterioration rather than small blemishes and scratches. If repainting is necessary, it is important to properly prepare all surfaces and select paints that are compatible with the existing finish.

3. *Corrosion*

   Small scratches in the galvanized surface are not detrimental as the exposed surfaces will be protected by cathodic action of the adjacent zinc. If corrosion is observed, the source should be determined and noted. The affected areas should be wire brushed clean to bare metal and then painted with a zinc rich prime coat and, if necessary, a finish enamel coat of the appropriate color.

4. *Connections*

   All bolts should be checked for tightness. Any loose bolts should be tightened in accordance with the original installation instructions.

5. *Alignment*

   The tower structure should be checked for alignment using an engineer's transit. This check should be done only on a calm day, i.e., with wind velocity less than 10 mph, and in conjunction with measuring the guy tensions (described later).

   Two transit positions, each a distance of at least one-half the tower height from the tower base and separated by a 90 degree azimuth angle should be used.

   When the transit has been properly leveled, set the vertical cross-hair on the edge of one of the vertical legs at the tower base and lock the instrument in this position. By moving the telescope upward it is then possible to observe the straightness of the tower over its entire height. The magnitude of misalignment can be accurately estimated by comparison with the tower leg diameter. A record should be made of the observations at each guy level. Tolerances for plumbness and straightness should be as provided by the designer. EIA Standard RS-222 gives a plumbness tolerance of one to 400 for guyed towers, one to 250 for self-supporting towers, and a straightness tolerance of one to 1000. These are extremely generous and should never be exceeded. A good rule of thumb in the absence of other data is to keep the tower plumb and straight within the diameter of the leg members.

If straightening of the tower is required, it should be done by adjusting the guy wires as described later.

When checking the plumbness of top mounted poles and pylon antennas, the effects of direct sunlight on them must be considered. It is best to make these checks early in the morning or on a cloudy day.

Guys and Guy Insulators

Inspection of the guys can be done visually only for those portions adjacent to the anchors and tower. The range of this visual inspection can be extended by using binoculars, but its reliability is limited. If experienced riggers are available, it is possible to ride down the guy on a bosun's chair, but this method should be used only under the supervision of qualified personnel.

1. ***Damaged Components***

   A visual inspection should be made of the guy cables, insulators, and hardware. Cables and dead end grips should be checked for nicks or cuts in the individual strands. Break-up insulators should be checked for cracks or chips in the glazed ceramic surfaces. Fiberglass should be checked for deterioration of the epoxy coatings and exposure of individual glass strands.

2. ***Corrosion***

   If the guy cables show signs of corrosion, consideration should be given to coating or replacing them. The cost of cleaning and coating the cables should be considered along with the life expectancy of the coating when comparing it to the cost of replacement. All guy hardware should be checked using the same procedures for inspection and corrective actions as previously described for the tower structure.

3. ***Connection***

   All pins should be checked for tightness and the condition of the cotter keys. Dead end grips should be checked to ensure that their ends are completely snapped close, preventing any ice from forming inside. The surface appearance of the guy strand immediately next to the connections should be noted for evidence of slippage. Threads should be given a light petrolatum coating.

4. ***Tensions***

   Guy tensions should be checked in conjunction with the tower alignment. These tensions should be measured at the anchor end and compared to the specified values. It is important to remember that they are dependent upon the ambient temperature.

For the usual guy arrangement with cables in three directions, it is necessary to measure the tensions in only one direction while keeping the tower plumb in all directions. For guy arrangements with cables in four or more directions, it is necessary to measure the tensions in only one of the two guys in the same vertical plane while keeping the tower plumb in that plane.

There are several methods of measuring guy tensions with varying degrees of accuracy. For small guys up to ¾ inch, a shunt dynometer calibrated for the size and type of strand is often used.

For larger guys, a series dynamometer may be placed in a temporary line between the anchor and a clamp on the cable. This line is then tightened until the permanent connection is relieved, and the tension is indicated on the dynamometer. Hydraulic jacks with a calibrated pressure gauge or load cells can be used in place of the temporary line and dynamometer. These are particularly effective for large guys attached with bridge sockets.

There are two indirect methods of measuring tensions in guys that do not have any large insulators or other loads in them. The intercept method consists of sighting along a straight bar attached at the bottom of the guy and measuring the vertical distance between the point where the line of sight intercepts the tower and the point where the guy is attached. This distance can be accurately estimated by counting the number of bracing panels in it. The tension in the guy is directly related to this intercept distance, the weight of the guy, and its length and slope.

The tension in a guy cable is also directly related to its length, weight, and natural frequency of free vibration. The natural frequency can be determined by putting the guy in motion with your hand and measuring the fundamental period with a stop watch. It should be noted that because a guy slopes, the tension on it varies along its length, and this method will only provide the average tension and not the tension at the anchor point. For long cables, this difference can be significant.

All tension measurements should be recorded along with temperature and wind speed and direction. If any substantial changes are noted from the values previously measured, careful checks for slippage of all connections should be made.

Tolerances for guy tensions should be as provided by the designer. In the absence of any other tolerance, tensions should be within plus or minus five percent of the specified values.

SUGGESTED INSPECTION AND MAINTENANCE SCHEDULE

ITEM	Daily	Monthly	Before Each Use	Annually	After a major wind or ice storm	Manufacturer's Recommendation
Tower Structure:					•	
Damaged or deformed members				•		
Condition of paint				•		
Corrosion				•		
Connections				•		
Alignment				•	•	
Guys and Insulators:						
Damaged components				•	•	
Corrosion				•		
Connections				•	•	
Tensions				•	•	
Base Insulator				•		
Tower Base and Guy Anchors				•	•	
Ladder Safety Device			•			
Elevator System						•
Operate		•				
Lighting System						•
Lamp Failure	•					
Conduit Systems, fixtures				•		

Fig. 11. Suggested Inspection and Maintenance Schedule.

Any necessary adjustments in tensions can be made by adjusting the turnbuckle or bridge socket at the anchor. Make such adjustments slowly and carefully. Never leave less than three threads sticking through the turnbuckle body or nut on the socket U-bolt. Remember that the tower must be kept plumb.

Base Insulator

The porcelain surface should be wiped clean with a soft cloth to remove any salt deposits or other foreign substances. A check should be made for any evidence of cracks in the porcelain surfaces. Any such defects should be noted.

Any signs of corrosion in the upper and lower bearing plates, rain shield or lightning gap should be noted and corrected in a manner similar to that described for the tower structure. The lightning gap should only be adjusted in accordance with instructions from the station engineer.

Tower Base and Guy Anchors

The tower base and guy anchors above grade should be visually inspected for spalling and cracking of the concrete. The soil surrounding the tower base foundation should be inspected for evidence of settlement. The anchor arms and surrounding soil should be examined for evidence of movement of the anchor. Any such settlement or movement should be noted.

Appurtenances

1. *Ladder and Safety Device*

   The ladder and its connections should be checked for corrosion and tightness along with the tower. The sleeve and belt of the safety device should be visually examined and tested near the ground level before each use.

2. *Elevator System*

   Inspection and maintenance of the elevator system should be in accordance with the manufacturer's instructions. It is a good practice to operate the elevator at least once a month.

3. *Lighting System*

   Inspection and maintenance of the lighting system should be in accordance with the manufacturer's instructions. Checks for corrosion in the conduit, junction boxes and light fixtures should be made along with the tower inspection. Any obstructions in the breather or drain in the conduit should be removed. Broken or cracked glass and any leaking gaskets should be replaced.

Frequency of Inspection and Maintenance

A suggested schedule for inspection and maintenance performance is shown in Fig. 11.

Reports

A written report of each maintenance and inspection procedure performed should be made and filed with the station engineer.

2.2

Lightning Protection for Broadcast Facilities

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Lightning, shown by National Oceanic and Atmospheric Administration studies to be the leading cause of weather-related deaths in America, is at the same time the most frequent yet least well understood of the atmospheric forces.

Lightning is also a leading destroyer. Identified as electric current by Benjamin Franklin more than 230 years ago, lightning has kept pace with every electrical and electronic advance of man, exhibiting a new destructive facet to match each technological advance.

As semiconductors, and later, integrated circuits found widespread use in the electronics industry, it became apparent that measures were necessary to protect these components from exposure to surges. Protection was required not only from lightning but from man made sources as well.

It is hoped that the reader will obtain a basic understanding of the fundamentals of protection from this chapter. A wealth of information is available to the reader who wishes to understand this subject in greater detail. Several of these sources are listed in the references at the end of this chapter.

THE THUNDERSTORM CELL

Thunderclouds are created by convective action of the atmosphere, as an invasion of cool air causes lighter, warm moist air to migrate upward into the cooler upper atmosphere. Cooling of this moisture-laden air causes condensation of the moisture on small dust particles forming a cloud. Cooler dry air surrounding the cloud is forced downward as displacement occurs. This updraft and downdraft mechanism can become quite intense as demonstrated by an aircraft flying through a cloud.

The convective action generally stems from solar heating of the earth's surface and adjacent atmosphere or from frontal activity where warm moist air is displaced upward by an encroaching cooler air mass.

The exact mechanisms of cloud electrification are not completely understood and at present there is no consensus of opinion by researchers. It is known, however, that a separation of electrical charges occurs causing pockets of positive and negative charge within the cloud. As this activity continues, the lower portion of the cloud typically assumes a net negative charge with respect to both the earth and upper portions of the cloud.

THE LIGHTNING DISCHARGE

The cloud action continues until sufficient potentials are achieved to cause a point discharge. This mechanism is not unlike dielectric breakdown of a capacitor where the charged bodies represent plates and the atmosphere represents the dielectric. Discharges can occur within the cloud, between clouds or between cloud and ground. For purposes of this document, only the latter will be considered.

An intense electric field is developed between the cloud and earth prior to a discharge. Voltage gradients are present ranging from very positive to very negative between the cloud and ground. As field intensity increases, corona discharge or "St. Elmos Fire" is sometimes observed from conductive bodies. This is a form of leakage between the charge bodies and is similar to leakage caused by impurities and irregularities in a capacitor.

As field intensity continues to increase, the air between cloud and ground begins to ionize and pockets of ionized air are formed and shifted by the wind. These pockets are more conductive than the surrounding air and form irregular conductive paths of increased current flow.

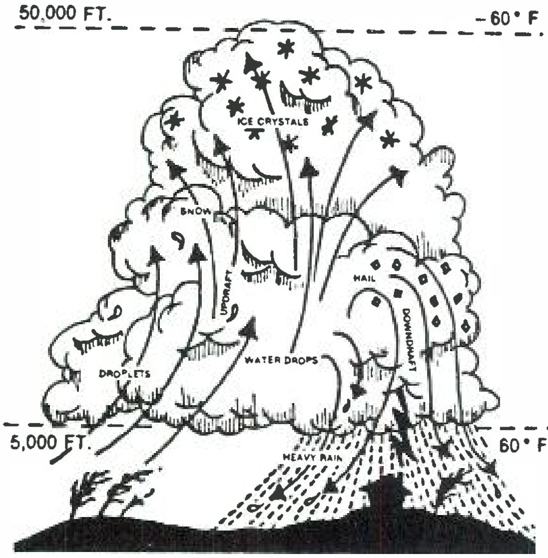


Fig. 1a. This thundercloud has reached its mature stage and a downdraft has developed on the cloud's lee side, producing a sudden drop in temperature, wind gusts, rain and perhaps hail, and lightning flashes.

These are the sequential stages of a typical lightning flash to a protected structure....

(1) typical charge configuration of a thundercell prior to a lightning flash; (2) local discharge between a small P region at the cloud's base and its N region; (3) free electrons start downward, propagating in steps averaging 150 feet; (4) leader stroke may fork as it moves downward, neutralizing positive ion pockets; (5) as negative stepped leader nears effective earth, positive point-discharge currents strain upward; (6) several positive streamers may reach upward; (7) when a positive return stroke rises upward; (8) the return stroke makes the trip from earth to cloud at near the speed of light as thousands of amperes of current flow down the channel to earth.

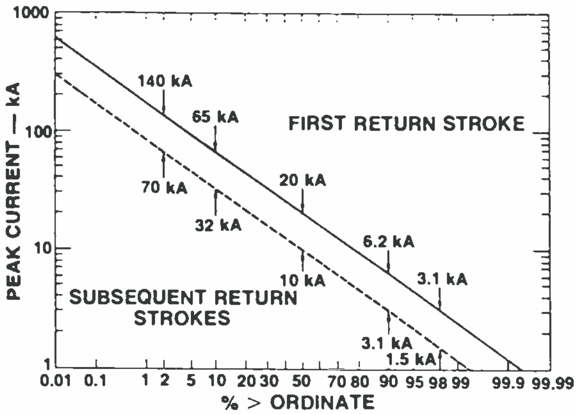


Fig. 1b. Lightning stroke intensity. Courtesy SRI International (Stanford Research Institute), Menlo Park, California 94025.

THE LIGHTNING ROD

From the previous discussion on behavior of upward streamers, it is apparent that lightning rods and tall grounded objects such as towers are effective in controlling where a lightning point discharge will occur.

A certain amount of protection is afforded to bodies in areas of lower elevation in the vicinity of a lightning rod or tower. For many years this "zone of protection" was described as a 45 degree cone extending downward from the uppermost tip or structure. Statistical data is revealing that this zone should be reduced by defining the sides of the cone with a concave hyperbolic shape. It is also not uncommon for the upper sides of a tower or other tall structures to receive a direct strike from lightning.

THE LIGHTNING CONDUCTOR

Lightning currents must be carried safely to ground by allowing them to travel along a predetermined path. This path consists of dedicated lightning conductors or through the steel framework of a tower or building. The lightning current waveform will typically have a very fast risetime on the order of 1 microsecond. Decay will be slower and is largely dependent on impedance characteristics of the current carrying circuit. Lightning currents of 200,000 amperes are not uncommon with the average stroke falling within the 20 to 30 kiloampere range.

Inductance plays a major role in performance of any conductor to be used for lightning protection or bonding. Inductance of a straight circular conductor is approximately 1 to 1.5 microhenries per meter and does not change appreciably with conductor size. During the fast risetime of the current, the inductance is responsible for most of the voltage drop through the conductor. During the slower decay, the resistive voltage drop is a larger part of the total. This behavior may be best explained by example.

Voltage drop through a lightning conductor is given by the formula:

$$E = IR + L(di/dt) \qquad [1]$$

Where:

- I = current in amperes
- R = conductor dc resistance in ohms
- L = conductor inductance in henries
- di = change of current in amperes
- dt = change of time in seconds (risetime)

Assuming:

- conductor length = 10 meters
- conductor material: copper
- conductor size = #6 AWG
- total DC resistance = .013 ohms
- total inductance = 10 microhenries
- current = 1,000 amperes
- risetime = 1 microsecond

$$E = (1000. \times .013) + .000010\ (1000/.000001)$$
$$E = 13 + 10{,}000$$
$$E = 10013 \text{ volts}$$

The resistive voltage drop is only 13 volts. The reactive voltage drop, however, is 10,000 volts. The lesson to be learned by this example is that conductor length is far more important than size. Minimum conductor size is a function of thermal properties (temperature rise), corrosion resistance, and mechanical properties.

Conductor arrangement should be such that conductors always run either horizontally or downward along their path to the ground. Multiple "down" conductors are required by most codes for two reasons. First, if one should become damaged, a path to the ground will be maintained by the others. The second and equally important reason is to lower the impedance of the overall network. As you recall, increasing the size of conductors has little effect on its surge impedance. Providing multiple paths, however, will substantially decrease system impedance and provide a better path to ground.

GROUNDING

Grounding of protected buildings and metallic structures such as towers, earth stations, etc., may be accomplished in a number of ways. Driven rods, buried electrodes, counterpoise system, and underground mats are among the common grounding systems. The specific method used will depend largely on soil and rock conditions at the site.

Grounding effectiveness will vary depending on soil conductivity, type of system, and size of the system used. Lightning protection codes explain grounding requirements and indicate those systems which are considered acceptable.

For a better understanding of the fundamentals of grounding, it is necessary to examine the lightning current on its way to ground. Assuming consistent soil structure, a lighting current entering a ground rod will radiate equally in all directions. Passage of this current through the resistive soil will establish a voltage gradient decreasing in strength with distance. The ground rod will also exhibit a similar impedance to that described for conductors, thereby reducing effectiveness of deeper portions of the rod.

If one were to install a number of ground rods or electrodes at a reasonable distance apart, the overall system effectiveness would increase due to division of currents between rods. A greater distance between rods will result in less overlap of their individual voltage gradients and better overall grounding. The counterpoise system, common to AM radio tower, provides a very effective ground if installed properly.

BONDING

In the section dealing with lightning conductors, it became apparent that substantial voltages are developed as lightning currents pass through a conductor. It is also virtually impossible to achieve a perfect ground leading to production of even higher voltages along the conductor.

Voltages of this type may pose a hazard to personnel or equipment whether on dedicated lightning conductors or finding their own way through a building. The most common problems are as follows:

Touch Voltages:
Injury of a grounded person in contact with a conductive body energized by a lightning current.

Step Voltages:
The earth forms a voltage divider around a grounding electrode during a discharge. A person or livestock standing on the ground may be subjected to injury due to potential difference between different parts of their body.

Sideflash:
Voltage on a lightning conductor or other energized body reaches enough magnitude to create

a secondary lightning flash or "sideflash" to a nearby grounded body.

Dealing with these voltages is where bonding plays an important role. Bonding is simply the practice of equalizing the potential difference between conductive bodies through metallic connections.

As an example of bonding, we will examine a typical television transmitter site with remote studio facilities:

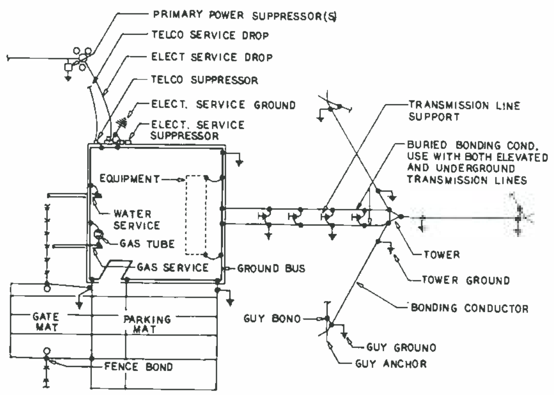


Fig. 2. Typical transmitter site.

The tower structure for this example constitutes a superb lightning rod due to its height and conductivity. Vertical tower elements must be electrically contiguous; if not, copper or aluminum lightning downconductors should be used. The base of the tower should connect to a suitable grounding system such as a counterpoise or a ground rod array.

Except in the case of AM towers, each guy cable should be bonded to the tower and to a ground rod array at each anchor or to the counterpoise system.

If a counterpoise system is not used, a bonding conductor should be installed between the ground array at each guy anchor and the base of the tower. This bonding arrangement will help to minimize step voltages near the base of the tower. The transmitting antenna should be properly bonded to the tower through its mounting. Transmission lines should be bonded to the tower at a minimum of 100 foot intervals.

Transmission lines supporting structures, between the tower and transmitter building, should be bonded to the tower grounding system with the bonding conductor extended into the transmitter building and attached to a ground bus. All transmitter, utility and other grounds should attach to this bus. Any combustible gas service should be bonded to this bus through a spark gap arrestor if direct bonding is not permitted by local codes. (Stray voltages may present a spark hazard to gas companies.)

Surge suppression devices should be installed on all electrical and communications services entering the building with their ground leads attached to the bus. Transmission line suppressors should also be bonded to the grounding system.

A ground mat should be installed below grade along paths traveled by personnel and at vehicle parking locations. This mat should be bonded to the tower grounding system to minimize step voltage hazard to personnel.

Bonding requirements for an AM radio facility will differ slightly since the tower is an active radiator. In this case, a spark gap arrestor should be installed across the base insulator in parallel with a choke coil or isolation stub. The spark gap serves as a discharge path for lightning currents. The choke coil or stub provides a path for draining static charges to ground.

Lightning rods are essential to protect warning lights or other vulnerable equipment from direct strikes. And a full lightning downconductor system is recommended on towers whose electrical continuity may be interrupted, either by design or by an accumulation of rust at joints with aging. Proper maintenance should prevent the latter, but the additional safety of the downconductor system is still important.

Fig. 3 shows optimum protection with lightning rods at the top of the tower and at the ends of all outriggers. In this instance, grounding consists of standard copperclad steel rods driven to a minimum depth of 10 feet. If superior grounding is required due to soil conditions, three rods may be used in an in-line or triangular configuration, with a minimum 10 feet separation between rods.

It is not possible to cover all conceivable aspects of bonding in this document. As stated earlier, the goal in bonding is to equalize potentials during a surge. These potentials may rise to many thousands of volts during a strike. If all conductive bodies rise and fall in potential at the same rate, there will be no stray current flow and no damage or injury.

SURGE SUPPRESSION: BONDING THE UNBONDABLE

By now, you realize the importance of bonding to equalize potential. Surge suppressors provide a means of bonding a wide variety of circuits, but only during a surge.

Many of us recall the days when lightning induced transients had little effect on equipment. Technology keeps marching on and much of today's equipment has remarkably low tolerance for noise and surges.

Most manufacturers of equipment provide limited surge suppression in the design of their

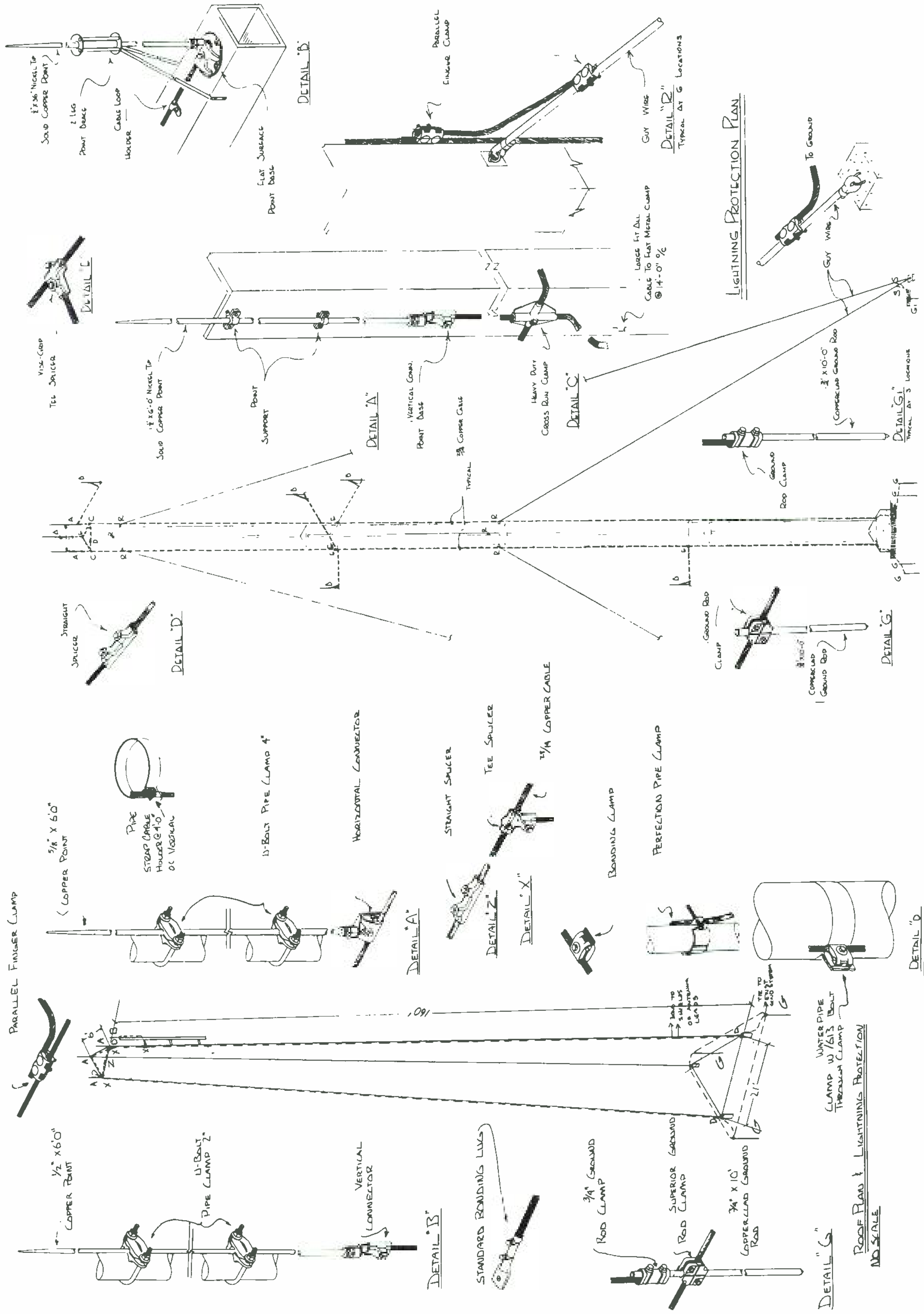


Fig. 3. "Total" lightning protection for towers.

equipment. This suppression is often not adequate for locations where exposure to transients is high.

A surge suppression device must meet the following criteria to be of value to the user:

1. Under normal operating conditions, it must not interfere with the circuit it protects.
2. Its clamping voltage must not be greater than the surge withstand rating of the protected equipment.
3. Clamping speed must be fast enough to prevent damage to the protected equipment.
4. The device must be capable of withstanding surges without damage.

SURGE SUPPRESSOR COMPONENTS

Surge suppression assemblies are packaged by a number of manufacturers to protect a variety of circuits. To understand the operation of these devices, one must be knowledgeable in the characteristics of their component parts. The following section describes each basic type of device with its inherent advantages and disadvantages.

Spark Gaps

The spark gap consists of two electrodes placed in free air or some arc quenching material. One important characteristic of the spark gap involves "flow current" when used on power circuits. Once an arc is established by a surge, the normal circuit voltage may be high enough to sustain the arc. This characteristic is normally dealt with by using a series interrupting device (circuit breaker), magnetic blow out, series resistive element or deionizer.

Advantages:

1. Simple and reliable.
2. High energy handling capacity.
3. Very low voltage drop across gap during conduction (typically 10-20 volts).
4. Bipolar operation.
5. Reasonably fast response.
6. Zero power consumption.
7. Long life expectancy.
8. Low capacitance.

Disadvantages:

1. Used alone, will not extinguish follow current.
2. Limited to use on circuits of relatively high voltage.
3. Firing voltage depends on atmospheric conditions and surge risetime.

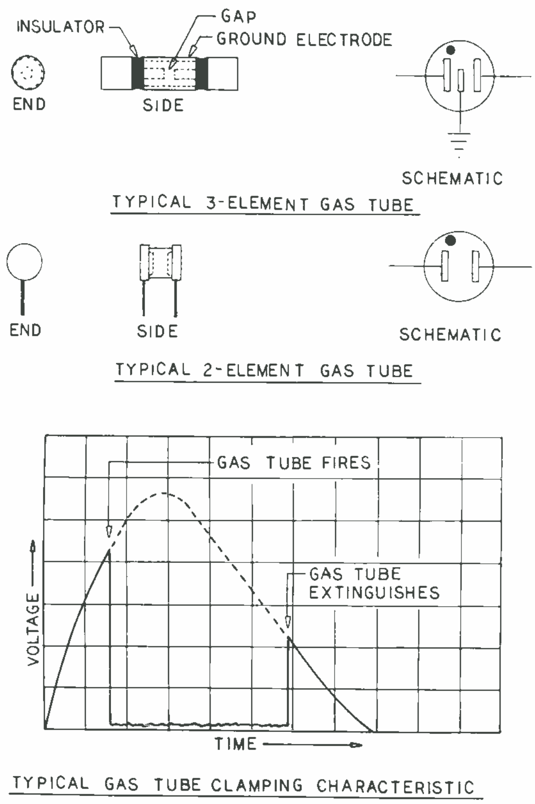


Fig. 4. Typical gas tube details.

Gas Tubes

Gas tubes exhibit many of the characteristics of the spark gap. The problems associated with atmospheric influence are eliminated by enclosing the gap in an atmosphere of neon, argon, krypton, or other gas easily ionized at low pressure.

Advantages:

1. Low cost.
2. Small physical size.
3. Good life expectancy.
4. Fairly low capacitance.
5. High energy capacity.
6. Lower breakdown voltage than spark gap.
7. Very high current capacity and low clamping voltage.

Disadvantages:

1. Follow current limiting required on power circuits.
2. Firing voltage depends on surge risetime.
3. Does not absorb appreciable surge energy.
4. May be ionized by strong RF fields.

Metal Oxide Varistors

Metal oxide varistors, or MOVs, are composed of sintered zinc oxide particles pressed in to a wafer and equipped with connecting leads or terminals. These devices exhibit a non-linear resistance characteristic and a more gradual clamping action than either spark gaps or gas tubes. As a surge voltage increases, these devices conduct more heavily and provide clamping action. Unlike spark gaps or gas tubes, these devices absorb energy during surge conditions.

Advantages:

1. Available for low voltage applications.
2. Absorb energy.
3. No external follow current protection required.
4. Fast response time.

Disadvantages:

1. Clamping time depends on surge wavefront.
2. External fusing required for power applications (fails partially shorted).
3. Limited surge life expectancy.
4. High capacitance.

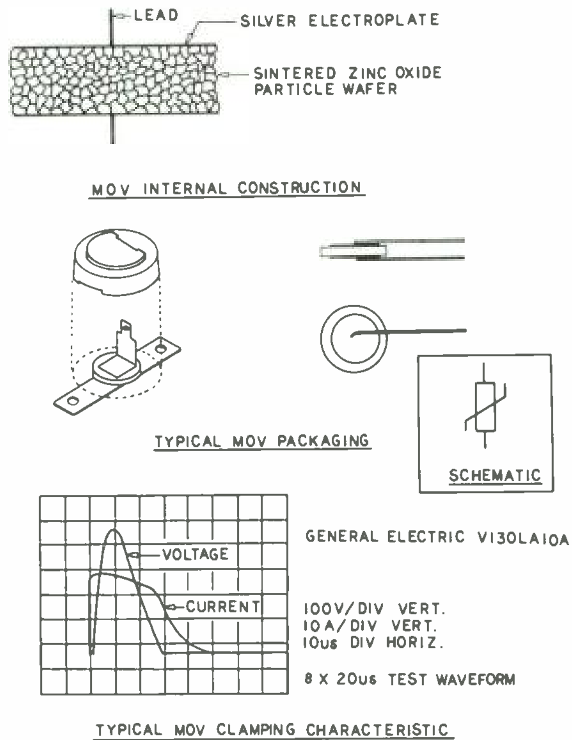


Fig. 5. Typical varistor details.

Silicon Avalanche Devices

Silicon avalanche devices used for surge suppression are similar to Zener diodes except they are designed to handle large surge currents without damage. Junction construction for these devices is typically 10 times larger than an equivalent Zener device. The junction is sandwiched between silver electrodes to improve current distribution and aid in thermal dissipation. These devices exhibit an extremely fast clamping action with an absolute clamping level.

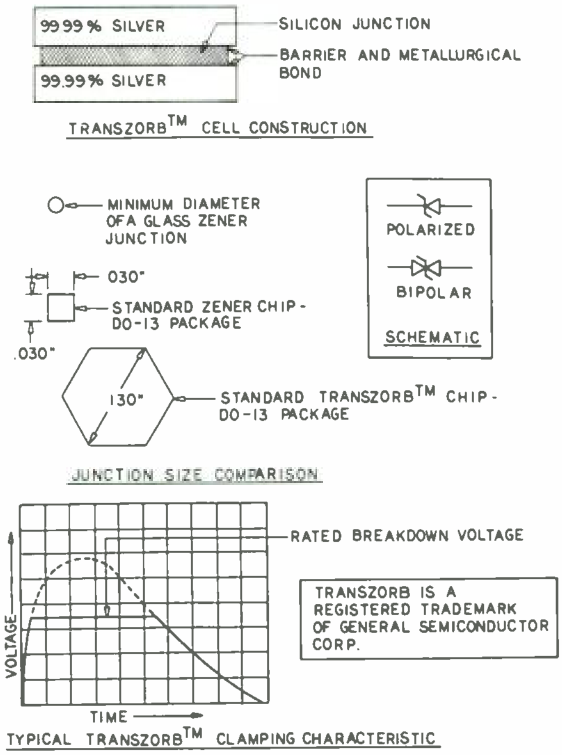


Fig. 6. Typical silicon avalanche suppressor details.

Advantages:

1. High clamping speed (less than one nanosecond).
2. Hard clamping threshold.
3. Available in bipolar configuration.
4. Small size.

Disadvantages:

1. Subject to damage by large surges.
2. Lead length substantially affects clamping time.

After reviewing characteristics of the basic surge suppression components, it is apparent that no single component is appropriate for all situations. It is, however, possible to use these devices in combination to fit almost any surge suppression need.

SURGE SUPPRESSOR ASSEMBLIES FOR POWER APPLICATION

To best explain the function of power surge suppressors, it is appropriate to examine the path a surge might follow on its way to your equipment. For this example, we will assume the surge begins on the power company primary electrical system and your equipment is located within your control room at the studio.

The Primary Suppressor

The first line of defense against a power line lightning or switching surge is the primary suppressor installed by the power company. These devices are installed between each phase conductor and the grounded neutral. They are commonly located at step down transformers and at poles serving underground primary distribution.

These devices are intended to clamp surges to a value below the insulation breakdown rating of power company transformers and cables.

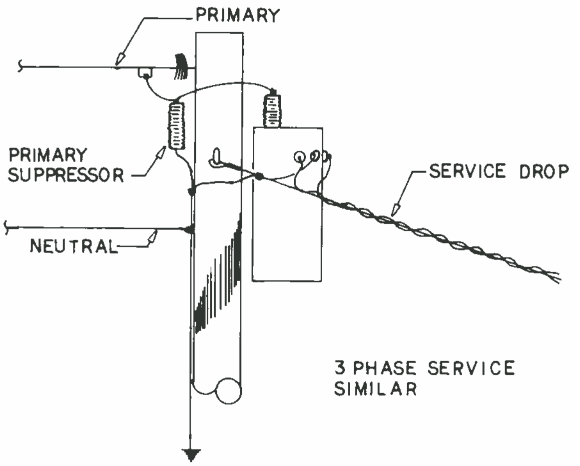


Fig. 7. Typical primary suppressor installation.

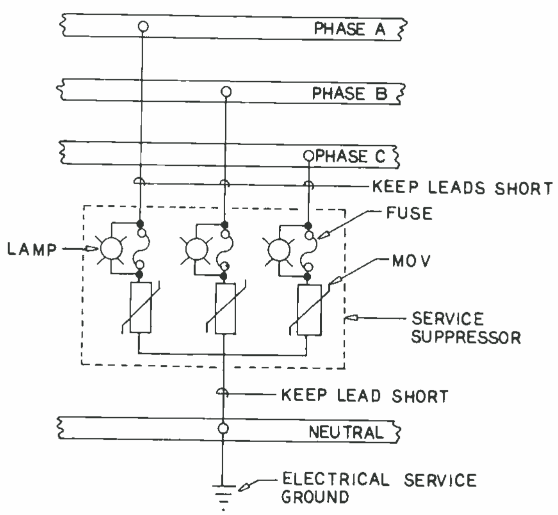


Fig. 8. Typical electrical service suppressor.

The Secondary Suppressor

The second line of defense against surges is a suppressor installed at the building electrical service location. Most of us are familiar with the common cylindrical lightning arrestors installed on commercial and residential electrical services. These devices consist of a low voltage spark gap with a series thyrite element connected between each phase conductor and the grounded neutral. The thyrite element provides follow current limiting allowing the arc to extinguish following a surge. This type of suppressor will clamp a typical surge at a level of 1000 to 2000 volts, dependent on surge current and waveform. Clamping at this level is sufficient to prevent insulation breakdown on internal wiring, motors, and more rugged electrical devices.

A more effective device utilizes a large metal oxide varistor (with protective fuse) connected between each phase conductor and the grounded neutral. Inductance of the connecting leads plays a major role in the effectiveness of the suppressor. The voltage drop through these leads is additive with the rated clamping voltage of the device. (Keep suppressor leads as short as possible.)

It is interesting to note that many codes do not require service surge suppressors on underground electrical services even though the service is fed from a pole a few feet away. It is advisable to provide service suppression in all applications.

Equipment Suppressors

It is quite possible to experience voltage surges, within a building, of 2000 volts. These surges may be in the form of residual energy from an external event or generated within the building itself.

Equipment surge suppressors range in both complexity and cost. These factors are usually in direct proportion to the clamping effectiveness of the device. Most of these devices depend on installation of a suppressor at the electrical service to prevent their exposure to large transients.

One of the simplest and most common forms of equipment suppressors is a varistor and thermal fuse connected across the line and neutral conductors. Packaging is usually in the form of a series plug and socket arrangement or as part of a plugstrip. For a typical 2000 volt, 15 ampere surge, these devices will typically limit equipment exposure to 500 volts.

For more sensitive equipment, hybrid suppressors are available which provide a lower clamping voltage and very fast response time. These devices use a high energy metal oxide varistor first stage with the varistor and fuse connected in series between line and neutral. The line voltage then passes through a large air core inductor to a silicon avalanche second stage consisting of series connected bipolar suppression diodes between line and neutral. This configuration permits the varistor to absorb the majority of the surge while the diodes provide fast clamping. The inductor provides sufficient voltage drop during the surge to prevent damage to the diodes.

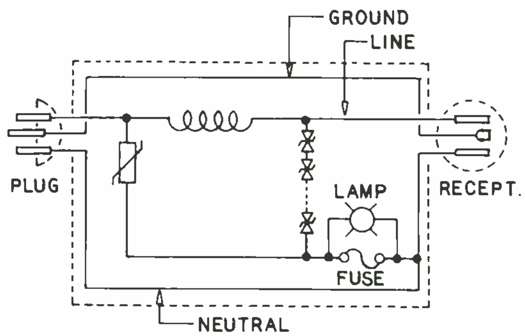


Fig. 9a. Typical 120 VAC hybrid equipment suppressor.

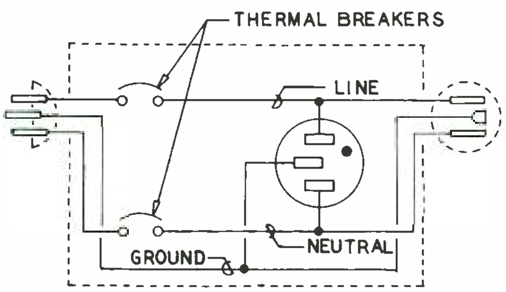


Fig. 9b. Typical 120 VAC gas tube equipment suppressor.

SURGE ASSEMBLIES FOR SIGNAL APPLICATION

Surge suppression for signal lines encompasses a broad variety of circuit types and characteristics. Suppression techniques for video, RF, telephone, audio, data and similar circuits are slightly different but the fundamentals remain the same.

Careful consideration of the operating characteristics for each circuit and the level of protection required will usually make one device stand out as most appropriate for the application.

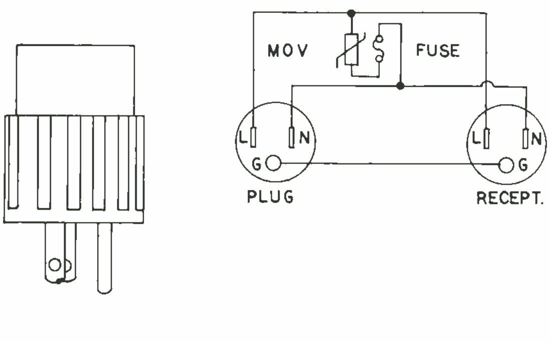
Shielding and use of twisted pairs is also an important part of obtaining an acceptable level of protection. During tests conducted in Orlando, Florida, we found common mode transients of 300 volts on a 24 volt dc unshielded circuit. This would not be too remarkable except the circuit was in PVC conduit, buried 24 inches deep, and the lightning discharges were several miles away.

Let us examine methods for protecting several different circuit types.

Single (Non-Paired) Conductors

Circuit protection for individual conductors will depend largely on the sensitivity of the equipment being protected and on impedance characteristics of the circuit. For low sensitivity applications, a simple varistor or gas tube, connected from the line to ground, will suffice. The gas tube would be the obvious choice if normal leakage current through a varistor could not be tolerated.

For more sensitive applications, the gas tube should be followed by a series inductor and a silicon avalanche second stage from the circuit to ground. A resistance may be substituted for the inductor (typically 10 ohms) if the circuit will tolerate the additional voltage drop.



TYPICAL 120 VAC MOV EQUIPMENT SUPPRESSOR

Fig. 9c. Equipment suppressor configurations.

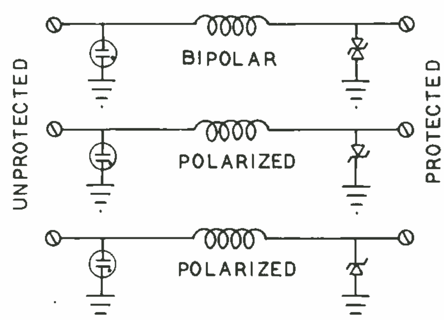


Fig. 10. Typical unbalanced signal line suppressors.

Balance Pairs

Balanced pairs are often protected with a 3-element gas tube. In this application, each side of the pair is connected to an element with the third element connected to ground. This configuration will insure both sides of the pair are clamped to ground at the same instant; thus avoiding possible damage from differential mode surges.

If equipment sensitivity dictates, a series inductance can be inserted in each side of the pair followed by a silicon avalanche device across the pair. Here again, resistors may be substituted if circuit characteristics permit.

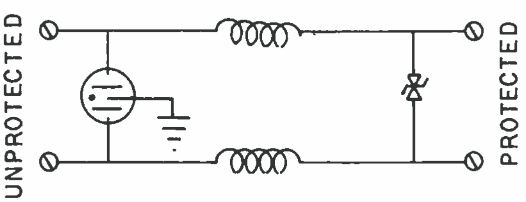


Fig. 11. Typical balanced line suppressor.

Low Level Audio Circuits

Low level audio circuits are treated in a manner similar to balanced pairs except they are normally shielded. Standard engineering practice normally requires these shields be bonded to ground at one point to prevent ground loop problems. In addition to suppression for the pair, a gas tube is connected between the shield and ground at its remote end and at intermediate points. With this configuration, the shield floats under normal conditions but is bonded during a surge.

Video Circuit Protection

Triaxial cable should be used for all video circuits. The outer shield of this cable should be kept electrically isolated from the inner shield and bonded to ground as often as possible. The inner, or signal, shield of the triaxial cable is generally grounded at one point only to minimize ground loop interference.

A video surge suppressor is a low capacitance device equipped with two coaxial connectors and a ground lug. At the point of installation, the following procedure should be observed:

1. Install appropriate connectors on the inner shield and center conductor and connect to the video surge suppressor.
2. Bond the outer shields together and to ground exercising care to prevent contact with the inner shield, connectors, or suppressor body.

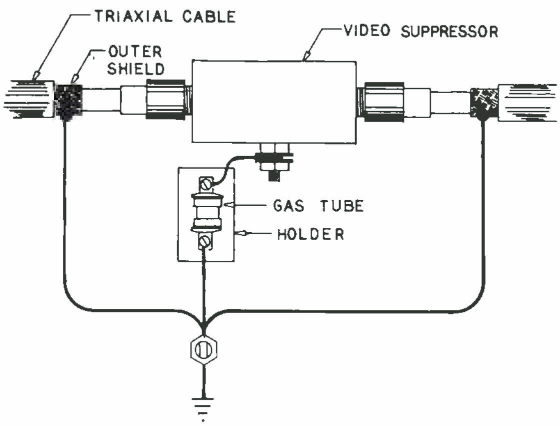


Fig. 12. Typical video suppressor connection.

3. Install a 2-element gas tube between the suppressor ground lug and grounded outer shield.

RF Circuit Protection

Coaxial RF cables should be equipped with a coaxial gap type suppressor with its ground lug bonded to ground. The coaxial sheath should be bonded to ground frequently in areas where exposure to lightning is high. Bonding in this manner will reduce potentials induced into the cable sheath.

SHIELDING—GENERAL GUIDELINES

A lightning discharge radiates an intense electric and electromagnetic field. It is not uncommon to find electric field intensities approaching 1 volt per meter at a distance of 10 kilometers

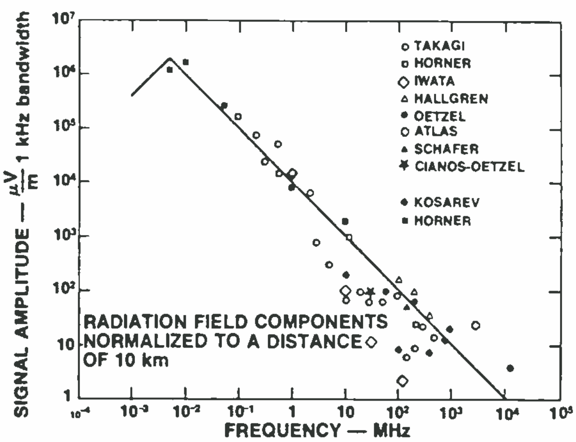


Fig. 13. Lightning signal amplitude vs frequency. Courtesy SRI International (Stanford Research Institute), Menlo Park, California 94025).

from a discharge. Close discharges may produce field intensities of 100 volts per meter. An exposed conductor subjected to an intense electrical field will produce a substantial voltage across its length.

Shielding and use of twisted pair wiring where possible (for common mode rejection) will help relieve some of the induced voltage problems. The following guidelines should be observed:

1. Bond shields to ground as often as possible. For ground loop reduction, bond through gas tubes.
2. Use metallic conduits instead on non-metallic types.
3. In direct burial application, use cable with polyethylene jacketing and a flooding compound between the jacket and shield. This compound seals jacket pinhole damage resulting from lightning, prevents water migration into the cable, and electrolytic decay of the shield.
4. Where pairs are required, consider using telephone type cables which have a corrugated copper shield.
5. If cable must be run aerially, bond the cable shield to the vertical ground conductor at the first, every fifth, and last pole. Bond more frequently if practical.
6. In areas of high lightning exposure, provide a grounded lightning shield wire several feet above the cable on the poles. This wire should be bonded to ground at every pole. For direct burial cables or duct banks in high exposure areas, a counterpoise system is recommended. This system consists of two or more bare wires buried above and to the side of the cable. Counterpoise conductors should be bonded together and to driven rods at manholes, 150 foot intervals, and at each change in cable direction.

CONCLUSIONS

Your interest in lightning protection and surge suppression will largely be dictated by the area of the country in which you live. For some, this information will prove invaluable; for others not plagued by lightning, it should provide a basic understanding of the principles involved.

In this chapter we have dealt briefly with the subjects of lightning physics, lightning protection, and surge suppression. Many volumes have been written on these subjects and the reader is encouraged to study them in greater detail.

Another point to consider is that lightning is an electrical current, and like any other electrical current, it is both predictable and can be controlled.

Please consult an engineer familiar with lightning protection or a lightning protection contractor when planning a lightning protection system or adding surge suppression devices to your electrical system.

REFERENCES

1. Golde, R.H.: *Lightning* (Volume 1 and 2), Academic Press, 1977.
2. Viemeister, Peter E.: *The Lightning Book*, The MIT Press, 1972.
3. Clark, O. Melville: *A Guide for Transient Suppression Using Tranzorbs*, General Semiconductor Industries; Tempe, AR, 1978.
4. *Electrical Protection Fundamentals:* Rural Electrification Administration, Telephone Engineering and Construction Manual, Sections 801-823, July 1974.
5. Fischer, F. A.: "Generation of, and Protection Against, Transients", General Electric Corporation Research and Development.
6. Martzloff, F. D.: "Surge Voltage Suppression in Residential Power Circuits", General Electric Corporation Research and Development, Report 76 CRDO92, May 1976.
7. "Transient Voltage Suppression Manual", General Electric, Semiconductor Products Department, Syracuse, NY (Varistor Data).
8. Alpeter, Henry M.: "Surge Protection for Todays Telephone Plant and Equipment", ITT Industries, Lindenhurst, NY.
9. "Lightning Protection Code—1980" (N.F.P.A.—78): National Fire Protection Association, Inc.; Quincy, MA 02269.

2.3

Transmission Lines

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INTRODUCTION

The intent of this chapter is to give detailed information, tables and charts, which can be used as a type of cookbook by broadcast station engineers in evaluating their present systems, planning modifications to their existing systems, or planning a completely new installation. The area of coverage will be from the transmitter output up to the antenna input, including AM, FM and TV installation.

The transmission line system for any transmission site has always been the vital link connecting the power generator to the antenna. We have seen the evolution from open wire line to coaxial lines and finally to hollow tube waveguide transmission systems. This evolution has been brought about by both higher frequencies and increased power requirements. In addition, the increased sophistication of the system in areas of performance and philosophy of operations have made the current transmission systems completely unrecognizable when compared with initial broadcast systems.

TRANSMISSION LINES

In general, this chapter deals with two basic types of transmission lines: coaxial and hollow tube waveguides. The use of open wire seems to be fading for new installations both in commercial broadcast, as well as the HF frequency band (international shortwave broadcast).

COAXIAL TRANSMISSION LINES

Coaxial transmission lines are characterized by a circular inner conductor supported within a circular outer innerconductor. Usually both conductors are copper, especially in the high power transmission line used in broadcast. There are two major categories of coaxial transmission lines, one being rigid and the second being a semi-rigid, and both types have achieved wide acceptance in AM, FM and TV installations. The designs for the most part have exhibited a well proven track record for trouble free operation over years of use. The graphs and charts that follow represent a cross-section of manufacturers' data available to the transmission line users. On close examination, one will see that, for a given size, rigid transmission lines with air dielectric will tend to have slightly lower attenuation and, therefore, slightly improved power handling capabilities. Also the rigid line is usually used in installations where extremely low VSWR is required of the system. The costs are for all practical purposes the same; however, during installation the semi-rigid line will provide a lower cost for the physical installation due to its continuous nature as op-

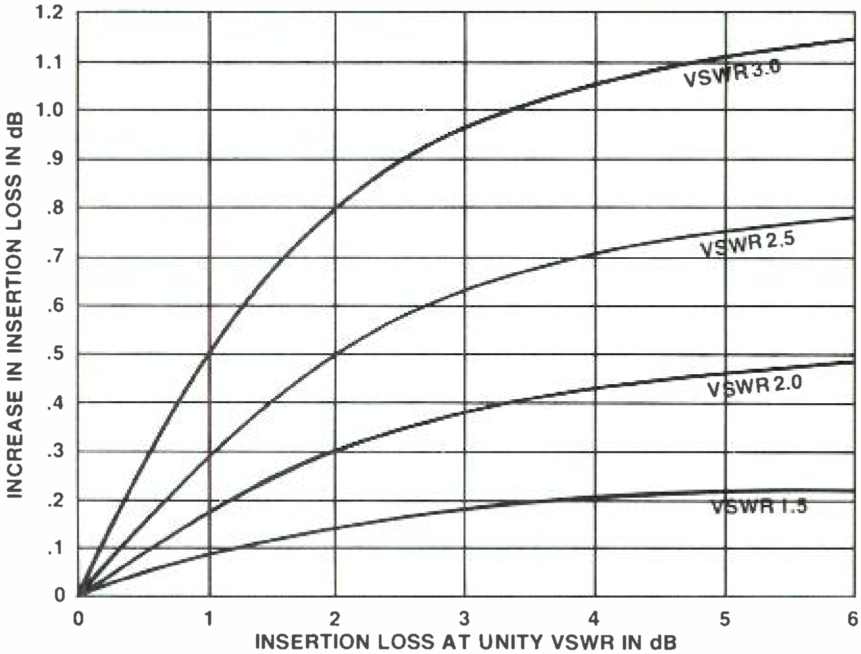


Fig. 1. Insertion loss correction due to load VSWR. (Courtesy of Cablewave Systems, Inc.)

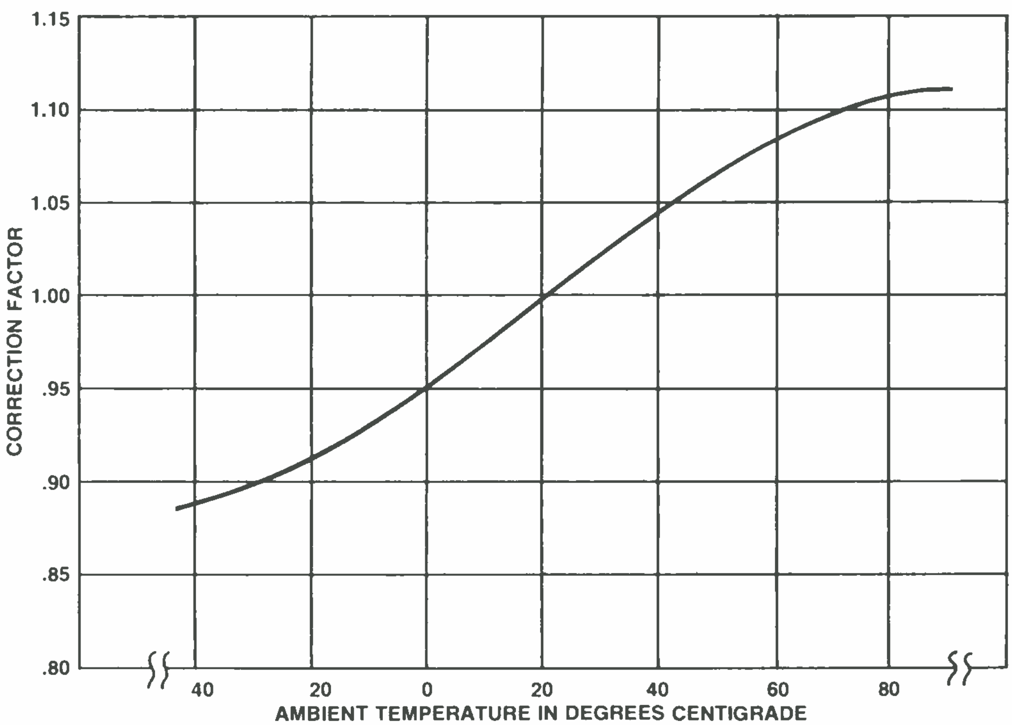


Fig. 2. Attenuation changes due to ambient temperature. (Courtesy of Cablewave Systems, Inc.)

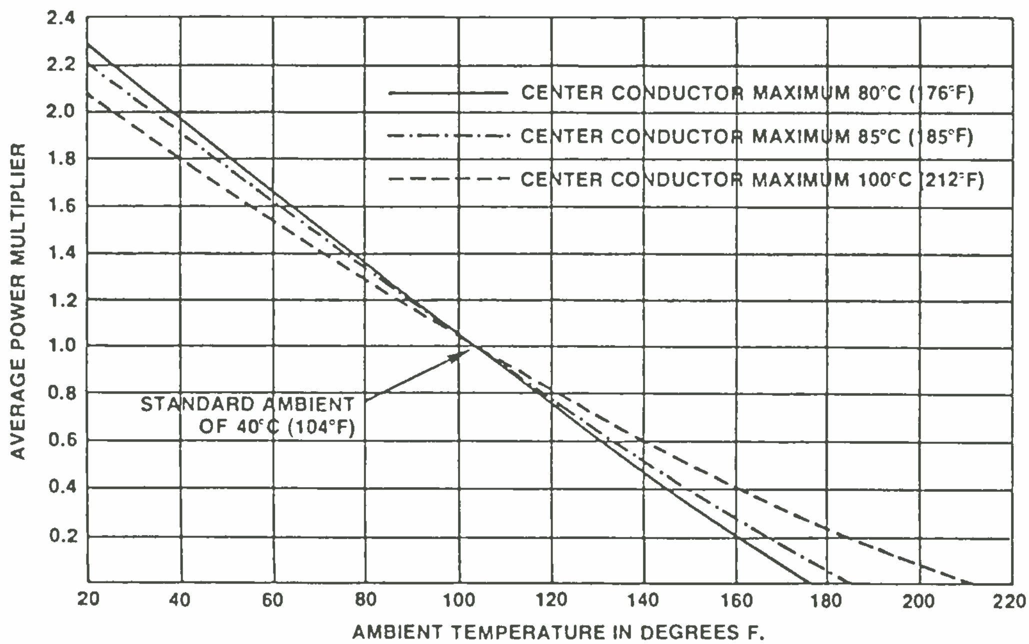


Fig. 3. Variation of average power rating with changes in ambient temperature. (Courtesy of Cablewave Systems, Inc.)

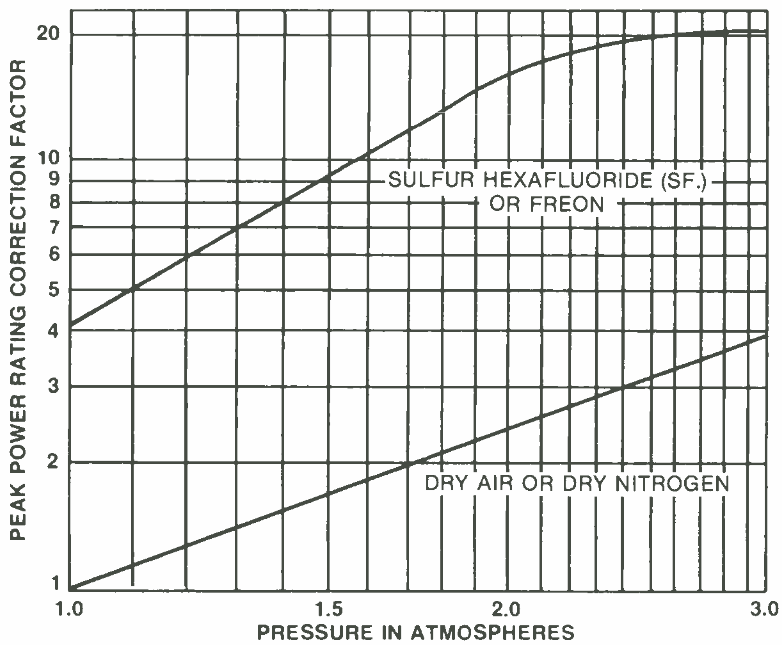


Fig. 4. Peak Power rating improvement due to pressurization. (Courtesy of Cablewave Systems, Inc.)

posed to the approximate 20 foot length in the rigid line sections. In addition semi-rigid line can be attached directly to the tower members while rigid line requires the use of hangers to allow for differential expansion between the tower and the rigid line.

The primary questions of any transmission line for broadcast use is, "how much power will it transmit?" Shown in respective areas are some attenuation and power curves taken from manufacturers' data and adjusting it for the exact conditions the transmission line has to operate in. Shown below are some general curves applicable to all transmission lines. Fig. 1 shows the increase in insertion loss due to VSWR at the output of the transmission system. Fig. 2 represents attenuation change due to ambient temperature, showing that as the temperature goes up so does the attenuation. Fig. 3 shows the variation of average power rating with changes in ambient temperature for three different center conductor temperatures. This is closely related to the change in attenuation due to ambient temperature. Fig. 4 shows the improvement in peak power handling one might achieve in coaxial lines due to pressurization with either dry air or sulfurhexafloride. It is essential always to use manufacturers' data in planning a new installation or evaluating or repairing an existing system. Almost all manufacturers of transmission line put out very complete data and performance curves for their product. These particular curves for any manufacturer represent the limits they have placed on their product. Close examination will show that these curves do differ slightly in various areas. Only through direct contact with the manufacturer should a broadcaster plan to exceed these ratings for whatever reason.

SEMI-RIGID TRANSMISSION LINE

The use of semi-rigid transmission line is almost as old as the use of transmission line itself in the broadcast area. As the power levels have increased in the broadcast industry, we have seen the use of solid dielectric cables give way to foam dielectric cables and further give way to air dielectric semi-rigid transmission line. The data shown at the end of this section reflect the performance curves of one manufacturer and should not be construed as being the absolute value for all manufacturers. The semi-rigid transmission line, especially in larger sizes, is generally characterized by a corrugated outer conductor of copper; this is how the flexibility is achieved. However, it should be noted that the term "semi-rigid" is used because in larger sizes, 1⅝" and up, the semi-rigid bending radius becomes quite large (Fig. 5). The major manufacturers of semi-rigid transmission line have a very wide variety of adapters from most cable sizes to either rigid line or flexible fittings, such as type N, L, C, etc. Typical construction of these is shown in Fig. 6.

LINE SIZE	TYPICAL BEND RADIUS
1 5/8"	20"
3"	30"
3 1/2"	30"
4 1/8"	30"
5"	35 1/2"
6 1/8"	47"
8"	67"

Fig. 5. Typical bend radius for semi-rigid cable.

Installation

General

Smooth wall aluminum and copper corrugated cables can be installed without special tools or equipment. Hoisting grips are employed to support the cable to the hoisting line during lifting. Wrap-lock or cable hangers are used to affix the cable securely to the tower and angle and round member adaptors eliminate any need to drill holes.

Preparation For Installation

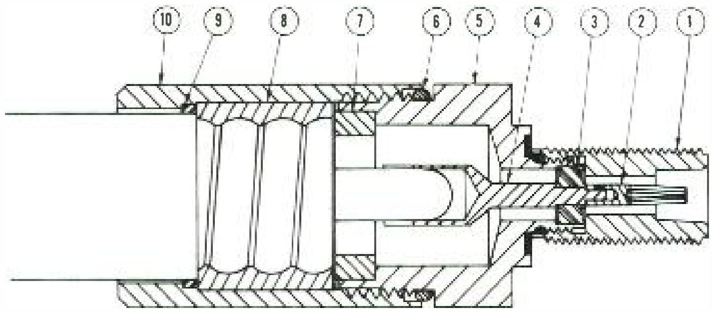
Coaxial cables are usually shipped coiled in crates or cartons, or on non-returnable deposit-type wooden reels. Although cable on reels is protected by wooden lagging or a fiberboard wrap, it should be handled carefully. Reels should rest on their flanges and never be dropped during handling. If fork lifts are used, the forks must be long enough to engage both flanges or cable damage can result. When cable is ordered with factory installed connectors, the antenna end is wound on the outside of the coil and hoisted by means of a cable grip, which can also be factory installed if specified on the order.

After carefully unlagging the reel, inspect the cable for any signs of shipping damage. Air dielectric cables have been pressure tested and each assembly is tagged with the factory pressure test verification, there should also be instructions to be followed should the pressure be found to have declined substantially in shipment. Factory installed EIA connectors (Gas Pass) include a sealing cover to retain pressure during shipment. This cover may be left in place for protection during cable hoisting.

Hanger Spacing

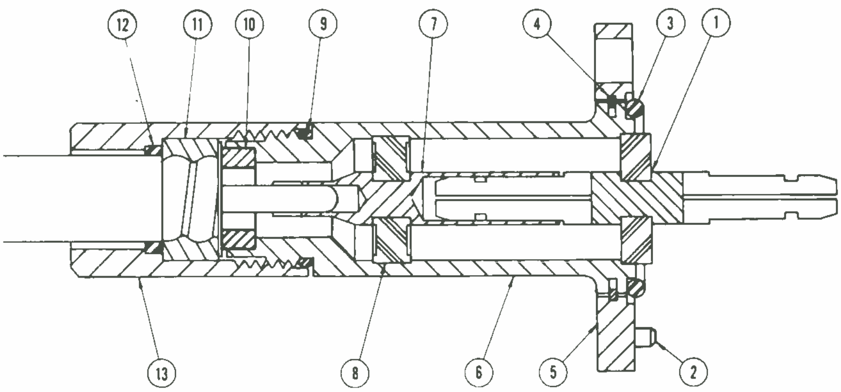
The coaxial cable should be attached to a good electrical ground by grounding kits at the top of

Connector For Foam Wellflex Cable



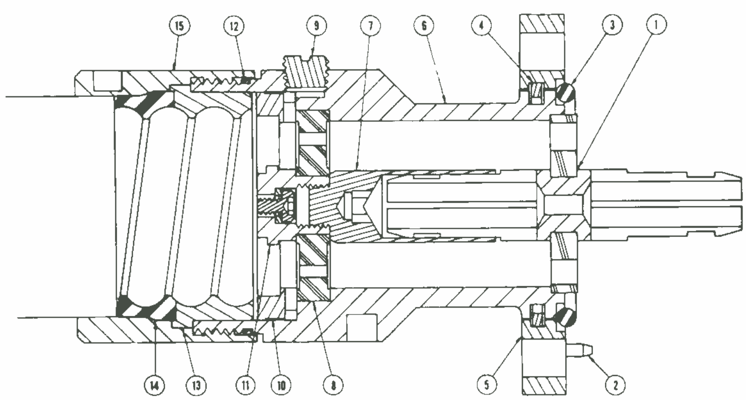
1. NF NOSE
2. NF CONTACT
3. BEAD
4. CONTACT
5. BODY
6. 'O' RING
7. INSERT
8. COLLET
9. REAR SEAL
10. BACK NUT

Connector (EIA) For Foam Wellflex Cable



1. BULLET ASSY
2. PIN
3. 'O' RING
4. SNAP RING
5. FLANGE
6. EIA BODY
7. CONTACT
8. BEAD
9. 'O' RING
10. INSERT
11. COLLET
12. REAR SEAL
13. BACK NUT

Connector For Air Wellflex Cable



1. BULLET ASSY
2. PIN
3. 'O' RING
4. SNAP RING
5. FLANGE
6. EIA BODY
7. CONTACT
8. BEAD (G.P.)
9. PIPE PLUG
10. INSERT
11. ANCHOR SUB-ASSY
12. 'O' RING
13. COLLET
14. THREADED GASKET
15. BACK NUT

Fig. 6. Typical connectors.

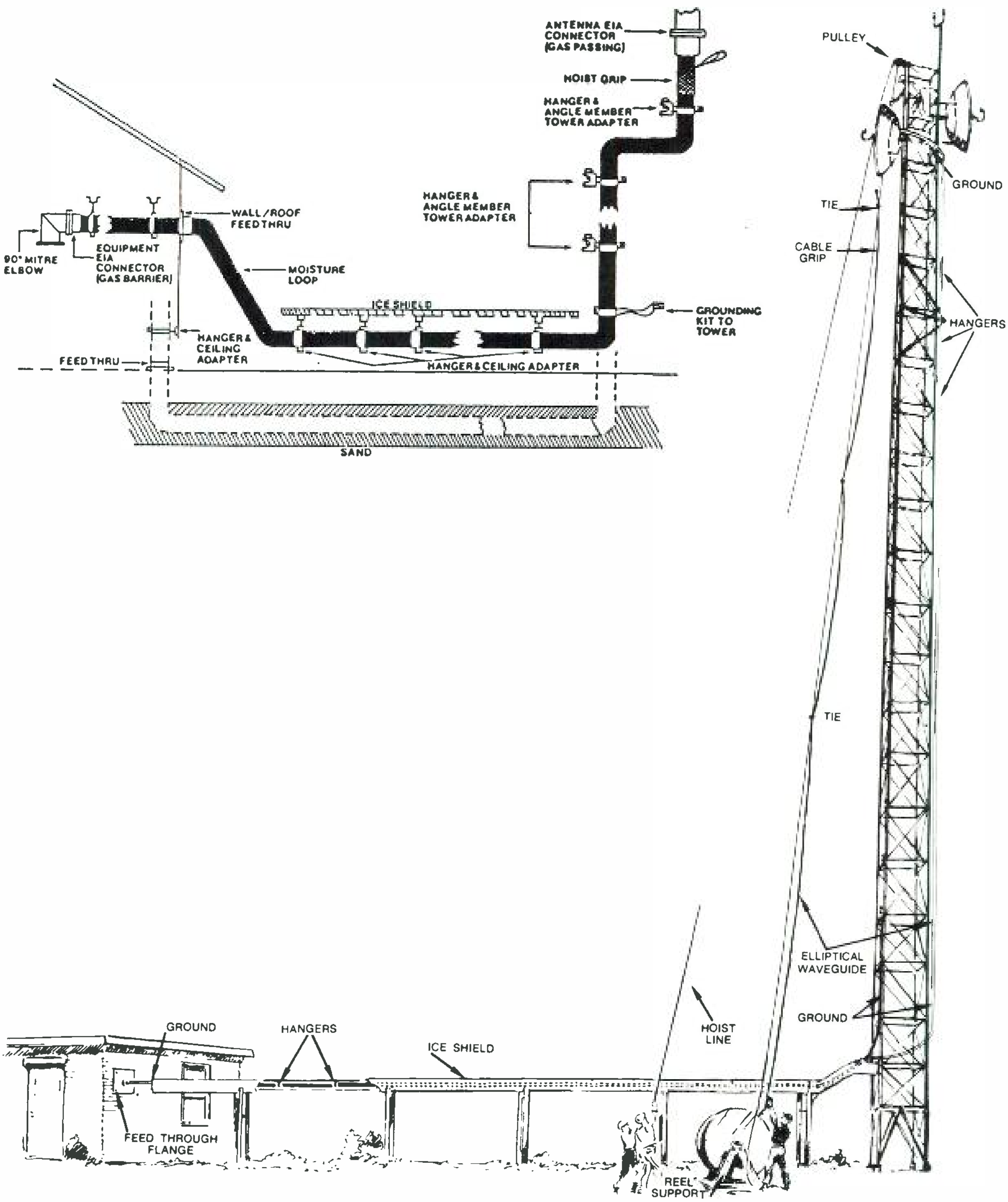


Fig. 7. Typical tower installation.

Rated Max. Wind Speed mph	(km/h)	Radial Ice inches	(mm)	1⅝" to 3" feet	(m)	⅞" feet	(m)	⅜" to ½" feet	(m)
90	(145)			6	(1.8)	4	(120)	3	(90)
110	(180)	no		5	(1.5)	4	(120)	3	(90)
130	(210)	ice		5	(1.5)	3	(90)	3	(60)
180	(290)			4	(1.2)	3	(90)	2	(60)
90	(145)	½	(12)	6	(1.8)	4	(120)	3	(90)
110	(180)			5	(1.5)	3	(90)	2	(60)
130	(210)			4	(1.2)	3	(90)	2	(60)
90	(145)	1	(25)	4	(1.2)	3		2½	(75)
110	(180)			4	(1.2)	3	(90)	2	(60)
130	(210)			3	(0.9)	2	(60)	1½	(45)
90	(145)	2	(50)	4	(1.2)	3	(90)	2	(60)
110	(180)			3	(0.9)	2½	(75)	1½	(45)
130	(210)			3	(0.9)	2	(60)	1½	(60)

Fig. 8. Recommended cable hanger spacing.

the vertical run near the antenna, at the bottom of the tower and at the building entrance. Further information on this is included in the "Lightning Protection" chapter in this section of the Handbook.

Tower Installation

Few tower installations are identical and only typical planning considerations are outlined herein. A pulley and line are recommended for safe lifting of coaxial cables. The hoist line should be long enough to allow tying it to the cable along the vertical run about every 50 feet (15 m) for hoisting. Cable grips are used to support the cable every 200 feet (60 m) and may be fastened to the tower as permanent hangers.

For short lengths, uncoil the cable along the ground, away from the base of the tower, and attach the hoist line. For longer lengths, position reel at the base of the tower, supported on an axle to allow smooth and controlled unreeling. Attach the hoisting grip and line. Place a protective wrap covering over the connector to prevent damage during hoisting and slowly hoist the cable.

After the cable has been raised, the cable grip is permanently secured to the tower and the connector attached to the antenna. For the standard case, ties or cable hangers may be spaced approximately 3 feet (1 m) apart for cables up to 1⅝" diameter, and 5 feet (1.6 m) apart for 3" cable. The chart of recommended hanger spacing for different wind and ice loadings is shown in Fig. 8.

Horizontal Runs Supported By An Ice Shield

Horizontal cable runs suspended from ice shields or support structures normally require the same hanger intervals as the vertical run. A broad drip loop will prevent undesired moisture buildup at the building entry feed-thru.

Horizontal Runs Supported By Messenger Cables

Horizontal cable runs may be supported by a steel messenger cable from the tower to the equipment building. The size of the messenger is dependent upon the weight of cable and length between supports. Cable may be spun to the messenger by a spinning machine similar to those used by many utility companies.

Buried Horizontal Runs

Jacketed smooth wall aluminum cables can be safely buried in many cases; however, jacketed corrugated copper cable is inherently more corrosion resistant and is normally recommended. Cable should be located below the frost line and placed in the middle of a 12" inch layer of sand to protect the jacket from stones or sharp objects. A duct or conduit should be used to protect cable which runs under a service road or in similar situations. All buried connectors or splices should be carefully sealed with a splice protection kit, and the cables should include good electrical grounds at both ends to reduce any lightning effects. In any buried installation there is always the possibility that certain soil conditions can lead to premature deterioration of the cable. Therefore, it is desirable to review local practice and, if in doubt, contact an experienced engineering firm for specific guidance.

Pressurization

Air dielectric coaxial cables should be pressurized with dry air or nitrogen to prevent moisture condensation within the cable and deterioration of electrical performance. If any cable has suffered from condensation it should be dried out by flushing with dry air. The cable may be considered "dry" when the insulation resistance between the center and outer conductors, tested on a "megger," reaches 100,000 megohms.

Power Handling of Semi-Rigid Transmission Line

Line sizes of primary interest to the broadcast engineer range from 1⅝" diameter up to 8" diameter. The attenuation, peak power handling, and average power handling for typical lines in these sizes are given in Fig. 9a & b. Again, caution should be exercised in using exact data from the manufacturer of the transmission line that is to be installed.

RIGID COAXIAL TRANSMISSION LINE

Rigid coaxial line has been used by the broadcast industry since the mid-Forties. It represents a well-proven method of transmitting RF power to the antenna. In general, a high quality broadcast transmission line has the following features:

- High conductivity of the inner conductor,
- Flange expansion joint on the inner conductor which will compensate for the differential mechanical expansion between inner and outer conductors,
- Welded flange to prevent excessive softening of the outer conductor especially in the area of the flange expansion joint,
- Expansion connection designed to capture any contamination generated by the mechanical motion,
- Retention of the inner conductor within the outer for vertical installations,
- Teflon support structures on the inner conductor and the interfacing connector joints.

On long transmission lines, allowances must be provided for differential expansion between outer and inner conductors. Therefore, the inner conductor provides for some relative movement of inner and outer conductors. The result is a very small electrical discontinuity which is a function of differential temperature and which can be compensated to zero at only one temperature differential. Since these discontinuities are a fixed distance apart and numerous in a run of, for example, 300 feet, the combination can produce an undesirable VSWR at frequencies where each section length is a multiple of a half wavelength. The resulting VSWR is, of course, also a function of temperature and is sharply frequency sensitive. If the operating frequency should coincide with one of the critical frequencies for 20-foot section lengths, 19½-foot sections may be used to avoid the possible buildup of standing wave ratio. Fig. 10 gives the critical frequencies for both section lengths. It is not advisable to work closer than ± 2 MHz to the frequencies listed.

Small reflections at inner conductor connectors under flanged areas may add at the following frequencies. For 20-foot and 19½-foot sections, the frequencies in megahertz are 24.52 n and 25.12 n where n is any integer. For other lengths, the critical frequencies in megahertz may be calculated by:

$$f = \frac{490.4n}{L} \quad [1]$$

Where: L is the length in feet.

Fig. 10 shows recommended section lengths for various frequencies. In addition 17½-feet length has been established as an accepted length for Multi Station FM installation. Fig. 22 gives typical mechanical dimensions for coaxial line 1⅝" thru 9³⁄₁₆". The dimensions shown are for EIA style transmission lines which is the most common flange in the broadcast industry. At present however, it should be noted that other styles of flanges i.e., universal, bolt universal are in existence. In the area of power rating on coaxial lines, exact information should be obtained for the manufacturer of the line to ensure its accuracy.

Electrical Specifications

Rigid transmission line does offer generally better electrical specifications than semi-rigid as comparison for dealing with normal sections 20 feet long as opposed to the continuous run. Typical VSWR figures, both as installed and with special tunning, are given in Fig. 11. The average power rating vs. frequency for typical high quality coaxial lines is given in Fig. 12. The attenuation of these various lines is given in Fig. 13. In addition, Figs. 14 through 19 contain tabulated data for attenuation vs. frequency as well as power transfer efficiency for various lengths of transmission lines.

Installation Instructions

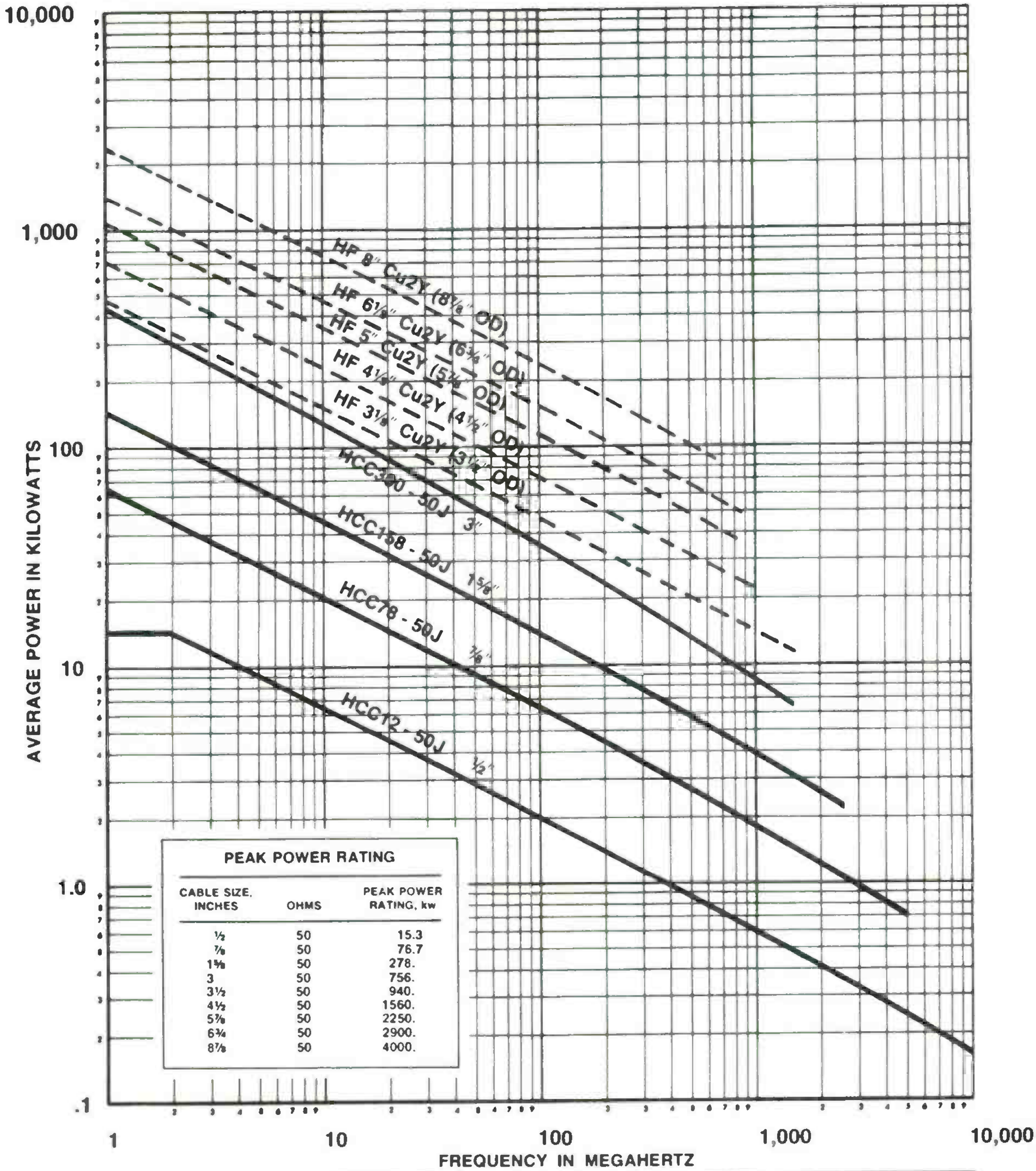
Installation Precautions

Care is required in handling the various transmission line components to prevent damage and assure proper installation. Procedures are outlined in "Transmission Line Do's and Don'ts" (Fig. 23). These recommendations are important.

Tower steel must be designed to support the vertical run in a straight line and maintain line clearance within spring hanger guide rings under load.

Air Wellflex Average Power Rating

CORRUGATED COPPER/50 OHM/AIR DIELECTRIC



PEAK POWER RATING

CABLE SIZE, INCHES	OHMS	PEAK POWER RATING, kw
½	50	15.3
⅞	50	76.7
1⅝	50	278.
3	50	756.
3½	50	940.
4½	50	1560.
5⅞	50	2250.
6¾	50	2900.
8⅞	50	4000.

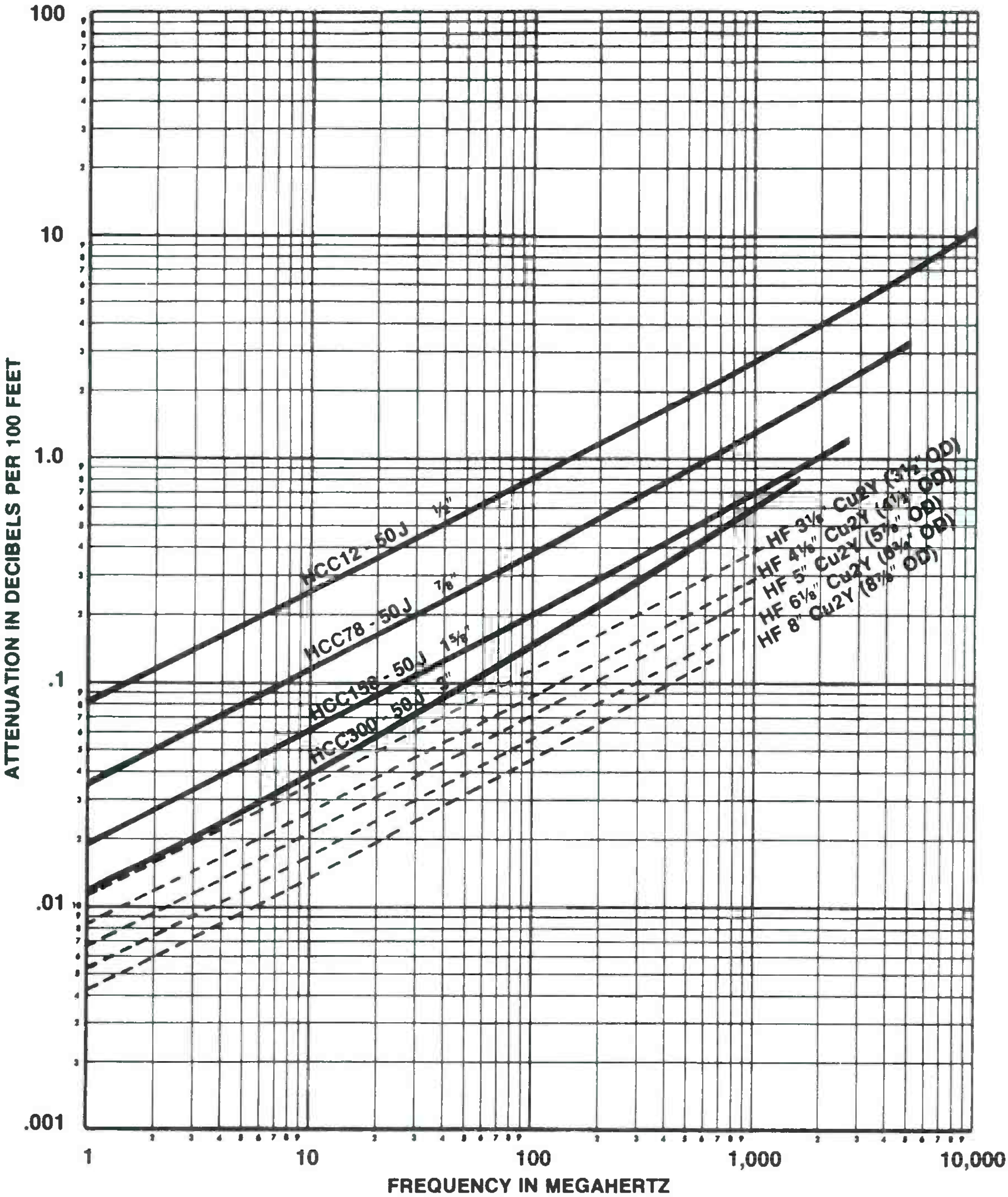
Power ratings based on:
VSWR 1.0
Ambient Temperature 40°C(104F)
Unpressurized dry air (0 psig)

Conversion Data:
Ambient temperature 50°C(122F), multiply by .78 to .80
For 5 psig dry air pressure, multiply by 1.07
For 15 psig dry air pressure, multiply by 1.2

Fig. 9a. Air wellflex average power rating.

Air Wellflex Cable Attenuation

CORRUGATED COPPER/50 OHM/AIR DIELECTRIC



Attenuation curves based on:	Conversion Data:
Ambient Temperature 20°C (68°F)	1 db/100 feet = 3.28 dB/100 meters
Unpressurized dry air (0 psig)	For 75 ohm cables, multiply by .94

Fig. 9b. Air wellflex cable attenuation.

Channel No.	20′ Only	19½′ Only	Either 19½′ or 20′	Channel No.	20′ Only	19½′ Only	Either 19½′ or 20′	Channel No.	20′ Only	19½′ Only	Either 19½′ or 20′	Channel No.	20′ Only	19½′ Only	Either 19½′ or 20′
2			●	19	●			36	●			53	●		
3			●	20			●	37		●		54		●	
4			●	21		●		38			●	55			●
5	●			22			●	39			●	56			●
6			●	23	●			40	●			57	●		
7	●			24			●	41		●		58		●	
8			●	25		●		42		●		59			●
9			●	26			●	43			●	60			●
10		●		27	●			44	●			61	●		
11	●			28			●	45		●		62		●	
12			●	29		●		46		●		63			●
13			●	30			●	47			●	64			●
14			●	31	●			48	●			65	●		
15	●			32	●			49		●		66		●	
16			●	33		●		50		●		67			●
17		●		34			●	51			●	68			●
18			●	35			●	52	●			69	●		
												70		●	

Fig. 10. Recommended section lengths—U.S. TV channels.

CHANNEL RANGE	LENGTH T/L RUN	3⅛ DIA.	4 1/16 DIA.	6⅛ DIA.	8 3/16 9 3/16 DIA.
2-6 and F M	0 to 1000′	Regular 1.05	Regular 1.05	Regular 1.05	Regular 1.05
	1000′ to 1500′	Regular 1.06	Regular 1.06	Regular 1.06	Regular 1.06
	0 to 1000′	*Special 1.04	*Special 1.04	*Special 1.035	*Special 1.03
	1000′ to 1500′	*Special 1.05	*Special 1.05	*Special 1.05	*Special 1.05
7-13	0 to 1000′	Regular 1.05	Regular 1.05	Regular 1.05	Regular 1.05
	1000′ to 1500′	Regular 1.06	Regular 1.06	Regular 1.06	Regular 1.06
	0 to 1000′	*Special 1.04	*Special 1.04	*Special 1.035	*Special 1.03
	1000′ to 1500′	*Special 1.05	*Special 1.05	*Special 1.05	*Special 1.05
14-30	0 to 800′	Regular 1.05	Regular 1.05	Regular 1.05	Regular 1.05
	800′ to 1500′	Regular 1.07	Regular 1.07	Regular 1.07	Regular 1.07
	0 to 800′	*Special 1.035	*Special 1.035	*Special 1.03	*Special 1.03
	800′ to 1500′	*Special 1.05	*Special 1.05	*Special 1.05	*Special 1.05
31-62	0 to 800′	Regular 1.06	Regular 1.06	Regular 1.05	----------------
	800′ to 1500′	Regular 1.08	Regular 1.08	Regular 1.08	----------------
	0 to 800′	*Special 1.05	*Special 1.05	*Special 1.04	----------------
	800′ to 1500′	*Special 1.05	*Special 1.05	*Special 1.05	----------------
31-52	0 to 800′	----------------	----------------	----------------	Regular 1.05
	800′ to 1500′	----------------	----------------	----------------	Regular 1.08
	0 to 800′	----------------	----------------	----------------	*Special 1.04
	800 to 1500′	----------------	----------------	----------------	*Special 1.05

Fig. 11. VSWR maximum limit values.

POWER RATING VS. FREQUENCY

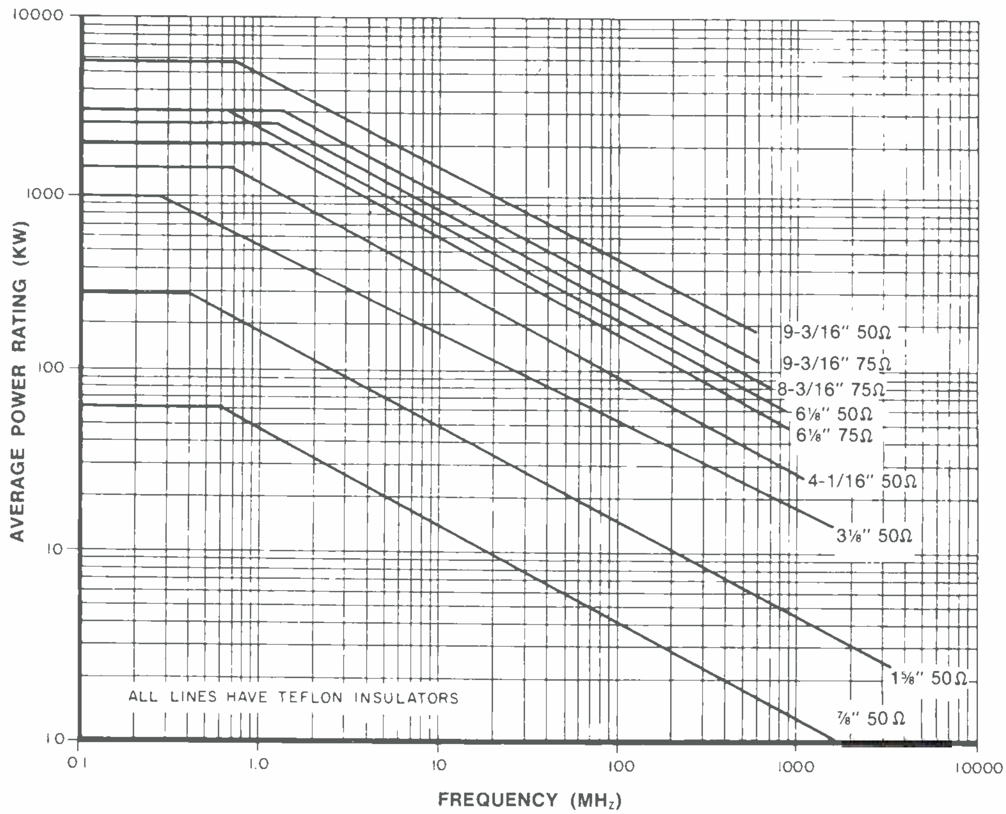


Fig. 12. Power rating of rigid transmission line.

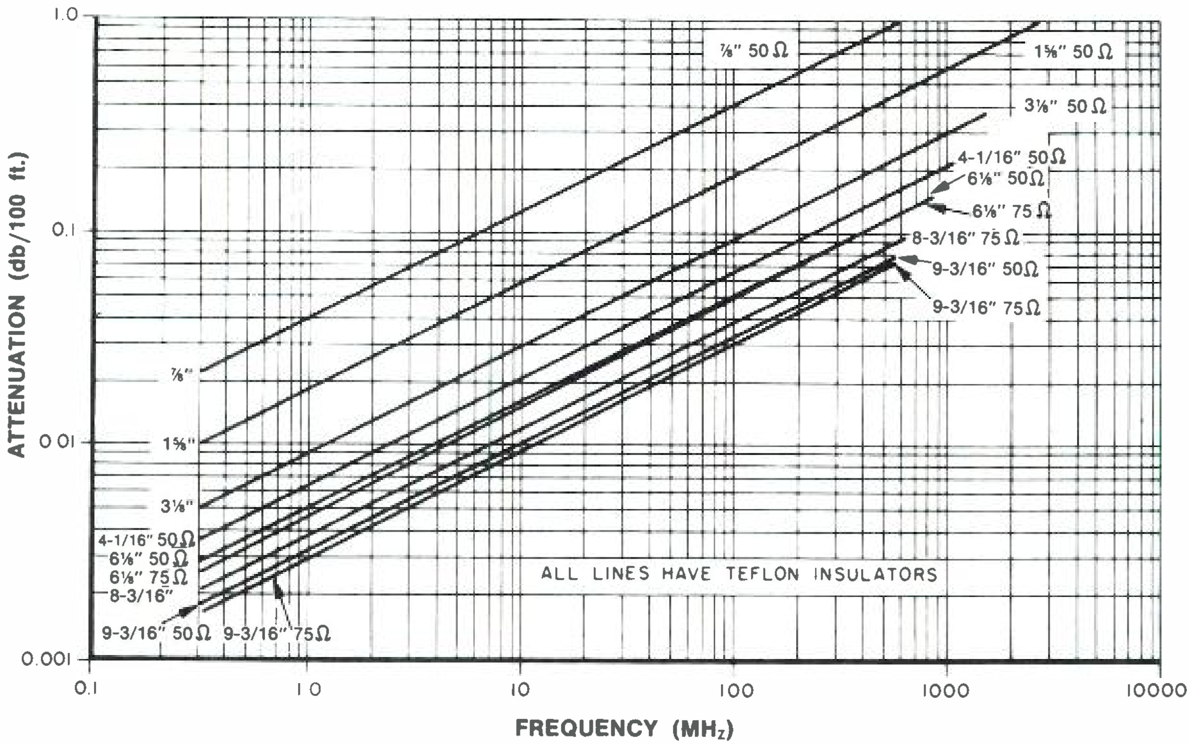


Fig. 13. Transmission line attenuation.

Channel	Loss dB/100' (30.48 m)	200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
		Total Length in Feet (Meters)									
2	0.072	96.7	93.6	90.5	87.5	84.7	81.9	79.2	76.6	74.1	71.7
3	0.076	96.6	93.2	90.0	87.0	83.9	81.0	78.2	75.5	72.9	70.3
4	0.080	96.4	92.9	89.5	86.3	83.2	80.2	77.3	74.5	71.7	69.2
5	0.086	96.1	92.4	88.9	85.4	82.1	78.9	75.9	72.8	69.8	67.4
6	0.089	96.0	92.1	88.4	84.9	81.5	78.2	75.1	72.0	69.2	66.4
7	0.130	94.2	88.7	83.6	78.7	74.1	69.9	65.8	62.0	58.3	54.9
8	0.132	94.1	88.5	83.4	78.4	73.8	69.5	65.3	61.5	57.9	54.4
9	0.134	94.0	88.3	83.1	78.1	73.4	69.2	64.9	61.0	57.3	53.8
10	0.136	94.0	88.1	82.9	77.8	73.1	68.8	64.5	60.6	56.8	53.4
11	0.138	93.8	88.1	82.6	77.6	72.8	68.3	64.1	60.2	56.4	52.9
12	0.141	93.7	87.8	82.3	77.1	72.3	67.7	63.5	59.5	55.8	52.2
13	0.143	93.6	87.7	82.1	76.8	71.9	67.4	63.1	59.1	55.3	51.6
14	0.223	90.2	81.4	73.5	66.3	59.8	54.0	48.7	44.0	39.6	35.7
15	0.225	90.2	81.3	73.3	66.1	59.6	53.7	48.4	43.7	39.3	35.5
16	0.227	90.1	81.1	73.1	65.8	59.3	53.4	48.1	43.3	39.0	35.1
17	0.229	90.0	81.0	72.9	65.6	59.0	53.1	47.8	43.0	38.6	34.8
18	0.231	89.9	80.8	72.7	65.3	58.8	52.8	47.5	42.7	38.4	34.5
19	0.233	89.8	80.7	72.5	65.1	58.5	52.5	47.2	42.4	38.0	34.2
20	0.234	89.8	80.6	72.4	65.0	58.3	52.4	47.0	42.2	37.9	33.9
21	0.235	89.7	80.5	72.3	64.9	58.2	52.2	46.9	42.1	37.8	33.8
22	0.237	89.7	80.4	72.1	64.6	57.9	52.0	46.6	41.8	37.4	33.5
23	0.239	89.6	80.2	71.9	64.4	57.7	51.7	46.3	41.5	37.0	33.2
24	0.240	89.5	80.2	71.8	64.3	57.5	51.5	46.1	41.3	36.9	33.0
25	0.242	89.5	80.0	71.6	64.0	57.3	51.2	45.8	41.0	36.7	32.8
26	0.243	89.4	80.0	71.5	63.9	57.2	51.1	45.7	40.9	36.4	32.7
27	0.245	89.3	79.8	71.3	63.7	56.9	50.8	45.4	40.6	36.2	32.3
28	0.247	89.3	79.7	71.1	63.5	56.6	50.5	45.1	40.3	36.0	32.0
29	0.249	89.2	79.5	70.9	63.2	56.4	50.3	44.8	40.0	35.7	31.8
30	0.250	89.1	79.4	70.8	63.1	56.2	50.1	44.7	39.8	35.5	31.5
31	0.252	89.0	79.3	70.6	62.9	56.0	49.8	44.4	39.5	35.1	31.3
32	0.254	89.0	79.1	70.4	62.6	55.7	49.6	44.1	39.2	34.9	31.1
33	0.255	88.9	79.1	70.3	62.5	55.6	49.4	43.9	39.1	34.8	30.9
34	0.256	88.9	79.0	70.2	62.4	55.5	49.3	43.8	38.9	34.5	30.8
35	0.257	88.8	78.9	70.1	62.3	55.3	49.2	43.7	38.8	34.4	30.5
36	0.258	88.8	78.9	70.0	62.2	55.2	49.0	43.5	38.7	34.3	30.4

Channel	Loss dB/100' (30.48 m)	200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
		Total Length in Feet (Meters)									
37	0.260	88.7	78.7	69.8	61.9	55.0	48.8	43.3	38.4	33.9	30.2
38	0.262	88.6	78.6	69.6	61.8	54.7	48.5	43.0	38.1	33.7	29.9
39	0.264	88.6	78.4	69.4	61.5	54.5	48.2	42.7	37.8	33.5	29.7
40	0.265	88.5	78.3	69.3	61.4	54.3	48.1	42.6	37.7	33.2	29.4
41	0.266	88.5	78.3	69.3	61.3	54.2	48.0	42.4	37.5	33.1	29.3
42	0.267	88.4	78.2	69.2	61.2	54.1	47.8	42.3	37.4	33.0	29.2
43	0.269	88.3	78.0	69.0	60.9	53.8	47.6	42.0	37.1	32.8	28.9
44	0.270	88.3	78.0	68.9	60.8	53.7	47.4	41.9	37.0	32.7	28.8
45	0.272	88.2	77.8	68.7	60.6	53.5	47.2	41.6	36.7	32.3	28.6
46	0.274	88.1	77.7	68.5	60.4	53.2	46.9	41.3	36.4	32.1	28.3
47	0.275	88.0	77.6	68.4	60.3	53.1	46.8	41.2	36.3	32.0	28.2
48	0.276	88.1	77.6	68.3	60.1	53.0	46.6	41.1	36.2	31.8	28.0
49	0.278	88.0	77.4	68.1	59.9	52.7	46.4	40.8	35.9	31.5	27.7
50	0.279	87.9	77.3	68.0	59.8	52.6	46.3	40.7	35.8	31.4	27.6
51	0.281	87.9	77.2	67.8	59.6	52.4	46.0	40.4	35.5	31.2	27.4
52	0.282	87.8	77.1	67.7	59.5	52.2	45.9	40.3	35.4	31.1	27.2
53	0.283	87.8	77.1	67.6	59.4	52.1	45.7	40.2	35.3	30.9	27.1
54	0.284	87.7	77.0	67.5	59.3	52.0	45.6	40.0	35.1	30.8	27.0
55	0.285	87.6	76.9	67.5	59.2	51.9	45.5	39.9	35.0	30.6	26.9
56	0.286	87.7	76.8	67.4	59.1	51.8	45.4	40.0	34.9	30.5	26.8
57	0.287	87.6	76.8	67.3	58.9	51.6	45.2	39.6	34.7	30.4	26.6
58	0.290	87.5	76.6	67.0	58.6	51.3	44.9	39.3	34.4	30.0	26.3
59	0.292	87.4	76.4	66.8	58.4	51.1	44.6	39.0	34.1	29.8	26.1
60	0.294	87.3	76.3	66.6	58.2	50.8	44.4	38.8	33.9	29.6	25.8
61	0.295	87.3	76.2	66.5	58.1	50.7	44.3	38.6	33.7	29.4	25.7
62	0.297	87.2	76.1	66.3	57.9	50.5	44.0	38.4	33.5	29.1	25.5
63	0.298	87.2	76.0	66.3	57.8	50.3	43.9	38.3	33.4	29.0	25.3
64	0.299	87.1	75.9	66.2	57.7	50.2	43.8	38.1	33.2	28.9	25.2
65	0.300	87.1	75.9	66.1	57.5	50.1	43.7	38.0	33.1	28.8	25.1
66	0.301	87.1	75.8	66.0	57.4	50.0	43.5	37.9	33.0	28.7	25.0
67	0.302	87.0	75.7	65.9	57.3	49.9	43.4	37.8	32.9	28.6	24.9
68	0.2025	87.0	75.7	65.8	57.3	49.8	43.4	37.7	32.8	28.5	24.8
69	0.303	87.0	75.6	65.8	57.2	49.8	43.3	37.7	32.7	28.5	24.8
70	0.3035	87.0	75.6	65.8	57.2	49.7	43.2	37.6	32.7	28.4	24.7

Fig. 14. Transfer efficiency (%) 3-1/8" 50-ohm line.

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)									
		200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
2	0.050	97.7	95 5	93.4	91.3	89.2	87.2	85.2	83.3	81.4	79.5
3	0.052	97.6	95.3	93.0	90.8	88.7	86.5	84.5	82.5	80.5	78.6
4	0.055	97.5	95.1	92.7	90.4	88.2	86.0	83.8	81 7	79.7	77.7
5	0.059	97.3	94.7	92.2	89.8	87.4	85.0	82.8	80.6	78.4	76.3
6	0.061	97.2	94.5	91.9	89.4	86.9	84.5	82.2	79.9	77.7	75.5
FM	0.066	97.0	94.1	91.3	88.6	86.0	83.4	81.0	78.6	76.2	74.0
7	0.089	96.0	92.2	88.5	84.9	81.6	78.3	75.2	72.2	69 3	66.5
8	0.090	95.9	92.0	88.3	84.7	81.3	78.0	74.8	71.8	68.8	66.0
9	0.092	95.9	91.9	88.1	84.5	81.0	77.6	74.4	71.4	68.4	65.6
10	0.093	95.8	91.8	87.9	84.3	80.7	77.3	74.1	71.0	68.0	65.2
11	0.094	95.7	91.7	87.8	84.0	80.4	77.0	73.7	70.6	67.6	64.7
12	0.096	95.7	91.5	87.6	83.8	80.2	76.7	73.4	70.2	67.2	64.3
13	0.097	95.6	91.4	87.4	83.6	79.9	76.4	73.1	69.9	66.8	63.9
14	0.146	93 5	87.4	81.7	76.4	71.4	66.8	62.4	58.4	54.6	51.0
15	0.147	93.4	87.3	81.6	76.3	71.3	66.6	62.2	58.2	54.3	50.8
16	0.148	93.4	87.3	81.5	76.1	71.1	66.4	62.0	58.0	54.1	50.6
17	0.149	93.4	87.2	81.4	76.0	71.0	66.3	61.9	57.8	53.9	50.4
18	0.150	93.3	87.1	81.3	75.9	70.8	66.1	61.7	57.6	53.7	50.1
19	0.151	93.3	87.0	81.2	75.7	70.7	65.9	61.5	57.4	53.5	49.9
20	0.152	93.3	87.0	81.1	75.6	70.5	65.7	61.3	57.2	53.3	49.7
21	0.153	93.2	86.9	81.0	75.5	70.4	65.6	61.1	57.0	53.1	49.5
22	0.154	93.2	86.8	80.9	73.4	70.2	65.4	61.0	56.8	52.9	49.3
23	0.154	93.1	86.7	80.8	75.2	70.1	65.3	60.8	56.6	52.7	49.1
24	0.155	93.1	86.7	80.7	75.1	69.9	65.1	60.6	56.4	52.5	48.9
25	0.156	93.1	86.6	80.6	75.0	69.8	64.9	60.4	56.2	52.3	48.7
26	0.157	93.0	86.5	80.5	74.9	69.6	64.8	60 3	56.1	52.1	48.5
27	0.158	93.0	86.5	80.4	74.7	69.5	64.6	60.1	55.9	51.9	48.3
28	0.159	92.9	86.4	80.3	74.6	69.4	64.5	59.9	55.7	51.8	48.1
29	0.160	92.9	86.3	80.2	74.5	69.2	64.3	59.7	55.5	51.6	47.9
30	0.161	92.9	86 2	80.1	74.4	69.1	64.2	59.6	55.3	51.4	47.7
31	0.161	92.8	86.2	80.0	74.3	68.9	64.0	59.4	55.2	51.2	47.5
32	0.162	92.8	86.1	79.9	74.2	68.8	63.9	59 3	55.0	51.0	47 3
33	0.163	92.8	86.0	79.8	74.0	68.7	63.7	59.1	54.8	50.8	47 2
34	0.164	92 7	86.0	79.7	73.9	68.5	63.6	58.9	54.6	50.7	47.0
35	0.165	92.7	85.9	79.6	73.8	68.4	63.4	58.8	54.5	50.5	46.8

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)									
		200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
36	0.166	92.7	85.8	79.5	73.7	68.3	63.3	58.6	54.3	50.3	46.6
37	0.167	92.6	85.8	79.4	73.6	68.1	63.1	58.5	54.1	50.1	46.4
38	0.167	92.6	85.7	79.4	73.5	68.0	63.0	58.3	54.0	50.0	46 3
39	0.168	92.5	85.6	79.3	73.4	67 9	62.8	58.1	53.8	49.8	46 1
40	0.169	92.5	85.6	79.2	73.2	67.8	62.7	58.0	53.6	49.6	45.9
41	0.170	92.5	85.5	79.1	73.1	67.6	62.5	57.8	53.5	49.5	45 7
42	0.171	92 4	85.5	79.0	73.0	67.5	62.4	57 7	53.3	49.3	45 6
43	0.172	92.4	85.4	78.9	72.9	67.4	62.3	57.5	53.2	49.1	45.4
44	0.172	92.4	85.3	78.8	72.8	67.2	62.1	56 4	53.0	49.0	45.2
45	0.173	92.3	85.3	78.7	72.7	67.1	62.0	57.2	52.8	48.8	45.1
46	0.174	92.3	85.2	78.6	72.6	67.0	61.8	57.1	52.7	48.6	44.9
47	0.175	92.3	85.1	78.6	72.5	66.9	61.7	56.9	52.5	48.5	44 7
48	0.176	92.2	85.1	78.5	72.4	66.8	61.6	56.8	52.4	48.3	44 6
49	0.176	92.2	85.0	78.4	72.3	66 6	61.4	56.6	52.2	48.2	44.4
50	0.177	92.2	84 9	78.3	72.2	66.5	61.3	56 5	52.1	48.0	44.2
51	0.178	92.1	84.9	78.2	72.1	66.4	61.2	56.4	51.9	47.8	44.1
52	0.179	92.1	84.8	78.1	72.0	66.3	61.0	56.2	51.8	47 7	43.9
53	0.179	9.21	84.8	78.0	71.9	66.2	60.9	56.1	51.6	47.5	43.8
54	0.180	92.0	84.7	78.0	71 8	66.0	60.8	55.9	51.5	47 4	43.6
55	0.181	92.0	84.6	77 9	71.6	65.9	60.6	55.8	51.3	47.2	43.5
56	0.182	92.0	84.6	77.8	71.5	65.8	60.5	55.7	51.2	47 1	43.3
57	0.183	91.9	84.5	77.7	71.4	65.7	60.4	55.5	51.0	46.9	43.1
58	0.183	91.9	84.5	77.6	71.3	65.6	60.3	55.4	50.9	46.8	43.0
59	0.184	91.9	84.4	77.5	71.2	65.5	60.1	55.3	50 8	46.6	42.8
60	0.185	91.8	84.3	77.5	71.1	65.3	60.0	55.1	50.6	46.5	42.7
61	0.186	91 8	84.3	77.4	71.0	65.2	59.9	55.0	50.5	46.3	42.5
62	0.186	91 8	84.2	77.3	71.0	65.1	59.8	54.8	50.3	46.2	42.4
63	0.187	91.7	84.2	77.2	70.9	65.0	59.6	54.7	50.2	46.1	42.3
64	0.188	91 7	84.1	77.1	70.8	64.9	59.5	54.6	50.1	45.9	42.1
65	0.189	91 7	84.1	77.1	70.7	64.8	59.4	54.5	49.9	45.8	42.0
66	0.189	91.7	84.0	77.0	70.6	64.7	59.3	54.3	49.8	45.6	41.8
67	0 190	91 6	83.9	76.9	70.5	64.6	59.2	54.2	49.7	45 5	41.7
68	0.191	91.6	83.9	76.8	70.4	64.5	59.0	54 1	49.5	45.4	41.5
69	0.191	91.6	83.8	76.8	70.3	64.3	58.9	53.9	49.4	45.2	41.4
70	0.192	91.5	83.8	76.7	70.2	64.2	58.8	53.8	49.3	45.1	41.3

Fig. 15. Transfer efficiency (%) 4-1/16" 50-ohm.

Channel	Loss dB/100' (30.48 m)	200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
		Total Length in Feet (Meters)									
2	0.039	98.2	96.4	94.7	93.0	91.4	89.7	88.1	86.5	85.0	83.5
3	0.041	98.1	96.3	94.5	92.7	90.9	89.2	87.5	85.9	84.3	82.7
4	0.043	98.0	96.1	94.2	92.4	90.5	88.7	87.0	85.3	83.6	82.0
5	0.046	97.9	95.8	93.8	91.8	89.9	88.0	86.2	84.3	82.6	80.8
6	0.048	97.8	95.7	93.6	91.5	89.5	87.6	85.7	83.8	82.0	80.2
FM	0.051	97.7	95.4	93.1	91.0	88.8	86.7	84.7	82.7	80.8	78.9
7	0.069	96.9	93.8	90.9	88.0	85.3	82.6	80.0	77.5	75.1	72.7
8	0.070	96.8	93.7	90.7	87.8	85.0	82.3	79.7	77.2	74.7	72.3
9	0.071	96.8	93.6	90.6	87.7	84.8	82.1	79.4	76.8	74.4	71.9
10	0.073	96.7	93.5	90.5	87.5	84.6	81.8	79.1	76.5	74.0	71.6
11	0.074	96.7	93.4	90.3	87.3	84.4	81.6	78.8	76.2	73.7	71.2
12	0.075	96.6	93.3	90.2	87.1	84.2	81.3	78.6	75.9	73.3	70.9
13	0.076	96.6	93.2	90.0	87.0	84.0	81.1	78.3	75.6	73.0	70.5
14	0.113	94.9	90.1	85.5	81.2	77.1	73.2	69.4	65.9	62.6	59.4
15	0.114	94.9	90.0	85.5	81.1	76.9	73.0	69.3	65.8	62.4	59.2
16	0.115	94.9	90.0	95.4	81.0	76.8	72.9	69.1	65.6	62.2	59.0
17	0.115	94.8	89.9	85.3	80.9	76.7	72.7	69.0	65.4	62.0	58.8
18	0.116	94.8	89.9	85.2	80.8	76.6	72.6	68.8	65.2	61.8	58.6
19	0.117	94.8	89.8	85.1	80.7	76.4	72.5	68.7	65.1	61.7	58.4
20	0.117	94.7	89.8	85.0	80.6	76.3	72.3	68.5	64.9	61.5	58.3
21	0.118	94.7	89.7	85.0	80.5	76.2	72.2	68.4	64.7	61.3	58.1
22	0.119	94.7	89.6	84.9	80.4	76.1	72.0	68.2	64.6	61.1	57.9
23	0.119	94.7	89.6	84.8	80.3	76.0	71.9	68.1	64.4	61.0	57.7
24	0.120	94.6	89.5	84.7	80.2	75.8	71.8	67.9	64.3	60.8	57.5
25	0.121	94.6	89.5	84.6	80.1	75.7	71.6	67.8	64.1	60.6	57.4
26	0.121	94.6	89.4	84.6	80.0	75.6	71.5	67.6	63.9	60.5	57.2
27	0.122	94.5	89.4	84.5	79.9	75.5	71.4	67.5	63.8	60.3	57.0
28	0.123	94.5	89.3	84.4	79.8	75.4	71.2	67.3	63.6	60.1	56.8
29	0.123	94.5	89.3	84.3	79.7	75.3	71.1	67.2	63.5	60.0	56.7
30	0.124	94.4	89.2	84.3	79.6	75.2	71.0	67.0	63.3	59.8	56.5
31	0.125	94.4	89.2	84.2	79.5	75.0	70.9	66.9	63.2	59.6	56.3
32	0.125	94.4	89.1	84.1	79.4	74.9	70.7	66.8	63.0	59.5	56.1
33	0.126	94.4	89.0	84.0	79.3	74.8	70.6	66.6	62.9	59.3	56.0
34	0.127	94.3	89.0	84.0	79.2	74.7	70.5	66.5	62.7	59.2	55.8
35	0.127	94.3	88.9	83.9	79.1	74.6	70.4	66.3	62.6	59.0	55.7

Channel	Loss dB/100' (30.48 m)	200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
		Total Length in Feet (Meters)									
36	0.128	94.3	88.9	83.8	79.0	74.5	70.2	66.2	62.4	58.9	55.5
37	0.129	94.3	88.8	83.7	78.9	74.4	70.1	66.1	62.3	58.7	55.3
38	0.129	94.2	88.8	83.7	78.8	74.3	70.0	65.9	62.1	58.5	55.2
39	0.130	94.2	88.7	83.6	78.7	74.2	69.9	65.8	62.0	58.4	55.0
40	0.130	94.2	88.7	83.5	78.6	74.1	69.7	65.7	61.8	58.2	54.8
41	0.131	94.1	88.6	83.4	78.6	74.0	69.6	65.5	61.7	58.1	54.7
42	0.132	94.1	88.6	83.4	78.5	73.8	69.5	65.4	61.6	57.9	54.5
43	0.132	94.1	88.5	83.3	78.4	73.7	69.4	65.3	61.4	57.8	54.4
44	0.133	94.1	88.5	83.2	78.3	73.6	69.3	65.2	61.3	57.7	54.2
45	0.133	94.0	88.4	83.2	78.2	73.5	69.2	65.0	61.2	57.5	54.1
46	0.134	94.0	88.4	83.1	78.1	73.4	69.0	64.9	61.0	57.4	53.9
47	0.135	94.0	88.3	83.0	78.0	73.3	68.9	64.8	60.9	57.2	53.8
48	0.135	94.0	88.3	83.0	77.9	73.2	68.8	64.7	60.7	57.1	53.6
49	0.136	93.9	88.2	82.9	77.9	73.1	68.7	64.5	60.6	56.9	53.5
50	0.136	93.9	88.2	82.8	77.8	73.0	68.6	64.4	60.5	56.8	53.3
51	0.137	93.9	88.1	82.7	77.7	72.9	68.5	64.3	60.3	56.7	53.2
52	0.138	93.9	88.1	82.7	77.6	72.8	68.4	64.2	60.2	56.5	53.0
53	0.138	93.8	88.0	82.6	77.5	72.7	68.2	64.0	60.1	56.4	52.9
54	0.139	93.8	88.0	82.5	77.4	72.6	68.1	63.9	60.0	56.2	52.8
55	0.139	93.8	87.9	82.5	77.3	72.5	68.0	63.8	59.8	56.1	52.6
56	0.140	93.8	87.9	82.4	77.3	72.4	67.9	63.7	59.7	56.0	52.5
57	0.141	93.7	87.9	82.3	77.2	72.3	67.8	63.6	59.6	55.8	52.3
58	0.141	93.7	87.8	82.3	77.1	72.2	67.7	63.4	59.4	55.7	52.2
59	0.142	93.7	87.8	82.2	77.0	72.2	67.6	63.3	59.3	55.6	52.1
60	0.142	93.7	87.7	82.2	76.9	72.1	67.5	63.2	59.2	55.4	51.9
61	0.143	93.6	87.7	82.1	76.9	72.0	67.4	63.1	59.1	55.3	51.8
62	0.143	93.6	87.6	82.0	76.8	71.9	67.3	63.0	58.9	55.2	51.7
63	0.144	93.6	87.6	82.0	76.7	71.8	67.2	62.9	58.8	55.1	51.5
64	0.145	93.6	87.5	81.9	76.6	71.7	67.1	62.7	58.7	54.9	51.4
65	0.145	93.5	87.5	81.8	76.5	71.6	67.0	62.6	58.6	54.8	51.3
66	0.146	93.5	87.4	81.8	76.5	71.5	66.9	62.5	58.5	54.7	51.1
67	0.146	93.5	87.4	81.7	76.4	71.4	66.8	62.4	58.3	54.5	51.0
68	0.147	93.5	87.4	81.6	76.3	71.3	66.7	62.3	58.2	54.4	50.9
69	0.147	93.4	87.3	81.6	76.2	71.2	66.6	62.2	58.1	54.3	50.7
70	0.148	93.4	87.3	81.5	76.2	71.1	66.5	62.1	58.0	54.2	50.6

Fig. 16. Transfer efficiency (%) 6-1/8" 50-ohm.

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)									
		200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
2	0.0339	98.5	96.9	95.4	94.1	92.5	91.1	89.6	88.3	86.8	85.5
3	0.0355	98.4	96.8	95.2	93.7	92.1	90.7	89.2	87.7	86.3	84.8
4	0.0372	98.3	96.6	95.0	93.4	91.8	90.2	88.7	87.2	85.7	84.2
5	0.040	98.2	96.4	94.6	92.9	91.2	89.5	87.9	86.3	84.6	83.1
6	0.0417	98.1	96.2	94.4	92.6	90.8	89.1	87.4	85.8	84.0	82.4
7	0.0615	97.1	94.5	91.8	89.4	86.7	84.4	82.0	79.7	77.4	75.1
8	0.0625	97.1	94.4	91.7	89.1	86.6	84.1	81.7	79.4	77.0	74.9
9	0.0635	97.0	94.3	91.6	88.9	86.4	83.9	81.5	79.1	76.8	74.6
10	0.0645	97.1	94.2	91.5	88.8	86.2	83.7	81.2	78.9	76.5	74.3
11	0.0655	97.0	94.1	91.4	88.6	86.0	83.5	81.0	78.6	76.4	73.9
12	0.0665	97.0	94.1	91.2	88.5	85.8	83.2	80.7	78.3	75.8	73.6
13	0.0675	96.9	94.0	91.1	88.3	85.6	83.0	80.4	78.0	75.5	73.2
14	0.105	95.3	90.8	86.5	82.4	78.5	74.8	71.3	67.9	64.6	61.6
15	0.106	95.2	90.7	86.4	82.3	78.4	74.6	71.1	67.7	64.4	61.4
16	0.107	95.2	90.6	86.3	82.1	78.2	74.4	70.8	67.4	64.1	61.1
17	0.1075	95.2	90.6	86.2	82.0	78.1	74.3	70.7	67.3	64.0	60.9
18	0.108	95.2	90.5	86.1	82.0	78.0	74.2	70.6	67.2	64.0	60.8
19	0.109	95.1	90.5	86.0	81.8	77.8	74.0	70.4	66.9	63.6	60.5
20	0.1095	95.1	90.4	86.0	81.7	77.7	73.9	70.3	66.8	63.5	60.3
21	0.110	95.1	90.4	85.9	81.7	77.6	73.8	70.2	66.7	63.3	60.2
22	0.111	95.0	90.3	85.8	81.5	77.5	73.6	70.0	66.4	63.0	60.0
23	0.112	95.0	90.2	85.7	81.4	77.3	73.4	69.7	66.2	62.8	59.7
24	0.113	94.9	90.1	85.5	81.2	77.1	73.2	69.5	65.9	62.5	59.4
25	0.1135	94.9	90.1	85.5	81.1	77.0	73.1	69.4	65.8	62.4	59.3
26	0.1140	94.9	90.0	85.4	81.1	76.9	73.0	69.3	65.7	62.4	59.1
27	0.1145	94.9	90.0	85.4	81.0	76.8	72.9	69.1	65.6	62.2	58.9
28	0.115	94.8	90.0	85.3	80.9	76.7	72.8	69.0	65.5	62.0	58.8
29	0.116	94.8	89.9	85.2	80.8	76.6	72.6	68.8	65.2	61.7	58.6
30	0.117	94.8	90.0	85.1	80.6	76.4	72.4	68.6	65.0	61.6	58.3
31	0.1175	94.7	89.7	85.0	80.5	76.3	72.3	68.5	64.9	61.4	58.2
32	0.118	94.7	89.7	85.0	80.5	76.2	72.2	68.4	64.7	61.2	58.0
33	0.1185	94.7	89.7	84.9	80.4	76.1	72.1	68.3	64.6	61.1	57.9
34	0.119	94.7	89.6	84.8	80.3	76.0	72.0	68.2	64.5	60.9	57.8
35	0.120	94.6	89.5	84.7	80.2	75.9	71.8	67.9	64.3	60.8	57.7
36	0.1205	94.6	89.5	84.7	80.1	75.8	71.7	67.8	64.2	60.7	57.4

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)									
		200 (60.96)	400 (121.9)	600 (182.9)	800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)
37	0.121	84.6	89.5	84.6	80.0	75.7	71.6	67.7	64.0	60.5	57.3
38	0.1215	94.6	89.4	84.5	79.9	75.6	71.5	67.6	63.9	60.3	57.1
39	0.122	94.5	89.4	84.5	80.0	75.5	71.4	67.5	63.8	60.3	57.0
40	0.123	94.5	89.3	84.4	79.7	75.3	71.2	67.3	63.6	60.0	56.8
41	0.1235	94.5	89.2	84.3	79.6	75.2	71.0	67.1	63.4	59.9	56.5
42	0.124	94.5	89.2	84.3	79.6	75.2	71.0	67.1	63.3	59.7	56.5
43	0.1245	94.4	89.2	84.2	79.5	75.1	70.9	66.9	63.2	59.7	56.4
44	0.125	94.4	89.1	84.1	79.4	75.0	70.8	66.8	63.1	59.5	56.2
45	0.126	94.4	89.0	84.0	79.3	74.8	70.5	66.6	62.9	59.3	55.9
46	0.1265	94.3	89.0	84.0	79.2	74.7	70.0	66.5	62.7	59.1	55.8
47	0.127	94.3	89.0	83.9	79.1	74.6	70.4	66.4	62.6	59.1	55.6
48	0.128	94.3	88.9	83.8	79.0	74.0	70.2	66.2	62.4	58.8	55.3
49	0.129	94.2	88.8	83.7	78.9	74.3	70.0	66.0	62.2	58.5	55.2
50	0.130	94.2	88.7	83.6	78.7	74.1	69.8	65.8	61.9	58.3	54.9
51	0.1305	94.2	88.7	83.5	78.6	74.0	69.7	65.7	61.8	58.2	54.7
52	0.131	94.1	88.6	83.4	78.6	74.0	69.6	65.6	61.7	58.0	54.7
53	0.132	94.1	88.5	83.3	78.4	73.8	69.4	65.3	61.5	57.9	54.4
54	0.1325	94.1	88.5	83.3	78.3	73.7	69.3	65.2	61.4	57.7	54.3
55	0.133	94.1	88.5	83.2	78.3	73.6	69.3	65.1	61.3	57.6	54.1
56	0.1335	94.0	88.4	83.2	78.1	73.5	69.1	65.0	61.2	57.4	54.0
57	0.134	94.0	88.4	83.1	78.1	73.5	69.1	64.9	61.0	57.4	54.0
58	0.1345	94.0	88.3	83.0	78.0	73.4	69.0	64.8	60.9	57.3	53.8
59	0.135	94.0	88.3	83.0	78.0	73.3	68.9	64.7	60.8	57.1	53.7
60	0.136	93.9	88.2	82.9	77.8	73.1	68.7	64.5	60.6	56.8	53.4
61	0.1365	93.9	88.2	82.8	77.8	73.0	68.6	64.4	60.5	56.8	53.2
62	0.137	93.9	88.1	82.8	77.7	72.9	68.5	64.3	60.4	56.8	53.1
63	0.1375	93.9	88.1	82.7	77.6	72.9	68.4	64.2	60.3	56.5	53.1
64	0.138	93.8	88.1	82.6	77.6	72.8	68.3	64.1	60.2	56.4	52.9
65	0.1385	93.8	88.0	82.6	77.5	72.7	68.2	64.0	60.0	56.2	52.8
66	0.139	93.8	88.0	82.5	77.4	72.6	68.1	63.9	60.0	56.2	52.7
67	0.140	93.8	87.9	82.4	77.3	72.4	67.9	63.7	59.7	55.9	52.4
68	0.141	93.7	87.8	82.3	77.1	72.3	67.7	63.5	59.5	55.8	52.3
69	0.1415	93.7	87.8	82.2	77.1	72.2	67.6	63.4	59.4	55.6	52.1
70	0.142	93.7	87.7	82.2	77.0	72.1	67.5	63.3	59.3	55.5	52.0

Fig. 17. Transfer efficiency (%) 6-1/8" 75-ohm.

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)							
		800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)	2200 (670.6)
14	0.0789	86.5	83.4	80.4	77.5	74.8	72.1	69.5	67.0
15	0.0794	86.4	83.3	80.3	77.4	74.6	72.0	69.4	66.9
16	0.0799	86.3	83.2	80.2	77.3	74.5	71.8	69.2	66.7
17	0.0804	86.2	83.1	80.1	77.2	74.4	71.7	69.0	66.5
18	0.0809	86.2	83.0	80.0	77.0	74.2	71.5	68.9	66.4
19	0.0814	86.1	82.9	79.9	76.9	74.1	71.4	68.7	66.2
20	0.0819	86.0	82.8	79.7	76.8	74.0	71.2	68.6	66.0
21	0.0824	85.9	82.7	79.6	76.7	73.8	71.1	68.4	65.9
22	0.0829	85.8	82.6	79.5	76.6	73.7	70.9	68.3	65.7
23	0.0833	85.8	82.5	79.4	76.4	73.6	70.8	68.1	65.6
24	0.0838	85.7	82.4	79.3	76.3	73.4	70.7	68.0	65.4
25	0.0843	85.6	82.4	79.2	76.2	73.3	70.5	67.8	65.2
26	0.0848	85.5	82.3	79.1	76.1	73.2	70.4	67.7	65.1
27	0.0852	85.5	82.2	79.0	76.0	73.1	70.2	67.5	64.9
28	0.0857	85.4	82.1	78.9	75.9	72.9	70.1	67.4	64.8
29	0.0862	85.3	82.0	78.8	75.8	72.8	70.0	67.3	64.6
30	0.0866	85.3	81.9	78.7	75.6	72.7	69.8	67.1	64.5
31	0.0871	85.2	81.8	78.6	75.5	72.6	69.7	67.0	64.3
32	0.0875	85.1	81.7	78.5	75.4	72.4	69.6	66.8	64.2
33	0.0880	85.0	81.7	78.4	75.3	72.3	69.4	66.7	64.0
34	0.0884	85.0	81.6	78.3	75.2	72.2	69.3	66.5	63.9
35	0.0889	84.9	81.5	78.2	75.1	72.1	69.2	66.4	63.7
36	0.0893	84.8	81.4	78.1	75.0	72.0	69.1	66.3	63.6
37	0.0898	84.8	81.3	78.0	74.9	71.8	68.9	66.1	63.5
38	0.0902	84.7	81.2	77.9	74.8	71.7	68.8	66.0	63.3
39	0.0906	84.6	81.2	77.8	74.7	71.6	68.7	65.9	63.2
40	0.0911	84.6	81.1	77.7	74.6	71.5	68.6	65.7	63.0
41	0.0915	84.5	81.0	77.7	74.5	71.4	68.4	65.6	62.9
42	0.0920	84.4	80.9	77.6	74.3	71.3	68.3	65.5	62.8
43	0.0924	84.4	80.8	77.5	74.2	71.2	68.2	65.3	62.6
44	0.0928	84.3	80.8	77.4	74.1	71.0	68.1	65.2	62.5
45	0.0932	84.2	80.7	77.3	74.0	70.9	67.9	65.1	62.4
46	0.0937	84.2	80.6	77.2	73.9	70.8	67.8	65.0	62.2
47	0.0941	84.1	80.5	77.1	73.8	70.7	67.7	64.8	62.1
48	0.0945	84.0	80.4	77.0	73.7	70.6	67.6	64.7	62.0
49	0.0949	84.0	80.4	76.9	73.6	70.5	67.5	64.6	61.8
50	0.0954	83.9	80.3	76.8	73.5	70.4	67.4	64.5	61.7
51	0.0958	83.8	80.2	76.8	73.4	70.3	67.2	64.3	61.6
52	0.0962	83.8	80.1	76.7	73.3	70.2	67.1	64.2	61.4
53	0.0966	83.7	80.1	76.6	73.2	70.1	67.0	64.1	61.3
54	0.0970	83.6	80.0	76.5	73.1	70.0	66.9	64.0	61.2
55	0.0974	83.6	79.9	76.4	73.1	69.8	66.8	63.9	61.1
56	0.0978	83.5	79.8	76.3	73.0	69.7	66.7	63.7	60.9

Fig. 18. Transfer efficiency (%) 8-3/16" 75-ohm line.

Channel	Loss dB/100' (30.48 m)	Total Length in Feet (Meters)							
		800 (243.8)	1000 (304.8)	1200 (365.8)	1400 (426.7)	1600 (487.7)	1800 (548.7)	2000 (609.6)	2200 (670.6)
14	0.0682	88.2	85.5	82.8	80.3	77.8	75.4	73.1	70.8
15	0.0686	88.1	85.4	82.7	80.2	77.7	75.3	72.9	70.6
16	0.0690	88.1	85.3	82.6	80.0	77.5	75.1	72.8	70.5
17	0.0695	88.0	85.2	82.5	79.9	77.4	75.0	72.6	70.3
18	0.0699	87.9	85.1	82.4	79.8	77.3	74.9	72.5	70.2
19	0.0703	87.9	85.1	82.3	79.7	77.2	74.7	72.3	70.0
20	0.0707	87.8	85.0	82.2	79.6	77.1	74.6	72.2	69.9
21	0.0712	87.7	84.9	82.2	79.5	76.9	74.5	72.1	69.7
22	0.0716	87.6	84.8	82.1	79.4	76.8	74.3	71.9	69.6
23	0.0720	87.6	84.7	82.0	79.3	76.7	74.2	71.8	69.4
24	0.0724	87.5	84.6	81.9	79.2	76.6	74.1	71.6	69.3
25	0.0728	87.4	84.6	81.8	79.1	76.5	74.0	71.5	69.2
26	0.0732	87.4	84.5	81.7	79.0	76.4	73.8	71.4	69.0
27	0.0736	87.3	84.4	81.6	78.9	76.2	73.7	71.2	68.9
28	0.0740	87.3	84.3	81.5	78.8	76.1	73.6	71.1	68.7
29	0.0744	87.2	84.3	81.4	78.7	76.0	73.5	71.0	68.6
30	0.0748	87.1	84.2	81.3	78.6	75.9	73.3	70.9	68.5
31	0.0752	87.1	84.1	81.2	78.5	75.8	73.2	70.7	68.3
32	0.0756	87.0	84.0	81.1	78.4	75.7	73.1	70.6	68.2
33	0.0760	86.9	83.9	81.1	78.3	75.6	73.0	70.5	68.0
34	0.0764	86.9	83.9	81.0	78.2	75.5	72.9	70.3	67.9
35	0.0768	86.8	83.8	80.9	78.1	75.4	72.7	70.2	67.8
36	0.0772	86.8	83.7	80.8	78.0	75.3	72.6	70.1	67.6
37	0.0775	86.7	83.6	80.7	77.9	75.2	72.5	70.0	67.5
38	0.0779	86.6	83.6	80.6	77.8	75.0	72.4	69.8	67.4
39	0.0783	86.6	83.5	80.5	77.7	74.9	72.3	69.7	67.3
40	0.0787	86.5	83.4	80.5	77.6	74.8	72.2	69.6	67.1

Fig. 19. Transfer efficiency (%) 9-3/16" 75-ohm line.

Vertical Run Considerations

Provision must be made to accommodate the difference in expansion coefficients between the copper of the line and the steel of the tower. Copper temperature rise due to RF heating as well as ambient temperature changes must be taken into account. In the vertical run this is accomplished by fixing the line at the tower top and "floating" it down the tower on spring hangers with expansion accumulating at the bottom of the tower. To accommodate for this movement, the length of the horizontal run must be as specified in Fig. 20. In addition, the minimum distance from the horizontal run to the first vertical support ring must be maintained as specified in Fig. 21 to accommodate for movement of the horizontal run.

Generally, only standard lengths should be included in the vertical run except at the top where a field-cut section is utilized. However, one or two special lengths may be inserted if it permits a better pattern of hangers. Positions of flanges relative to hangers, guide rings and tower members must be carefully planned to avoid interference as the line moves relative to the tower. Where interference between line flanges and spring hangers may occur due to a particular spacing of tower horizontal members, a steel plate may be used to mount the hanger a sufficient distance above or below the flange to avoid such interference.

Ideally, spring hangers supporting the vertical run of transmission line should occur every 10 feet (3.1 m); however minor variations may be

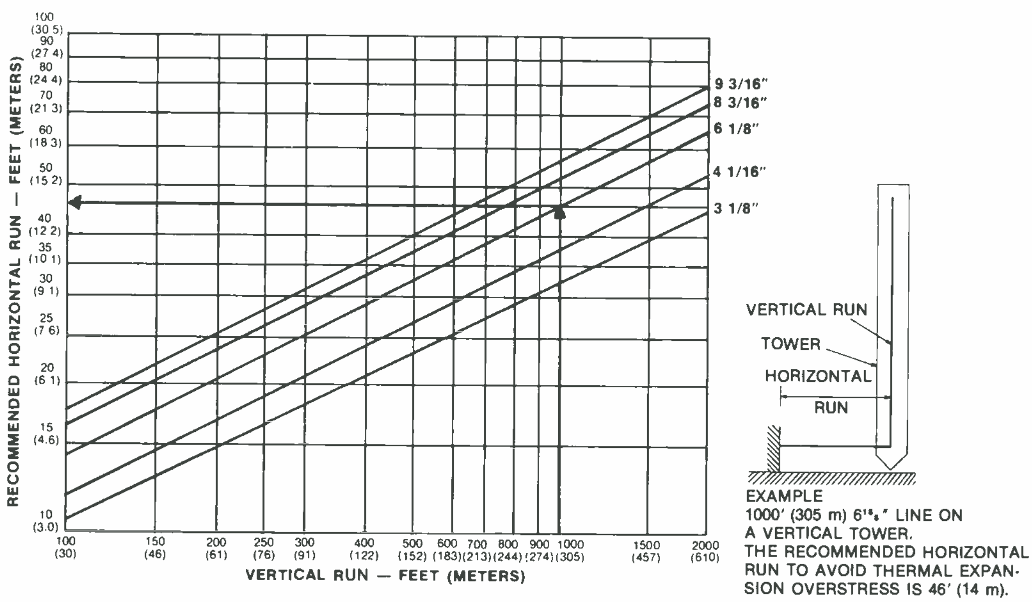


Fig. 20. Recommended horizontal run.

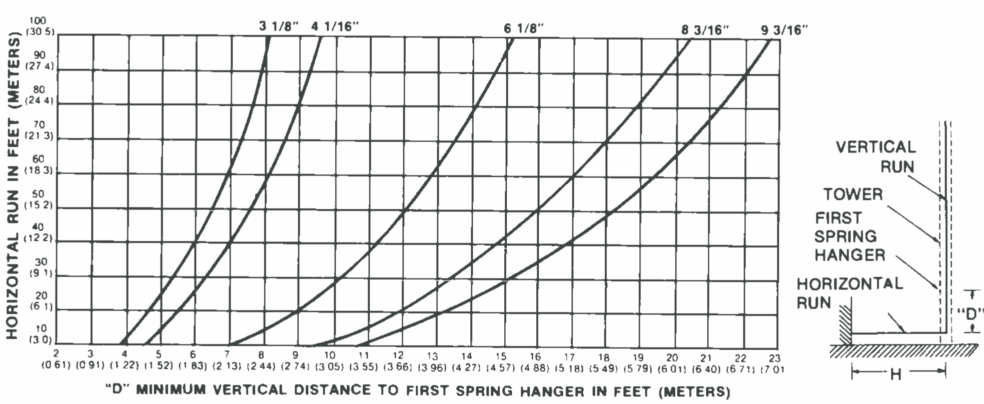


Fig. 21. Minimum distance to first support ring vs. horizontal run length.

used provided an average of one hanger for each 10 feet of line is maintained. The vertical portion of line near the top of the run should be anchored firmly using the appropriate fixed hanger(s). Spring-loading charts are used to set spring tensions of expansion hangers. As finally installed, the line must be vertical and free to move in the hanger guides, and the tower must be designed to keep the vertical hangers perpendicular to the line and the fixed hanger(s) from moving. When installing transmission line, the preferred method is to start at the bottom and work toward the top. The transmission line must be mounted with the anchor insulator of each section in the "up" position.

In most cases, the elbow which joins the vertical and horizontal runs should be a reinforced type.

Horizontal Run Considerations

In complex horizontal-line layouts involving elevation and direction changes, care must be exercised not to overstress mitre elbows or introduce excessive flexing of the line. Back-to-back elbows may be used to achieve desired vertical and horizontal angles.

As stated previously, the horizontal run should be at least as long as indicated in Fig. 20 to allow for sufficient movement due to expansion of the vertical run. Adequate bending of the vertical line to allow for movement of the horizontal run is assured by proper placement of the first vertical supporting ring as specified in Fig. 21. Three-point-suspension spring hangers should be used in the horizontal run for at least the distance shown in Fig. 20. Beyond the minimum distance specified, horizontal roller assemblies or swivel hangers may be used to support the line. Where several lines are in close proximity, special provision may be required to prevent lateral movement while allowing vertical movement. The line should be secured at the wall of the building using a horizontal anchor plate. Lines should be protected from falling ice.

Indoor Installation Considerations

The indoor part of the transmission line is normally not pressured. Therefore, a Gas Stop is installed inside the building wall, and unpressurized line components are used between that point and the output of the transmitter. The arrangement permits disconnection of the ungassed portion of the line anywhere before the Gas Stop without loss of pressure in the outside line.

Purging Moisture From New Line

A transmission line installation must be free of moisture before power is applied since operating a line with moisture inside is likely to cause substantial damage. If moisture is suspected, the uppermost part of the line should be opened by using the petcock supplied or by slightly loosening the most-distant flange. The line should then be bled with dry (oil-pumped) nitrogen. Lines should be continuously pressurized from a nitrogen or a dry-air source. After any complete loss of pressure where moisture may have entered, the line should be purged before it is again placed in use.

WAVEGUIDE TRANSMISSION LINE

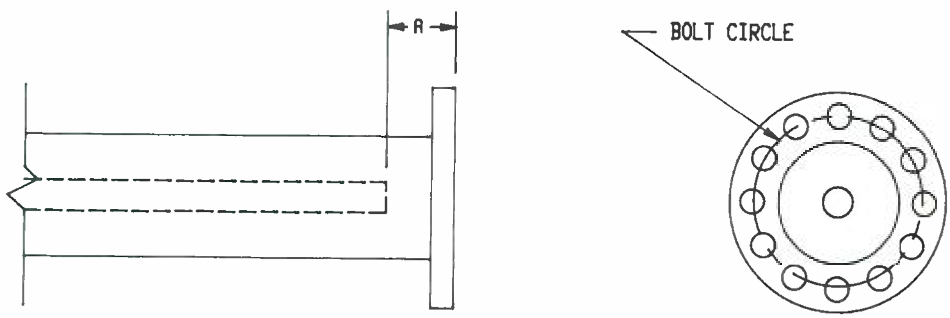
Any enclosure that restrains the electric magnetic fields and directs the flow of energy is a form of waveguide. In a sense, coaxial line is a form of waveguide, however, in the chapter when we refer to waveguide we are referring to a hollow tube waveguide. Which either takes the form of a hollow rectangular metal pipe with an approximate height to width ratio of 1 to 2 or a hollow circular pipe of varying diameters. Each commonly accepted form of transmission line has certain features which makes its use more advantageous over other types of transmission systems. Waveguide offers the following advantages:

1. Its simple construction with no inner conductor makes it less susceptible to distortion due to shock vibration due to shipment installation and operation.
2. Since there are no supports and the waveguide is air filled, there is very little dielectric loss and attenuation is minimized. The physical parameters of the waveguide are such that for dominant mode operation, the dimensional separation in waveguide minimizes charge concentration thus resulting in reduced electric field intensity as compared to coaxial transmission line.
3. The large cross sectional surface area provides for high power handling capacity. Consequently waveguide will handle all the significant power the broadcast industry is presently generating for any station or groups of stations in the U.S.

Due to its large size and lower attenuation, hollow tube waveguide will run with considerably less temperature rise for given power level than any of the coaxial lines. The major draw back for putting waveguide on the tower is the size waveguide which is generally larger than most coaxial lines and hence, you have an increase wind load which in some cases i.e., existing towers, could be a problem.

Circular Waveguide

The newest member of the high power transmission line family for broadcast industry, is Cir-



T/L SIZE	IMPEDANCE IN OHMS	APPROX. WT.		GENERAL SPECIFICATIONS				A	BOLT SIZE	BOLT CIRCLE	NO. OF BOLTS
				OUTER		INNER					
		U.S.	METRIC	OD	ID	OD	ID				
1 5/8	50	27 LB	(12.2 kg)	1.625" (41 mm)	1.527" (38 mm)	0.664" (17 mm)	0.588" (15 mm)	.777±.03	5/16	2.812	4
3 1/8	50	60 LB	(26.8 kg)	3.125" (79 mm)	3.027" (77 mm)	1.315" (33 mm)	1.231" (31 mm)	1.00±.03	3/8	4.375	6
4 1/16	50	110 LB	(49.9 kg)	4.062" (103 mm)	3.935" (110 mm)	1.711" (43 mm)	1.661" (42 mm)	1.22±.03	3/8	5.375	8
6 1/8	50	145 LB	(65.8 kg)	6.125" (156 mm)	5.981" (152 mm)	2.600" (66 mm)	2.520" (64 mm)	1.28±.03	3/8	7.375	12
6 1/8	75	140 LB	(63.5 kg)	6.125" (156 mm)	5.981" (152 mm)	1.711" (43 mm)	1.666" (42 mm)	1.400±.03	3/8	7.375	12
8 3/16	75	192 LB	(87 kg)	8.150" (207 mm)	8.000" (203 mm)	2.293" (58 mm)	2.229" (57 mm)	1.80±.06	3/8	10.312	18
9 3/16	75	229 LB	(103 kg)	9.166" (233 mm)	9.000" (229 mm)	2.580" (66 mm)	2.516" (64 mm)	1.81±.03	3/8	11.312	20

Fig. 22. Mechanical dimensions of rigid coaxial line.

cular Waveguide. This has come about as a natural extension of rectangular waveguide with an effort to reduce windloading on the tower. A typical installation is shown in Fig. 24. Circular Waveguide has been in use for a number of years at much higher frequency, however, it has only been in the last few years that installations have been attempting high power UHF broadcast. Consequently, the transmission line does not have a proven track record in the broadcast field. In general it has all the attributes of any hollow tube waveguide transmission system and in theory should prove to be a viable transmission system.

Fig. 24 shows a typical installation with components noted beside the layout. Fig. 25 lists a typical set of attenuation and average power ratings for three sizes of circular waveguide. Fig. 26 shows one manufacturer recommendation for horizontal vs. vertical length as a function of temperature. It should be noted that field experience on installation of circular waveguide is minimal and the mechanical configuration of the waveguide on the tower should be defined by the manufacturer of the waveguide.

Rectangular Waveguide

Rectangular waveguide has been used in high power UHF broadcast since the mid-Fifties, however, it has only been since the mid-Seventies that any reasonable amount of use has occured depending on the content and the attenuation design. There are four prevalent waveguide sizes currently being used in UHF broadcast. Typical dimensions for the flange and waveguide are given in Fig. 27. In addition, you will note that the flange holes are numbered and refer to the proper tightening sequence. In general, the material is 1100 aluminum which offers the highest conductivity available in aluminum material. General construction is flat aluminum welded at the four corners with a true flange welded at each end. The pressure seal is built into one flange of each waveguide component. The attenuation for the typical waveguide sizes is shown in Fig. 28. Again actual performance characteristics should be exactly defined by the manufacturer of the product. VSWR of an installation is approximately the same as could be expected in the coax installation. Typical length for broadcast waveguide is approximately 12 feet.

The physical parameters of the waveguide determine the electrical operating characteristics. The inside cross-sectional width, or "a" dimension, determines the frequency range of operation for the dominant mode. The "a" dimension must be greater than $\lambda/2$ and less than λ for efficient operation in the dominant mode (TE_{10}). The

DO'S

1. DO store packaged transmission line in clean dry place to prevent contamination.
2. DO withdraw and inspect inner and outer conductors completely if in previously opened or damaged shipping boxes.
3. DO withdraw and inspect all short pieces of line.
4. DO check operation of inner expander assembly* and any components suspected of contamination with dirt or moisture.
5. DO cap all unpacked components against the entry of mositure.
6. DO hoist components with connector end up unless component is marked otherwise.
7. DO check the line in the spring hanger guides after each section is installed to insure free movement for expansion. Shimming of guides at tower support may be necessary.
8. DO consult spring-loading dimensions chart (in Hangers section) for proper spring tension on expansion hangers and adjust each position on the tower accordingly.
9. DO ascertain that inner conductors of adjacent sections match alignment to prevent inadvertent damage to the connector. Hold top connector insulator in place and see that the insulator is well sealed before installing the next section.
10. DO tighten flange bolts alternately, one side, then the other, before final torquing. See Table 8.
11. DO use torque wrench for final tightening.
12. DO pressurize line immediately following installation and maintain 3 lbs/in^2 (0.21 kg/cm^2) at all times. Leaks must be repaired immediately.
13. DO keep ends of transmission line capped during installation. If installation is halted, seal installed line ends and pressurize to at least 0.5 lbs/in^2 (0.04 kg/cm^2) with dry air or nitrogen.
14. DO coat O-ring gaskets lightly with Dow-Corning DC-4 silicone compound to ease assembly.
15. DO check O-ring and its groove for dirt or other foreign material and ascertain that ring is properly seated before flange assembly.

DON'TS

1. DON'T withdraw complete line section if shipping box appears to be new and intact. ONLY inspect inner conductor expander.
2. DON'T hoist coupled sections of transmission line. The stresses involved damage components.
3. DON'T use force when fitting components one to another. If cause cannot be corrected or isn't evident visually, call for DC assistance.
4. DON'T assemble line components that contain water or condensation.
5. DON'T assemble line components that contain dust, dirt, packing material or other foreign objects. Consult Dielectric regarding any loose or suspicious material in the line as it is unpacked.
6. DON'T assemble match-marked components unless the marking is clear and understood. DON'T interchange match-marked items. Consult DC about proper assembly.
7. DON'T install any line component with dust, dirt or grease on insulators.
8. DON'T install line that exhibits any evidence of damage.
9. DON'T attempt to correct defects discovered unless instructed and authorized by Dielectric.
10. DON'T dismiss rigger until transmission line is completely installed and pressurized for at least 12 hours and the appropriate electrical tests performed.
11. DON'T power the transmission line until the line is known to be dry and pressurized to at least 3 lbs/in^2 (0.2 atm.).
12. DON'T exceed specified torque for flange bolts (see Table 8).
13. DON'T use a line flange with evidence of over-stressed.
14. DON'T use a damaged O-ring gasket. Use a new gasket whenever in doubt.
15. DON'T bend elbow components to fit. If leg angle is incorrect, consult Dielectric.
16. DON'T let rigging equipment damage components. Provide proper protection.
17. DON'T cut tubing without a cut-off gauge and remove all burrs and chips from inside and outside of tubing.
18. DON'T assemble a horizontal run without proper support.

*Check inner conductor expansion joint for an excursion of 0.2 inch (5 mm) travel and in the extended position check for presence of contacting spring through exposed groove on inner conductor. In some lines the contacting spring is not visible in the extended position. Presence of the spring can be determined by inserting a 6-mil (0.15 mm) thick feeler gauge (0.5-inch or 13-mm wide) between the tubing inner surface and the connector body outer surface. If spring is present the feeler gauge can be inserted 0.25 inch (6.4 mm). If gauge goes in 0.5 inch (13 mm), spring is missing and line section must not be used.

Fig. 23. Transmission line do's and don'ts.

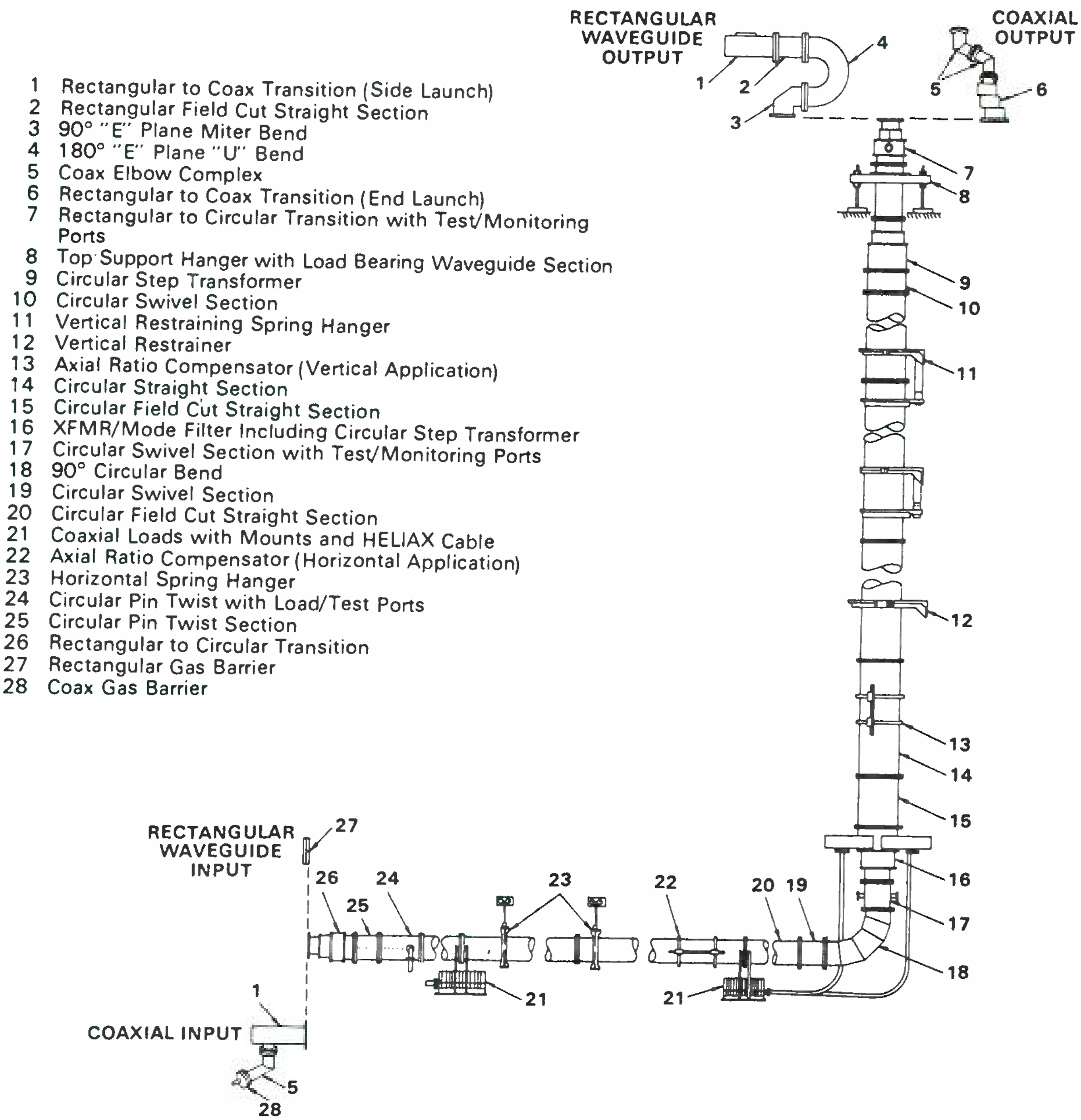


Fig. 24. Components for typical circular waveguide system. (Courtesy of Andrew Corporation)

Channel Number	Visual Carrier MHz	Attenuation dB/100 ft	Average Power Kilowatts
	WC1750		
14	471.25	0.0521	386.9
15	477.25	0.0502	401.9
16	483.25	0.0484	416.4
17	489.25	0.0469	430.3
18	495.25	0.0454	443.7
19	501.25	0.0441	456.7
20	507.25	0.0480	469.2
21	513.25	0.0467	481.3
22	519.25	0.0454	493.1
23	525.25	0.0439	504.5
24	531.25	0.0391	515.6
25	537.25	0.0383	526.3
26	543.25	0.0375	536.7
27	549.25	0.0368	546.9
28	555.25	0.0362	556.7
29	561.25	0.0356	566.3
30	567.25	0.0350	575.7
31	573.25	0.0344	584.8
32	579.25	0.0339	593.6
33	585.25	0.0334	602.2
34	591.25	0.0330	610.6
35	597.25	0.0325	618.8
36	603.25	0.0321	626.7
37	609.25	0.0317	634.5
38	615.25	0.0314	642.2
39	621.25	0.0310	649.4
40	627.25	0.0307	656.6
41	633.25	0.0303	663.6
	WC1500		
39	621.25	0.0490	352.7
40	627.25	0.0482	358.9
41	633.25	0.0474	365.0

Channel Number	Visual Carrier MHz	Attenuation dB/100 ft	Average Power Kilowatts
	WC1500 (continued)		
42	639.25	0.0466	370.9
43	645.25	0.0459	376.7
44	651.25	0.0452	382.4
45	657.25	0.0445	387.9
46	663.25	0.0439	393.3
47	669.25	0.0433	398.6
48	675.25	0.0428	403.7
49	681.25	0.0423	408.8
50	687.25	0.0418	413.7
51	693.25	0.0413	418.5
52	699.25	0.0408	423.2
53	705.25	0.0404	427.8
54	711.25	0.0399	432.3
55	717.25	0.0395	436.7
56	723.25	0.0392	441.1
57	729.25	0.0388	445.3
58	735.25	0.0384	449.4
59	741.25	0.0381	453.4
	WC1350		
56	723.25	0.0530	293.9
57	729.25	0.0523	297.7
58	735.25	0.0516	301.5
59	741.25	0.0510	305.1
60	747.25	0.0504	308.7
61	753.25	0.0498	312.3
62	759.25	0.0493	315.7
63	765.25	0.0488	319.1
64	771.25	0.0483	322.4
65	777.25	0.0478	325.7
66	783.25	0.0473	328.9
67	789.25	0.0469	332.0
68	795.25	0.0464	335.0
69	801.25	0.0460	338.0

STANDARD CONDITIONS
For Attenuation VSWR 1.0, Ambient Temperature 24°C (75°F).

For Average Power VSWR 1.0, Ambient Temperature 24°C (75°F)
Waveguide Temperature 64°C (147°F).

Fig. 25. Attenuation and average power ratings. (Courtesy of Andrew Corporation)

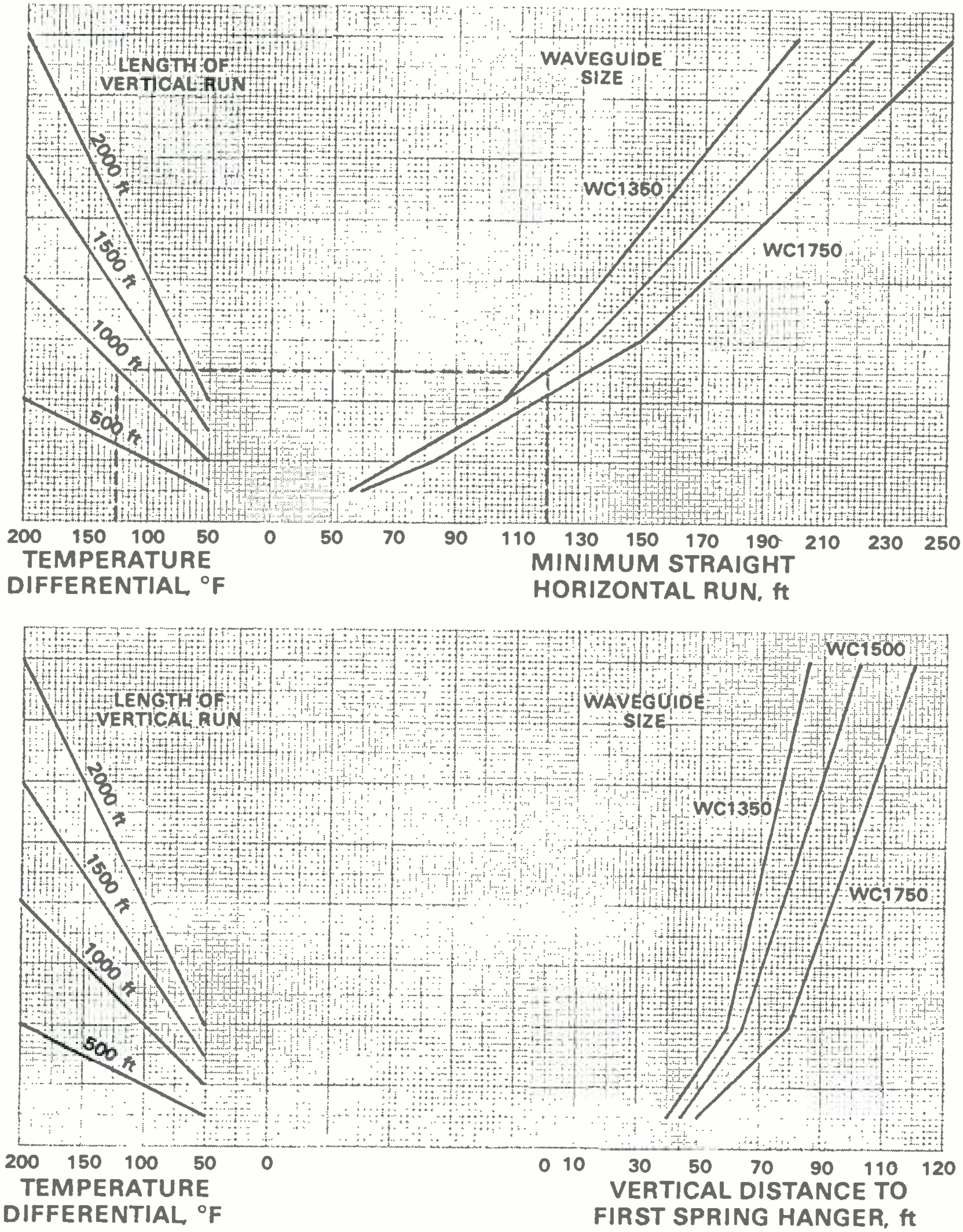
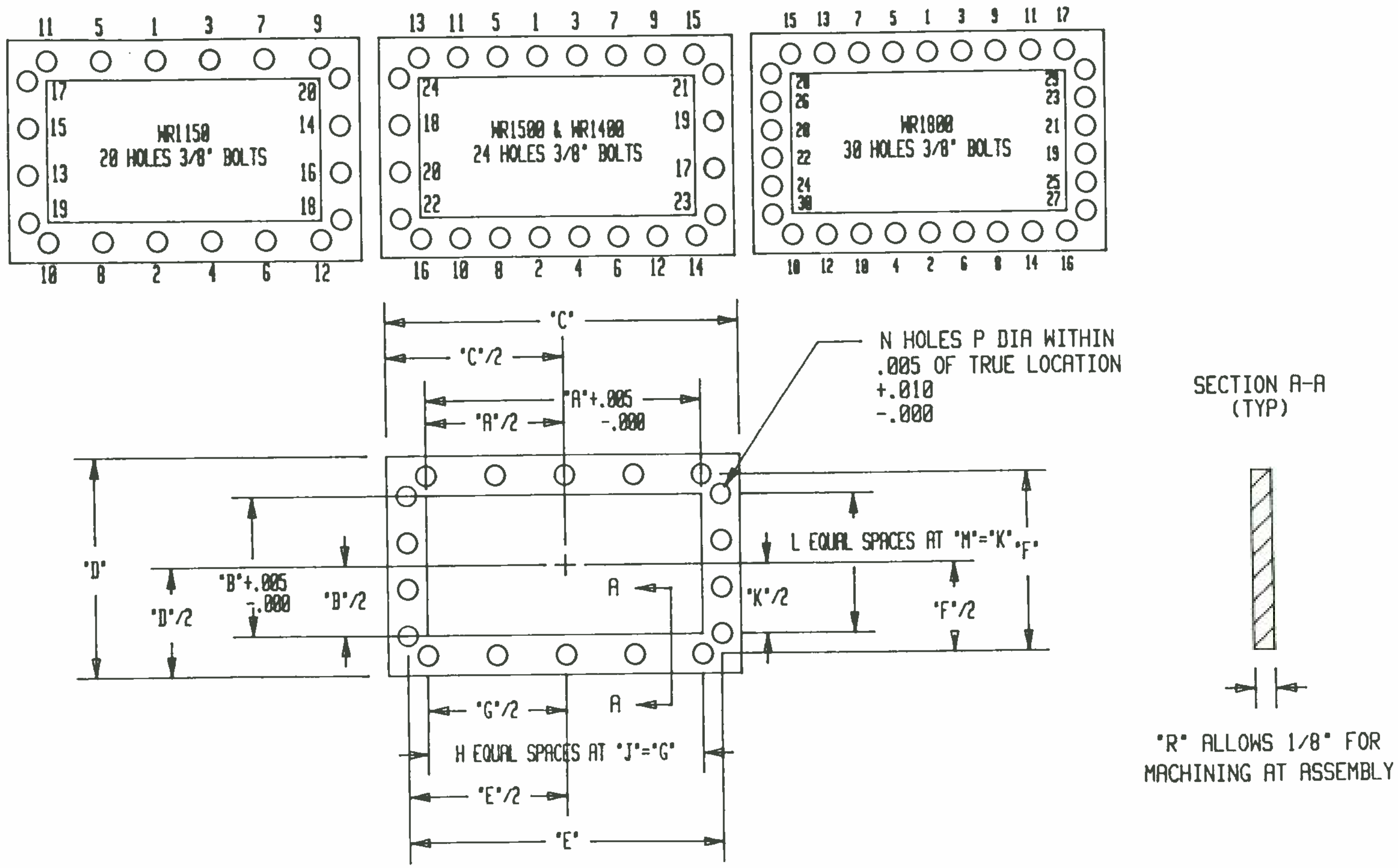


Fig. 26. Mechanical setting for circular waveguide installations. (Courtesy of Andrew Corporation)



WAVEGUIDE SIZE	A	B	C	D	E	F	G	H	I	J	K	L	M	N	P	R	UNIT FLANGE WEIGHT
WR1800	18.00"	9.00"	21.50"	12.50"	20.000"	11.000"	16.000"	8	NA	2.000"	9.063"	5	1.813"	30"	.406"	.625"	6.7 LBS.
WR1500	15.00"	7.50"	18.50"	11.00"	17.000"	9.500"	14.000"	7	NA	2.000"	6.000"	3	2.000"	24"	.406"	.438"	4.7 LBS.
WR1400	14.00"	7.50"	17.50"	11.00"	16.000"	9.500"	14.000"	7	NA	2.000"	6.000"	3	2.000"	24"	.406"	.438"	4.5 LBS.
WR1150	11.50"	5.75"	15.00"	9.50"	13.500"	7.750"	10.000"	5	NA	2.000"	5.814"	3	1.938"	20"	.406"	.438"	3.5 LBS.

Fig. 27. Typical waveguide flange detail.

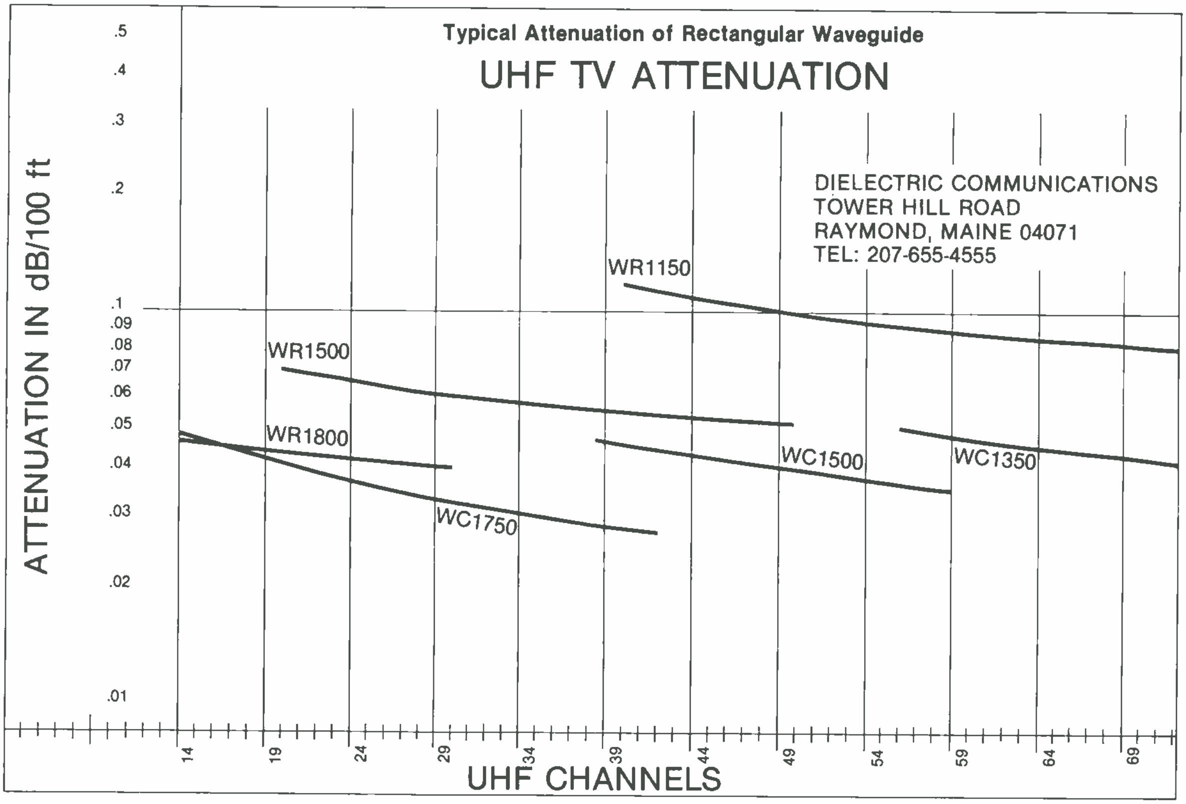


Fig. 28. Typical attenuation of rectangular waveguide.

WAVEGUIDE SIZE	CHANNEL	SECTION LENGTH REQ'D
1800	17,18,22,23,24,28,29	11.5 ft.
1800	14,15,16,19,20,21,25, 26,27, and 30	11.95 ft.
1500	20,21,25,26,30,31,35, 36,40,41,45,46 and 47	11.5 ft.
1500	22,23,24,27,28,29,32, 33,34,37,38,39,42,43, 44,48,49, and 50	11.95 ft.
1150	40,41,45,49,50,54,59, 64,65,69, and 70	11.5 ft.
1150	42,43,44,46,47,48,51 52,53,55,56,57,58,60, 61,62,63,66,67, and 68	11.95 ft.

Fig. 29. Recommended waveguide section length per channel.

generally accepted operating range is from .6λ to .95λ or 60% to 95% of the cut off frequency of the next higher mode (TE_{20}).

The inside cross-sectional height, or "b" dimension, determines the voltage breakdown and as "b" is reduced, the power handling capacity is also reduced. It should also be noted that as the "b" dimension is reduced the attenuation of the waveguide increases.

The practical combination of mechanical and electrical parameters for large waveguide is recommended by the Electronic Industries Association to be a b:a ratio of approximately 1:2.

A typical feed system includes such items as straight waveguide, sweeps and elbows, mitre bends, twists, switches, couplers, and other components as required for a specific application. In order to provide system compatibility, each component should be manufactured with stringent electrical and mechanical controls.

Waveguide Installation

General Information

As in all transmission line installations, preliminary layout work must be done for the installation of rectangular waveguide. (see Fig. 29)

It must be noted that prior to doing the layout work, up-to-date catalogs and literature must be obtained from the manufacturer.

List of Material

When creating a list of materials, the most common point to start is at the waveguide elbow located at the base of the tower. Working toward the building from the bend, use standard 11.95 ft. or 11.50 ft. lengths (as frequency dictates refer to Fig. 30) through the building opening. If a cut length is required and is known, specify on the L/M. If the dimension is not known, specify of the L/M as one piece of waveguide, length unknown. This is to advise the manufacturer that materials must be made available for last minute measurements. If more than one piece is required, specify as two or more line items same description. For each line item, one maximum length section will be set aside for the particular location.

The vertical run should be laid out by stacking each designated length of waveguide end-to-end until the appropriate height is reached for positioning the waveguide to coax transition. The same rule for unknown lengths should be applied as is in the horizontal run.

WR 1800	14 - 30
WR 1500	20 - 50
WR 1150	40 - 70

Fig. 30. Recommended waveguide size per channel.

Hangers

For layout of hangers, see the manufacturers catalog for dimensions required to attach hangers to the bridge or tower structure.

When laying out the hangers, you must keep in mind that the coefficient of thermal expansion of the aluminum is 13 × 10^{-6} per degree F, and of the structural steel approximately 6.5 × 10^{-6} per degree F. This leads to a relative differential movement of approximately ¾ inch per 100 feet for 100°F differential. Also keep in mind that ambient temperatures of the guide and tower are different and must be considered during installation.

When placing the waveguide inside the tower, sufficient clearance must be maintained around horizontal tower members so thermal expansion of the vertical run does not cause the horizontal portion to make contact with these horizontal members. Keep in mind that the heating of the waveguide due to RF will cause the waveguide to expand and the tower will not, as in the case of ambient temperature change where one is concerned with the differential expansion.

It also must be noted that all waveguide external to the building is pressure-tight; so the "sex" of the sections must be observed. The sections in the horizontal run are positioned so that the seal is away from the building, which results in the seal being on the top of each vertical section. This allows the rigger to observe the seal prior to the mating of the flanges.

Horizontal Hangers

Starting from the base elbow, always position the hanger approximately in the center of each piece of waveguide. Each section must be supported by one mount.

Vertical Hangers

Again, starting at the base elbow, each section of waveguide must be supported by one hanger. For specific hanger requirements, refer to manufacturers recommendation. Each hanger should be located as close to the center of each section of waveguide as possible.

Lateral Braces

On towers exceeding 350 feet, locate one every 150 feet to the top.

The last section of waveguide in the horizontal run (and vertical) may have to be fabricated to size by the manufacturer. If so, measure the required length and call this into the manufacturer.

Tower Top

The vertical run is secured at the top with an "Anchor Plate" which is usually attached to the waveguide flange bolts on the waveguide-to-coax transition.

Tuners

For VSWR adjustment, it is recommended that one section of waveguide with tuners be located every 72 feet, both in the vertical and horizontal runs. A good starting point is the elbow between the horizontal and vertical portions of the run. There should be a tuner located within a few feet of this elbow; it does not matter whether it is on the vertical or horizontal side. After this tuner has been placed, the rest may be spaced at 72 foot intervals both toward the antenna and toward the transmitter.

Unloading And Storage At Site

Unload sections and carefully stack in an area where tower work will not endanger it. Use Mylar plastic sheeting, available in rolls, to cover the waveguide. Plastic sheeting is available at contractor supply houses and some hardware stores. Lay the "Visqueen" on ground and stack waveguide on top of it. After waveguide is stacked, bring the sheeting up on the sides of the waveguide and tape using duct tape. Put "Visqueen" over the stacked waveguide, extending down and over the bottom sheet and tape the two pieces together. This results in a well protected waveguide, even from wind and rain. It is essential that the waveguide be clean and dry when installed as this will eliminate much work later.

Hanger Installation

Before any waveguide is uncovered, all hangers should be installed on the tower and bridge, taking care to use the proper hangers at the approximate locations on the tower, i.e. tall towers have hangers which are larger (stick out from tower further and have larger springs) on the bottom portion of the tower than on the upper portion. Also, the last several bottom hangers have long "arms" which attach the hangers to the waveguide to allow the vertical run to move further "in and out" due to expansion of the horizontal run without binding in the hangers. A check should be made to insure that, as the waveguide moves up and down due to expansion, the resulting "in and out" movement (due to hanger construction) does not allow the waveguide flanges to hit the horizontal member of the tower. If installation is properly designed mechanically, this will not happen; but check it. It has happened and all the hangers had to be removed and remounted with spacers.

Installing Waveguide

Two pieces of waveguide should be bolted to the "E" plane bend which is to be at the bottom of the tower. This will be the last section of the horizontal run and the first section of the vertical run with the "E" plane bend in between. The seal must be located away from the building or toward the tower top. Taking into account the ambient temperature, locate the placement of the combination of tower and bridge. This exercise is important as it locates the vertical run in relation to the tower, and the horizontal run in relation to the bridge. If this is not properly done, it is possible (depending upon length of vertical run) for the end of the horizontal run to hit the bridge when the waveguide "moves up" in the winter. This is really no different than in coax installation, except in coax the hangers have no movement and in waveguide, the hangers do move and precautions must be taken so expansion of the guide does not bind them. Initial alignment, therefore, is critical to proper installation.

After initial location of this group, fix the vertical section so that it cannot move down. This is best accomplished using a "come-along" (small ratchet hoist) to suspend the section to a point on the tower. The vertical waveguide section should be able to be raised by pushing on the bottom section of the waveguide, so it is important not to fix the waveguide so that it cannot move upward.

Small variations in materials and manufacturing processes can introduce a slight twist in waveguide. Over a long run, these twists can accumulate to a degree that causes binding in the hangers. To correct this, "reverse twist" sections are supplied and are inserted as needed.

In preparation for installing the waveguide sections, locate reverse twist sections, (they should be marked as such), and keep them separate from "regular" sections. This is best done at the same time as the initial stacking and covering upon arrival.

As the sections of waveguide are removed from the storage area for installation, check for dirt inside the guide. If any foreign matter is found, run a large, clean blanket through the sections to clean it.

Assembly of the waveguide is done by inserting locating pins in any two opposite corners of the flanges and installing bolts, washers and nuts in remaining holes of the flange. After torquing bolts, remove the pins and replace with bolts.

As a suggestion, drill a hole in the end of each locating pin and attach two of them together with a long and strong cord, such as lacing cord. Have the rigger wear them around his neck like a child's pair of mittens. This will keep him from dropping the pins from the tower while installing and removing them. They are difficult to find in the dirt when dropped from 1000 feet.

Now install the remainder of the horizontal run (back to the transmitter). If the horizontal run starts to twist, install a section of the "reverse twist'' waveguide to bring it back. Make sure the waveguide is fitting properly in the hangers to prevent distortion of the guide.

Once inside the building, install a gas dumping section and a gas barrier. The operation of the pressurization system and gas dump is discussed below.

The gas dump section should have a seal on both ends. The gas barrier, commonly called a "waveguide window", utilizes a polystyrene plate as the pressure barrier and is designed to operate at .25 PSIG for the WR1400 thru WR1800, and .50 PSIG for WR1150.

The last section of waveguide in the horizontal run (and vertical) may have to be fabricated to size by the manufacturer. If so, measure the required length and call this into the manufacturer.

At this time, install a waveguide to coax adaptor (match to the channel) to enable test equipment to be attached.

The vertical run is now installed from the bottom up as in coax. Unlike coax, the waveguide can twist and either bind in the hanger or not go in at all. If twist causes a bind in the hanger, a reverse section is selected and installed to bring the run back. The object is not to let it twist too far and cause the waveguide to bind but rather to install a reverse section that will bring the waveguide back past square, at which point the regular sections are again used. As hangers can tolerate some twist in either direction, this method will result in the best installation and the least problems. Try to plan so that the vertical run is kept square at the tower top.

After a number of sections of guide have been installed (the number is optional), determine if waveguide run can be pushed upward by one person pushing on the bottom of the vertical run. If this is not possible, the hangers are not properly tensioned and corrective action should be taken.

When the vertical run is complete, measure the last section needed to complete the run and call this dimension into the manufacturer. Install the necessary fixed anchor assembly to fix the run.

Pressurization Systems

Rectangular waveguide by the nature of its shape and relatively thin walls will not withstand high pressurization; but a slight positive pressure in any transmission line system is necessary to prevent condensation during temperature change. A pressure in the range of .25-.50 PSIG is typical. Too high a pressure will deform the walls, affecting VSWR, and the waveguide window could rupture.

Because of the large volume of air and large surface area of the guide, a rapid change of ambient temperature can cause a relatively fast change in the internal pressure. The extra pressure must be bled off rapidly, and this is accomplished by the gas dump. The gas dump consists of a precisely weighted cap over opening in the guide. The cap "pops" off at the maximum pressure for which the guide is designed. When the guide cools, the automatic dehydrator must have sufficient capacity to replace the air in a short time.

The coaxial output of the transition may require a gas barrier which may be connected directly to the conventional coax elbow complex.

Installations where both coaxial line and waveguide is used, a separate higher pressure air feed is run for the coax and/or antenna.

An automatic dehydrator system is ideally suited for most guide installations. This unit should provide 2400 SCFD at −40°F dew point and be equipped with humidity alarm and bypass. A one cubic foot storage tank charged to the standard 60 PSIG will provide a reserve of 4.8 cubic feet at .5 PSIG.

Tuning Waveguide

The waveguide may have been shipped and installed with the tuning probes installed in the tuning sections. If this is the case, they must be pulled out to where they are still in the sockets but do not protrude inside the guide, even a little bit. To do this, remove the caps which cover the probes. There are two small hex screws in the caps that must be loosened and the cap removed. There is an O-ring inside so you will have to pull hard. Once the cap is removed, you will notice a tapped hole in the Teflon probe. Screw in a ¼" 20 TPI bolt and pull the probe out until no part is inside the guide. Do this for all tuning sections keeping in mind that there are four probes per tuning section.

The elbow at the base of the tower is removed and a sliding load inserted into the end of the horizontal run. A test transition is installed at the input of the horizontal run and test equipment to measure VSWR attached to the transition. The tuning probes are adjusted for best match as indicated on the VSWR measuring equipment. Each tuning section is adjusted starting at the section closest to the measuring equipment and working toward the load.

When the horizontal run is completed, the sliding load is removed from the end of the run. At this point the top of the vertical run is opened and a rope dropped through the waveguide run to the bottom. The sliding load is attached to the rope in such a manner that the load can be pulled up the vertical run. Insert the sliding load into the bottom of the vertical run and re-install the elbow between the horizontal and vertical run. When this is completed, pull the sliding load up and stop at the section just above the tuning section. This can best be accomplished by removing one of the Teflon probes and watching to see when the load goes by. It is easy to judge when you are in the next section of waveguide.

The tuning probes are adjusted in the vertical run starting with the section closest to the bottom and working up. After each section is tuned it will be necessary to pull the sliding load up as was done before. Repeat the procedure until you reach the top when you will remove the load and re-install the top piece that was removed previously. Tuning is now complete.

2.4

AM Broadcast Antenna Systems

CHAPTER 2.4:
Part I: System Design
Part II: Phasing, Coupling
Part III: Maintenance

Part I: System Design

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INTRODUCTION

Standard broadcast (AM) antenna systems can reach a high degree of sophistication, much of which is based on advanced mathematics. The purpose of this section is to provide the station engineer with an understanding of some of the basic concepts of antenna design and an appreciation for the complexities of this specialty. An extensive bibliography is included for those who wish to pursue further study.

The chief purpose of a broadcasting antenna system is to radiate efficiently the power supplied to it by the transmitter. A simple antenna can do this job quite well. This is often a single vertical tower that radiates its signal equally in all directions along the ground in a so-called non-directional or omnidirectional pattern. A second purpose of an AM antenna system is often to concentrate the power in desired directions and to suppress it in other directions to protect the coverage of other stations sharing the same or closely-adjacent channels. This directionality may require a very complicated antenna system with several towers if the requirements are stringent.

The antenna is the last point in the system under the control of the broadcaster. The signals radiated from the antenna are propagated through space to each receiving antenna. The factors affecting the strength of the received signal include the strength of the signal radiated by the broadcasting station in a particular direction, the distance to the receiving site, losses incurred by the less-than-perfect conductivity of the ground along the propagation path, terrain obstructions, (large hills cast shadows even at AM frequencies) and, in the case of skywave transmission, the ionospheric conditions that determine how much of the radiated signal will be reflected back to each distant receiving location. Signal strength in a particular direction can also be affected by the presence of structures such as buildings or towers near the radiating system.

The polarization of the transmitted waves is also a factor; for standard broadcast stations vertical polarization is used because of its superior groundwave propagation and the simplicity of antenna design. The FCC has established maximum transmitter power limits for each of the three classes of AM channels (clear, regional and local) so the only variables available to the design engineer attempting to maximize the coverage of a radio station involve the antenna location, the pattern design, and a limited choice of power levels. These factors go hand in hand when designing a directional antenna system. Severe constraints are usually imposed on transmitter site selection because of aeronautical, zoning, environmental, and coverage requirements. The constraints encountered in the pattern design relate to the size and shape of the transmitter site, the extent to which the necessary signal suppression can be achieved at the desired transmitter power level and the cost of design, construction, adjustment, and maintenance of multi-tower systems. The pattern design can also seriously affect the stability, efficiency, and bandwidth of the completed system. These factors will be discussed later.

RADIATION VERSUS FIELD STRENGTH

Two independent factors determine the signal strength at any given point within a station's service area. First is the strength of the signal radiated in that direction; second is the path attenuation between the transmitting and receiving antennas. Attenuation is determined by both distance and ground conductivity. It is customary to express the radiation in units of millivolts-per-meter at one mile (or one km), unattenuated. This is the field that would exist at one mile over perfectly conducting earth. In this case the field strength would be inversely proportional to the distance from the transmitting antenna; hence, the radiation is also described as the "inverse distance field". The unattenuated radiation cannot be measured directly but can be inferred with great accuracy if sufficient field strength measurements are made to determine the ground conductivity. Field strength measurements are always dependent on radiation, distance, and ground conductivity.

THE SINGLE TOWER NONDIRECTIONAL ANTENNA

Current and Voltage Distribution

The majority of single-tower antennas are neither top-loaded nor sectionalized and most of them are insulated from ground. For such simple towers, the current is a maximum 90 electrical degrees down from the top (or at the base if the tower is shorter than 90 degrees in height. A typical guyed tower that is 90 degrees high physically is about 95 degrees high electrically, because the velocity of propagation is less in the tower than in air and is a function of the tower cross-section, slowing down as the cross-section is increased. The approximate shape of the current distribution on a thin tower of uniform cross-section is given by

$$i_a = I_a \sin (G-y)$$

Where: i_a is current in amperes at height y
I_a is the maximum current in amperes
G is the tower height in degrees
y is the height in degrees of the current element i_a

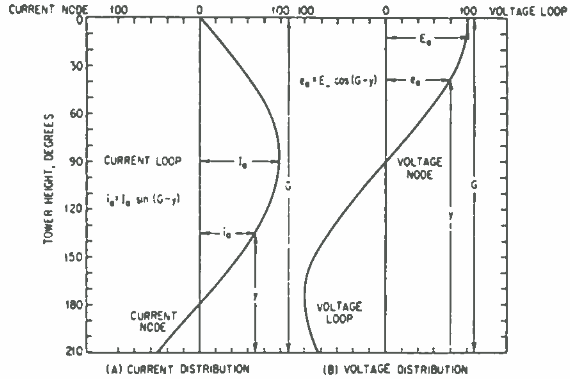


Fig. 1 Theoretical current and voltage distribution on a vertical radiator.

As an example, the general shape of the current and voltage distribution on a thin tower 210 electrical degrees high is as shown in Fig. 1. For shorter towers, the distribution would approximate that shown with the lower portions cut off; there always being a current node and a voltage maximum at the top of any such tower that does not employ top loading. It is important to visualize the shape of the voltage distribution along the tower because of the need of good insulators at the high-voltage points. Otherwise corona or arc overs may result to disrupt broadcasting service.

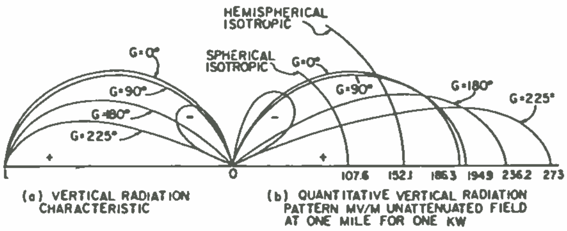
The tower current and voltage are not zero at the nodes shown along the tower. Rather, they reach minimum values and shift rapidly approximately 180 degrees in phase in traversing the node region. When towers considerably taller than 180 degrees in height are considered, the current near the base is in the opposite direction from that in the upper portion of the tower. Under these conditions, when viewed in the horizontal plane, the radiation from the lowest part of the tower is canceling a portion of the radiation from the part above the current minimum. Any increase in tower height above the optimum would actually reduce horizontal plane radiation.

Vertical Radiation Characteristics

Maximum groundwave radiation occurs for a tower 225 electrical degrees high (five eighths wavelength). The variations in tower current distribution with increasing tower height defines the shape of the radiation characteristic in the vertical plane. Fig. 2 shows the size and shape of the vertical plane radiation patterns for a single tower of various heights atop a perfect ground system is fed with one kilowatt of power.

Insulated Tower Base Impedance

The base impedance of a single nondirectional tower is determined principally by its electrical



$$f(\theta^\circ) = \frac{\cos(G^\circ \sin\theta^\circ) - \cos G^\circ}{(1 - \cos G^\circ)\cos\theta^\circ}$$

Fig. 2. Radiation characteristics in vertical plane.

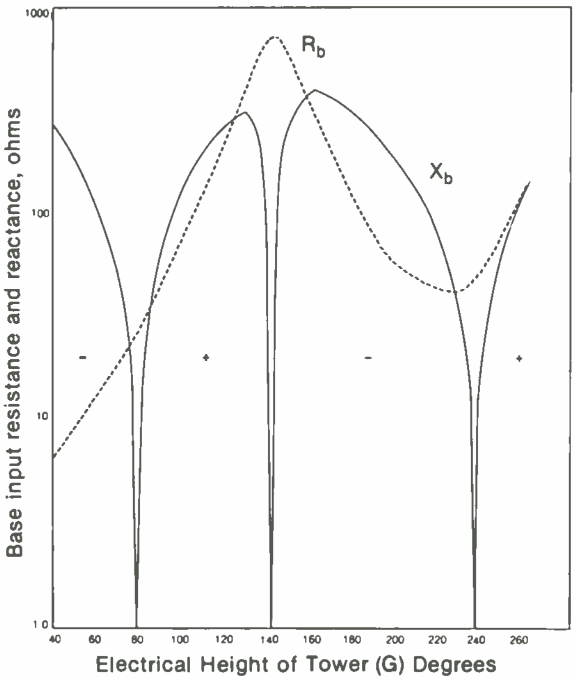


Fig. 3. Typical base input resistance and reactance of a uniform cross-section base insulated guyed tower.

height, its cross-section, the extent of the ground system, and the elevation of the feed point above ground. For typical guyed towers of uniform cross-section, which are base insulated and fed four or five feet above ground level, the resistive and reactive components of the base impedance approximate the values shown in Fig. 3. The base impedance of self-supporting towers departs radically from the values shown, not only because of their large and tapering cross-section, but also becuase of the capacitance of the base insulators necessary to support each leg of such towers.

Electrically short towers are inefficient radiators, not only because of the shape of their vertical radiation characteristics as shown in Fig. 2 but also because of proportionately higher ground losses. For example, with a tower 48 degrees high, having a base resistance of only 9 ohms, approximately 10% of the available power is wasted in the ground system resistance losses, which typically approximate one ohm.

Grounded Towers, Shunt Fed and Folded Monopole

Occasionally towers without insulated bases must be utilized as AM radiators. Such structures include FM or TV towers, water tanks, and ornamental flag poles. Although the impedance at the base of such a tower is necessarily essentially zero, the impedance rises with increasing height of the feed point. It is a simple matter to determine experimentally the height at which a shunt-fed tower must be driven to provide a desirable input impedance. A common technique is a "slant-wire" feed in which a wire is attached to the tower at a selected height above ground and brought down to near ground level at an angle approximating 45° to serve as the antenna input terminal. A slant-wire feed distorts the otherwise omnidirectional pattern of a single tower and tends to suppress radiation over the sector on the side where the slant-wire is attached. This effect can be avoided if, instead of the slant-wire, the feed conductors are insulated at the base and brought up outside of the tower and bonded to the tower, for example, 90° above ground to form a folded monopole. The conductors, in this concentric arrangement, in effect form the outer conductor of a coaxial transmission line with a short to the tower at the 90° point and an open at the base insulators. This quarter wave open circuit transmission line in effect puts an insulator at the tower base. The current up on the outer conductors and down on the tower essentially cancel so far as radiation is concerned. The tower with this insulated skirt performs like a base insulated tower. The concentric arrangement of conductors usually six, are tied together above the conductor base insulators and fed like a base insulated tower. There is a small amount of power loss in the 90° concentric transmission line shorted at the top and used to produce the open circuit at the bottom. The radiation current is up on the outer conductors, to where they are connected to the tower at the 90° point, and then on up to the top of the tower where the current is zero like on a base fed insulated tower.

Folded Conical Monopole

The folded conical monopole shown in Fig. 4 broadbands the input impedance and for a 90° tower the vertical radiation characteristic is that of a 75° tower but with an increased value of input resistance and reactance of about 50%. These results were obtained by applying the method of moments to compute the base impedance, current distribution and vertical pattern.

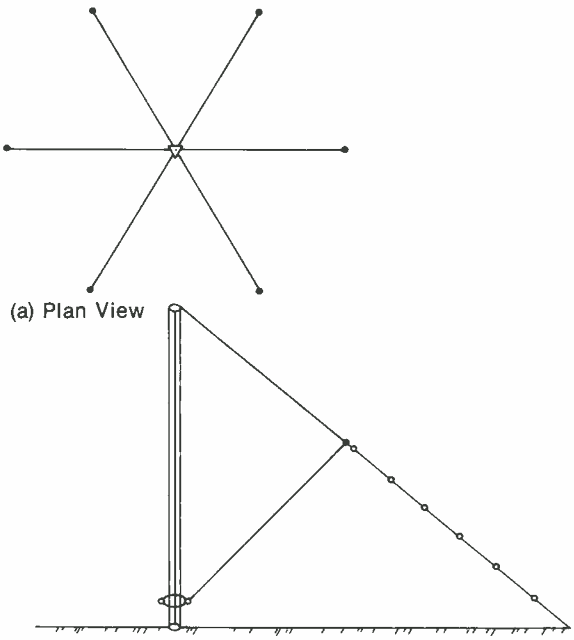


Fig. 4. Sketch of folded conical monopole antenna.

Top Loading

The performance of an electrically short tower (significantly less than 90 degrees) can be improved, both as to radiation efficiency and bandwidth by means of top loading. This consists of increasing the capacitance to ground from the top of the tower. This loading can take the form of either a flat more-or-less circular horizontal disk attached to the top of the tower (called a top hat) or as sections of guy wires bonded to the top of the tower and extending down a useful distance before encountering the first of the guy wire insulators. Many variations are possible. Some installations use 3, 6, or even 12 nonstructural guys for top loading that are very effective. By interconnecting the lower ends of the top loading cables the capacitive loading is increased some but this or spider web connections between the top loading cables increases the construction and maintenance problems. These problems can be eliminated by just increasing the top loading cables a small amount to give the same increase in capacity effect. Top loading is electrically less desirable than increased tower height, but is useful where towers must be electrically short due to either extremely low carrier frequencies or to aeronautical limitations. Top loading increases the base resistance and lowers the capacitive base reactance thus reducing the Q and improving the bandwidth on towers less than 90°. When the tower height is of the order of 130° top loading can be used to increase its electrical height to give maximum groundwave radiation and minimize skywave radiation.

Sectionalized Towers

A utopian vertical radiator would have a constant current throughout its height but in real life the current must ultimately reduce to zero at the tower top or at the end of the top loading cables. The current can be made to diminish less rapidly by inserting an inductance in series with the tower at a point part way up its height. This is the same technique as the familiar "loading coil" near the center of the vertical whips often used for mobile radio systems.

Top Loaded Sectionalized Tower

For a simple vertical radiator the radiation characteristic can be improved by increasing the tower height up to 225° for maximum ground wave or by top loading. This in effect raises the position of the current loop with respect to the ground. This principle can also be applied to the top section of a sectionalized tower.

The purpose of top loading a sectionalized tower is to provide a means of further controlling the current distribution on the lower section only. Considering efficiency and stability it is usually possible to achieve a more favorable radiation characteristic of the whole tower by employing top loading and sectionalization. See Fig. 5. In the case of tall towers used to support FM or TV antennas, it may not be practical to employ top loading.

Depending on the height of tower in wavelengths, the tower can be sectionalized at one or more points to accomplish the highest efficiency

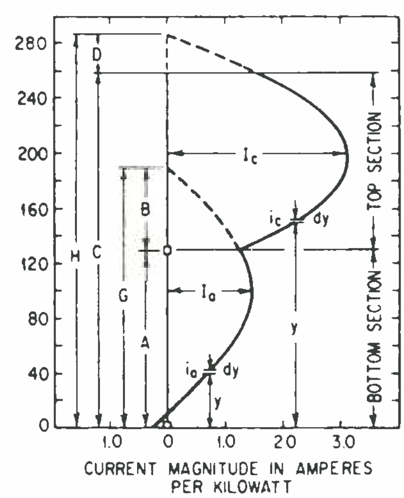


Fig. 5. Theoretical current distribution on top loaded sectionalized tower.

consistent with good operating stability. See Fig. 6.

Ground Systems

The current on a tower does not simply "disappear", rather it returns to earth through the capacitance between the earth and each incremental element of the tower or the top loading. For towers not exceeding 90° in height, the tower current is greatest at the base. For such towers the radial ground current is greatest near the tower and decreases with increasing distance from the tower. For single towers the ground currents are radial from the tower base. The ground losses are greatly reduced if the tower has a radial copper ground system so the ground current will be in the low-loss copper ground system rather in the earth which has a much higher resistance. A solid copper sheet of infinite radius would be the ultimate ground system, but experiments and experience have defined the dimensions of an adequate ground system. A system of 120 radial ground wires each 90 degrees long, 140 degrees is considered optimum and equally spaced out from the tower base constitutes a "standard" ground system. This is often augmented with an additional 120 interspersed radials 50 feet long or an expanded copper mesh ground screen 25 to 50 feet square centered at the tower. A superior ground screen material is the copperweld mesh ground mat often utilized by power companies for lightning protection under electrical substations.

Where the antenna site is too small to accommodate all the ground radials at full length a compromise often used, if easement can not be obtained beyond the property line, is to increase the number of radials by placing them 1 or 2 degrees apart rather than the standard 3 degree separation.

There is no magic in a "standard" ground system for non-directional towers; it simply represents a reasonable balance between cost and radiation efficiency.

The antenna system loss including the tower and ground system is normally assumed to be one ohm and is added to the tower base resistance.

Most ground systems under directional antenna arrays consist of the usual 120 radials per tower truncated and bonded to traverse copper straps where the radials from the several towers would otherwise intersect. Stability considerations may dictate larger than standard ground systems under critical directional antenna arrays; changes in soil conditions beyond the ground system can result in small changes in tower base impedance.

Ground system losses are minimized if the radial wires are placed above ground, thus the

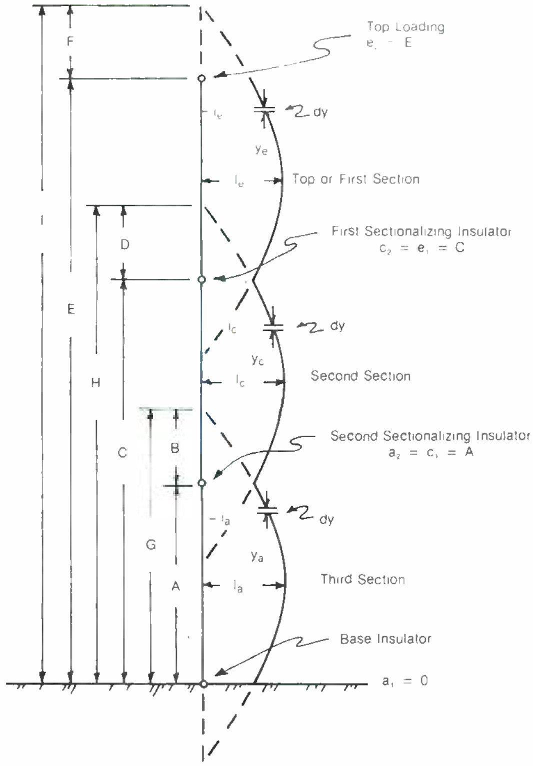


Fig. 6. Theoretical current distribution on three section top loaded tower.

E-field voltage from the tower and top loading cables terminate on these radial conductors so the H-field current can return to the tower base without penetrating the lossy earth. Ground radials are usually buried 6-8 inches for mechanical protection. Burial up to 24 inches is feasible where necessary to permit deep plowing for agricultural crops. However, the ground system should be very near the earth surface in the immediate vicinity of the tower. The earth losses are greater for the buried ground system. Ground systems laid on the earth surface, or tundra in the far north, has the highest loss and least stability of the base impedance. Changes in weather conditions change the dielectric constant and conductivity of any unshielded earth to the detriment of base current stability.

TWO TOWER DIRECTIONAL ANTENNA

Radiation Pattern Shape

When a nondirectional antenna, with a given power, does not radiate enough field strength to serve the community of interest and/or protect other radio stations then it is logical to resort to a directional antenna system to achieve these objectives. FCC Rules spell out the protection requirements to be provided to the various classes of stations, both daytime and nighttime. These limits, which must be met in the directional antenna design, tend to define the shape and size of the most desirable antenna pattern. Since the distances and directions to the other stations requiring protection are rarely the same, most directional antenna patterns are tailored to meet the specific requirements. A directional antenna functions by carefully controlling the amplitude and phase of the radio frequency currents fed to each tower. The resulting field in any direction is the vector sum of the individual tower radiation components. To visualize the resulting pattern in the horizontal plane, one must consider the individual tower radiation components when viewed from distant points in different directions. The relative amplitudes from the individual towers remain unchanged but the relative phases shift with azimuth because the signal from the closest tower arrives first. In a directional antenna system, one tower is usually defined as the reference tower and the amplitude and phase of each other tower is measured relative to this reference. The reference tower usually has the greatest current, thus the ratio of the current in each other tower relative to the reference tower current is a fractional number often expressed as a percent of the reference tower current. The relative amplitude and phase of the tower currents is measured by means of an antenna monitor.

The phase of the field radiated by each tower relative to the reference tower has two components when viewed from any distant point of observation. The relative electrical magnitude of the current fed to the tower is one component and is adjustable. The second component is the phase which appears to lead or lag the reference tower by virtue of being more distant or closer than the reference tower to the point of observation. This is termed the space phase component and varies continuously for each tower in a sinusoidal manner as the observation point is moved in azimuth along a distant circle around the array.

Fig. 7 shows three simple directional antennas and their resulting patterns which are easy to visualize. Fig. 7(a) shows two towers arranged along a north-south line separated by 180 degrees and fed with equal currents in phase. When viewed from the east or west, the fields from the two towers are in phase and the maximum field strength results. When viewed from the north or south, the field from the more distant tower is delayed by the 180 degrees of additional distance, thus canceling the field of the closer tower so as to result in a minimum or null. The deepest minimum or null occurs only when the fields are exactly equal in amplitude and opposite in phase.

Fig. 7(a) is termed a broadside array because the maximum radiation is broadside to a line through the towers. Fig. 7(b) shows a similar arrangement, but with the phase of the current in the north tower shifted by 180 degrees. Then the fields from

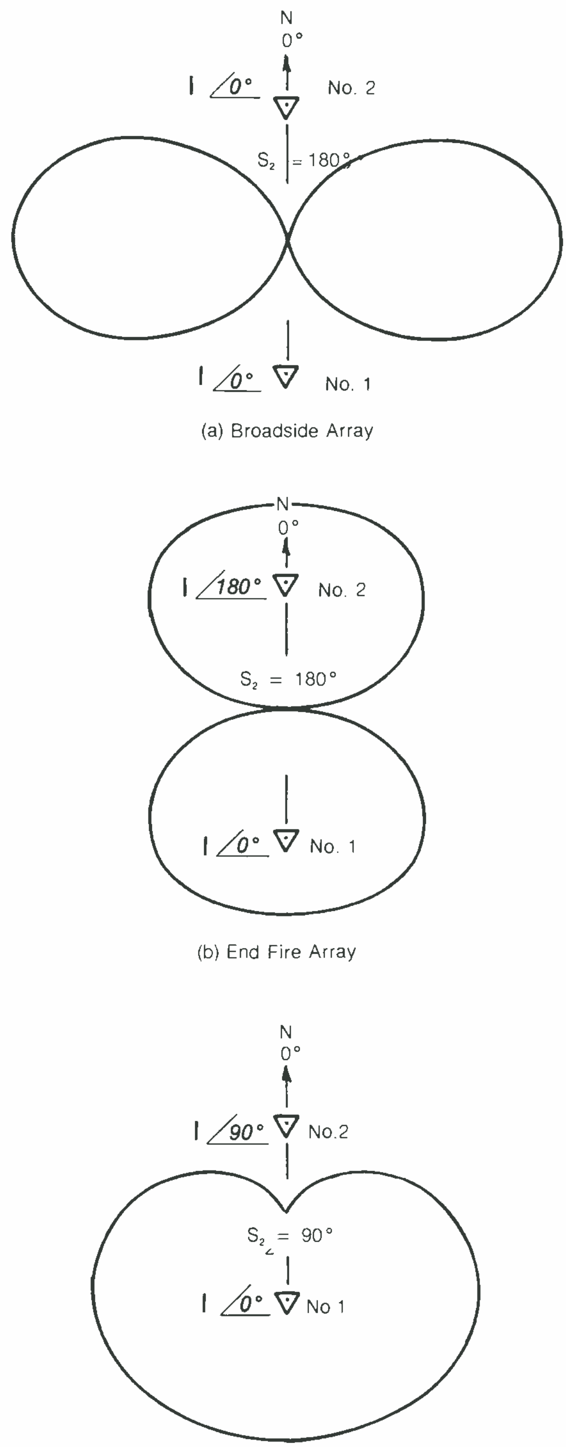


Fig. 7. Three simple directional antenna patterns.

the two towers cancel each other when viewed from the east or west but would produce maximum radiation north or south. This would be termed an end-fire array because maximum radiation coincides with a line through the ends of the array. Fig. 7(c) alters the spacing to 90 degrees and phasing to 90 degrees so as to produce a cardioid pattern. Other combinations of tower spacing and phasing can produce a great variety of pattern shapes. See Appendix B.

Multiplication of Two Tower Patterns

Perhaps the most widely used method of controlling pattern shape involves the multiplication of two tower patterns. This is illustrated in Fig. 8. When a two tower pattern such as pattern No. 1 with nulls at $\pm\phi_{n1}$ is multiplied by pattern No. 2 with nulls at $\pm\phi_{n2}$ the result is pattern No. 3 in a three tower array. The directions of all of the two tower array nulls are maintained in the three tower array. This is a very powerful design technique for protecting other stations and still serving a desired service area. In this special case the spacings S_2 and S_3 are equal resulting in an in line array with the fields of towers No. 2 and No. 3 being added in the center tower and the end tower of the three tower array is the multiplication of these fields as shown in pattern No. 3 of Fig. 8.

In the event that the protection directions are not symmetrically located, the two tower arrays can be placed on different azimuth angles as shown in Fig. 9 to produce a four tower parallelogram array. The nulls of the No. 1 pattern are maintained and the nulls of No. 2 pattern are maintained in the four tower parallelogram array. Furthermore, the spacing from No. 1 tower to No. 2 and No. 3 towers do not have to be the same. By this approach of using one or more parallelograms a wide variety of asymmetrical patterns are possible with relative simplicity of pattern calculations. However, modern computer techniques can optimize individual tower locations, currents and phases so as to produce an efficient pattern, frequently using fewer towers than required with the parallelogram approaches.

Systematization of Patterns

The pattern possibilities resulting from variations in spacing and phasing have been systematized and a sample of two-tower patterns is

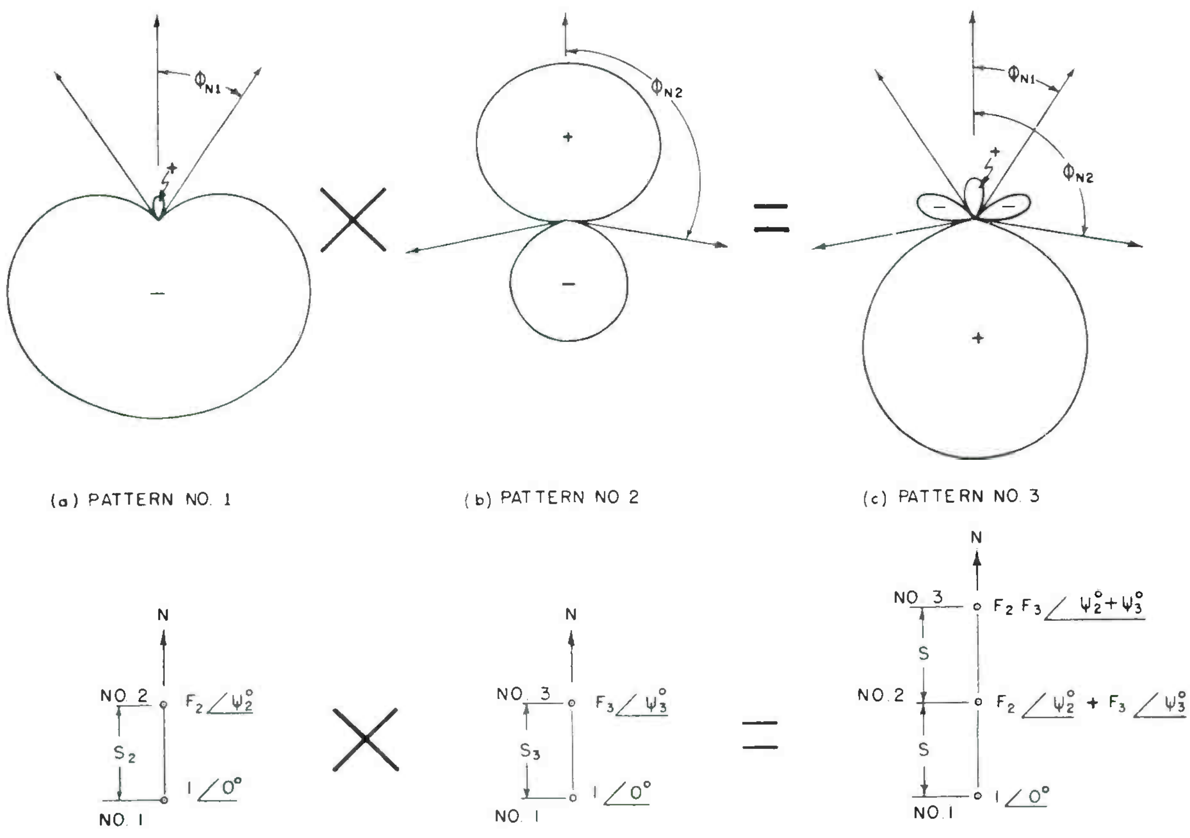
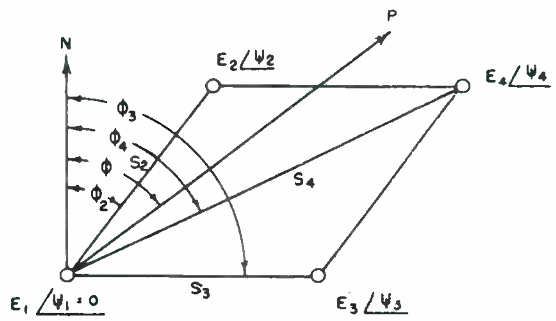


Fig. 8. Multiplications of patterns to produce a three tower in line array.



GENERAL FOUR TOWER CONFIGURATION

Fig. 9. Multiplication of two patterns to produce a four tower parallelogram array.

shown in Appendix B. See Reference 1 for 3-tower patterns.

Radiation Pattern Size

The pattern size is usually determined by integrating the energy flow outward through an imaginary hemispherical surface surrounding the directional antenna array. This method does not give information regarding the distribution of power radiated from the various towers of the directional antenna array, however, it is very useful for making comparisons of pattern size. This computation method is available in digital computer programs and is used by FCC.

There are other methods of determining pattern size such as the "Mutual Resistance Method" which employs Bessel Functions and the "Driving Point Impedance Method" which uses mesh circuit equations with self and mutual impedance information.

The "method of moments" is now available in large computer programs to determine; current distribution on towers and top loading cables, base driving point impedances and the vertical pattern of directional antenna arrays.

Driving Point Impedance

The input impedance of each tower in an array, called driving point impedance, is not that of the nondirectional tower. The driving point impedance contains the self impedance plus the mutual impedance multiplied by the current ratios that depend on the array as driven to produce the desired pattern. The driving point impedance will modify the self impedance depending on the array parameters and can even make the base resistance negative so that the tower draws power from the other towers and dissipates the power into a load resistor or delivers it back to the phasing system. Because the driving point impedance is affected by the currents in the other towers, it can only be measured by an operating bridge inserted in the tower feed point while the other towers are operating with essentially correct current magnitude and phase parameters.

Base Currents Versus Radiated Fields

In a directional array, the tower base current ratios will usually depart substantially from the calculated radiated field ratios when the pattern is correctly adjusted. This is caused by the mutual coupling between towers which distorts the sinusoidal current distribution otherwise assumed for each tower. Thus, the correct pattern is initially proved by means of a series of field strength measurements in significant radial directions from the station rather than by assuming that measurement of tower currents and phases can establish the correct pattern.

Near-Field Versus Far-Field Conditions

Theoretically a directional antenna pattern is not fully formed except at an infinite distance, where the separate towers can be considered as a point source. As a practical matter, near-field effects can persist as far as 20 miles from an antenna before far-field conditions prevail. This is especially true in the deep minimums of widespace arrays; however, misleading measurement results can often occur under apparently innocent circumstances. Near-field calculations involve consideration of the actual inverse distance attenuation and the actual phase delay from each antenna element to a series of observation points along a radial.

Fig. 10 shows the results of such calculations on a minimum radial and the resulting analysis of field strength measurements. Line A is the inverse distance line for the theoretical unattenuated radiation at one mile. Line B is the result of the near-field calculations assuming only inverse distance attenuation, that is, no soil losses. It converges with the inverse distance line with increasing distance. Line C represents a soil conductivity of 10mmhos/m as drawn in the conventional manner from analysis of nondirectional measurements on the radial. Line D is a composite of Lines B and C. It includes the near-field calculations and is attenuated with distance in accordance with the soil conductivity previously established. This composite line converges with the near-field calculations at short distances where soil attenuation is negligible and converges with the soil conductivity line at great distances where near-field effects disappear. Since curve D accounts for both near-field effects and soil losses, it is the proper curve against which the directional field strength measurement data should be fitted.

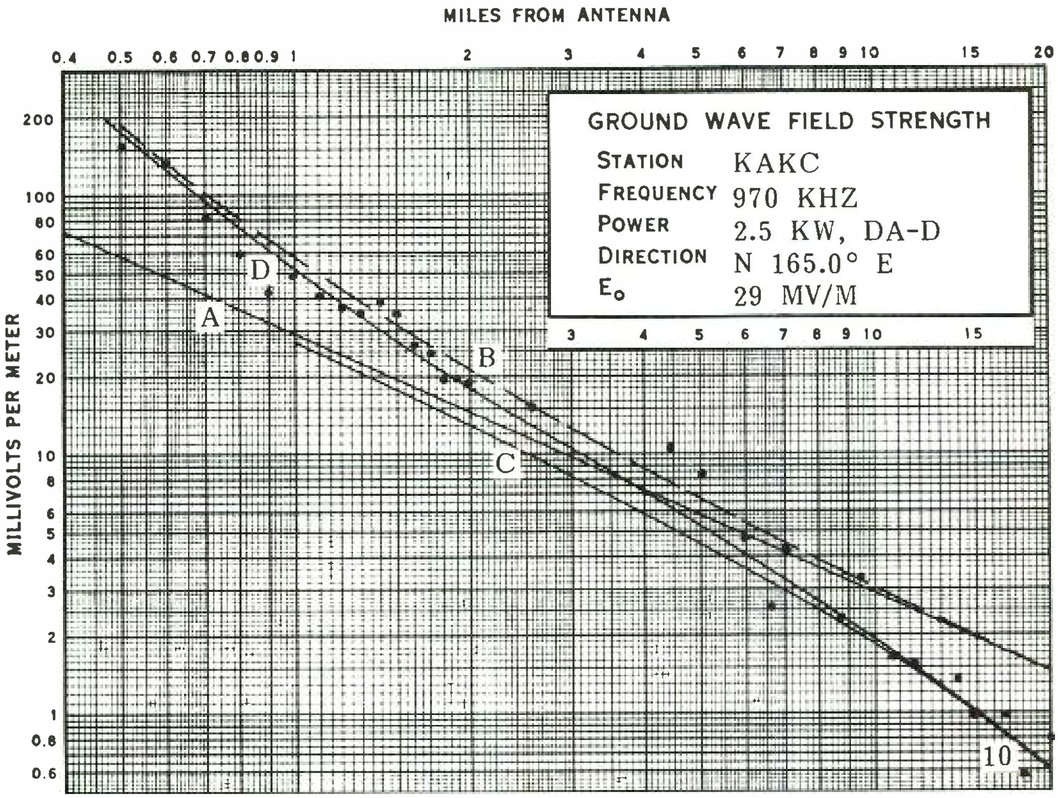


Fig. 10. Near-field effects.

Note the good fit to the measurement data, both close to the array and at distant points even though the first 19 measurement points fall considerable above the inverse distance Line A.

Pattern Size Versus Pattern Shape

The shape of a directional antenna pattern is determined by the adjustment of the phase and ratio parameters, whereas the pattern size is a measure of the power radiated and is affected by the transmitter power output and the losses within the phasing system and the ground system. Since pattern size and shape are essentially independent, it is most expeditious to adjust an array to get the correct shape before expending much concern on the size.

Field strength measurements on a previously-licensed directional antenna may appear to indicate a change in pattern shape or size when the change was in fact due to changes in soil conductivity. Such changes affect distant measurements more than close-in measurements. In some areas of the United States, the conductivity is typically higher during winter and spring months when the soil is more moist than in summer and fall months.

Seasonal conductivity variations are not observable in some portions of the country, yet are extreme in other areas. One well-documented case showed a seasonal doubling of signal strength at 20 miles in the main lobe of a correctly adjusted system operating on 1380 kHz. To avoid the misleading effects of seasonal conductivity changes that might appear to distort measured directional antenna patterns in size or shape, the FCC requires that all the field strength measurements in a directional antenna proof of performance be made under "similar environmental conditions".

Standard Patterns

Theoretical (also called calculated) patterns can have nulls wherein the radiation at specific azimuths goes completely to zero. In practice, it is not possible to prove by field strength measurements that a null exists. Reradiation and scatter from objects external to the array limit the depth to which a pattern minimum can be proven. Additionally, operational variations in phase and ratio parameters will increase radiation in any direction where the deepest possible minimum has been previously established. To accommodate these limitations, the FCC authorizes a "standard" pattern for each directional antenna station. Standard patterns exceed the theoretical pattern at all azimuths by specified and easily calculated amounts. It is required that the radiation from a directional station not exceed its standard pattern. All U.S. stations employing directional antennas have FCC specified standard patterns. These supersede all earlier patterns based on theoretical calculations or on field strength measurements. The standard pattern radiation values are now used exclusively in all calculations of coverage and interference.

Augmented Patterns

Augmentation is applied to the standard pattern when the measured field strength is exceeded in discrete directions but does not cause interference to other stations. When augmentation is desired, it is achieved by applying Eq. (C-7) in Appendix C.

REFERENCES

1. *Directional Antenna Patterns*
2. *Theory and Design of Directional Antennas*
3. *Standard Broadcast Antenna Systems*
4. *Design and Operation of Directional Antennas*
5. Directional Antenna Pattern Shapes
6. *Radiation Characteristics of Transmitting Antennae (An Introduction to Directional Antenna Pattern Design)*
7. *Directional Antenna Design Example*
8. *Parasitic Reradiation*
9. *Introduction to Directional Antenna Systems*
10. *Instructions for Installation of Radio Broadcast Stations Ground Systems*
11. *Log Periodic Antenna Design Handbook*
12. *Radio Broadcast Ground Systems*
13. Stuart Ballantine, "On the Optimum Transmitting Wavelength for a Vertical Antenna Over Perfect Earth", Proc. I.R.E. Vol. 12, pp. 833-839; December, 1924.
14. Carl E. Smith and Earl M. Johnson, "Performance of Short Antennas", Proc. I.R.E., Vol. 35, pp. 1026-1038; October 1947.
15. Carl E. Smith, John R. Hall and James O. Weldon, "Very High-Power Long-Wave Broadcasting Station", Proc. I.R.E., Vol. 42, No. 8, pp. 1222-1235; August, 1954.
16. Ralph N. Harmon, "Some Comments on Broadcast Antennas", Proc. I.R.E., Vol. 24, pp. 36-47; January, 1936.
17. George H. Brown, "A Critical Study of the Characteristics of Broadcast Antennas as Affected by Current Distribution", Proc. I.R.E., Vol. 24, pp. 48-81; January, 1936.
18. Carl E. Smith, "A Critical Study of Several Antennas Designed to Increase the Primary Coverage of a Radio Broadcasting Transmitter", Professional Thesis at Ohio State University, Columbus, Ohio.
19. Carl E. Smith, "A Critical Study of Two Broadcast Antennas", Proc. I.R.E., Vol. 24, pp. 1329-1341; October, 1936.
20. Morrison, J. F., and P. E. Smith: *The Shunt Excited Tower*, Proc. IRE, vol. 25, pp. 673-696, June, 1937.
21. Jeffers, C. L.: *An Antenna for Controlling the Nonfading Range of Broadcasting Stations*, Proc. IRE, vol. 36. pp. 1426-1431, November, 1948.
22. Smith, Carl E., D. B. Hutton, and W. G. Hutton: *Performance of Sectionalized Broadcasting Towers*, IRE Trans., pp. 22-34, December, 1955.

APPENDIX A

DIRECTIONAL ANTENNAS FOR PATTERN SHAPE

Space Configuration

The plan configuration of the k^{th} tower in an array is shown in Fig. A-1. A space view of the k^{th} tower and observation point P is shown in Fig. A-2.

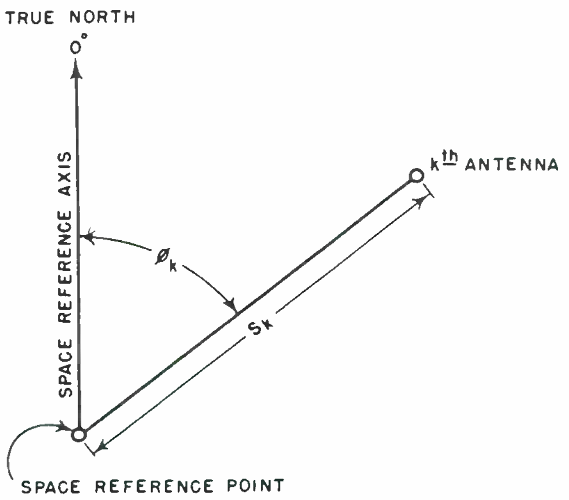


Fig. A-1. Plan view of space configuration of k^{th} antenna.

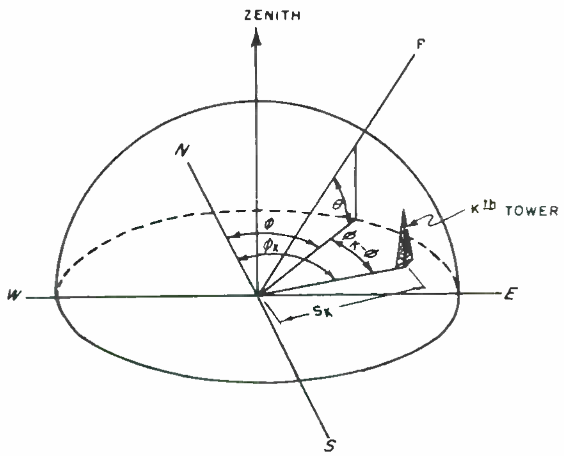


Fig. A-2. Space view of observation point P and the k^{th} tower.

Vector Diagram

The field strength at the point P in space for the k^{th} tower is shown in Fig. A-3. The space phasing in the horizontal plane is shown in Fig. A-4 and in the elevation plane the space phasing is reduced further as shown in Fig. A-5.

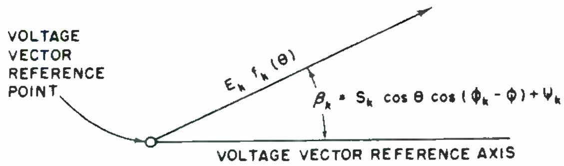


Fig. A-3. Voltage vector diagram for the k^{th} antenna.

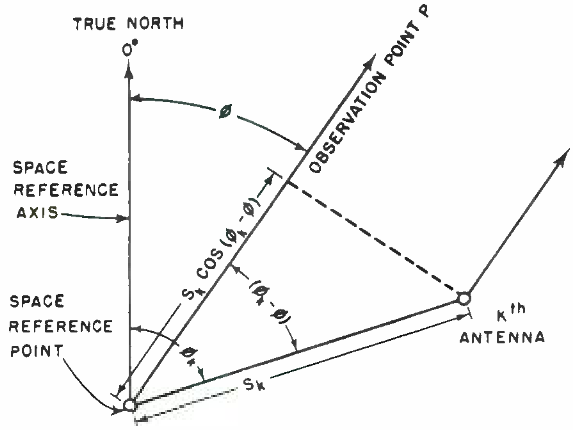


Fig. A-4. Plan view of k^{th} antenna showing space phasing in the horizontal plane.

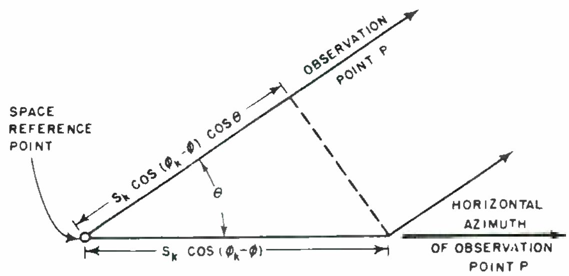


Fig. A-5. Elevation angle θ shortens the spacing S_k to the value of $S_k \cos\theta$.

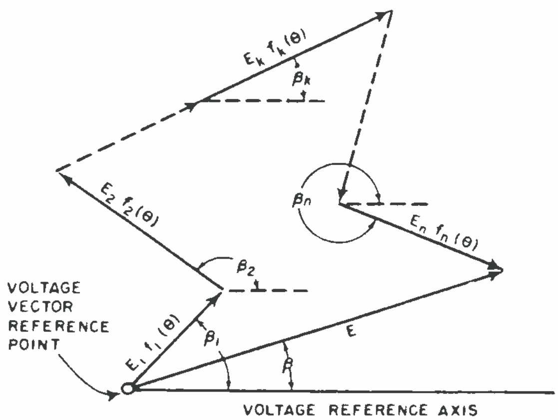


Fig. A-6. Summation of field strength vectors for n antennas in the directional antenna array.

Generalized Equation

The vector equation to express the vectors in Fig. A-6 is the generalized equation that can be used to express the pattern shape for a directional antenna array of n towers. The equation in condensed form is,

$$E = \sum_{k=1}^{k=n} E_k \; f_k(\theta) \;\underline{\big|\beta_k} \qquad \text{[A-1]}$$

Where:

E = the total effective field strength vector at unit distance (P) for the antenna array with respect to the voltage vector reference axis. This vector makes the angle β with respect to this axis as shown in Fig. A-6.

k = the k^{th} tower in the directional antenna system.

n = the total number of towers in the directional antenna array.

E_k = the magnitude of the field strength at unit distance in the horizontal plane produced by the k^{th} tower acting alone.

$f_k(\theta)$ = vertical radiation characteristic of the k^{th} antenna as given in Eq. A-3.

θ = elevation angle of the observation point P measured up from the horizon in degrees.

$$\beta_k = S_k \cos\theta \cos(\phi_k - \phi) + \psi_k \qquad \text{[A-2]}$$

= phase relation of the field strength at the observation point P for the k^{th} tower taken with respect to the voltage vector reference axis. $S_k\cos(\phi_k - \phi)\cos\theta$ is the space phasing portion of β_k due to the location of the k^{th} tower and ψ_k is the phasing portion of β_k.

S_k = electrical length of spacing of the k^{th} tower in the horizontal plane from the space reference point.

ϕ_k = true horizontal azimuth, orientation of k^{th} tower with respect to the space reference axis.

ϕ = true horizontal azimuth angle of the direction to the observation point P (measured clockwise from true north).

ψ_k = time phasing portion of β_k due to the electrical phase angle of the voltage (or current) in the k^{th} tower taken with respect to the voltage vector reference axis.

The shape of any directional antenna pattern can be computed by applying the above equations, however, many directional antenna arrays can be designed by simplified versions of this equation.

For a vertical antenna having a sinusoidal current distribution with a current node at the top, the vertical radiation characteristic takes on the form

$$f(\theta) = \frac{\cos(G\sin\theta) - \cos G}{(1 - \cos G)\cos\theta} \qquad \text{[A-3]}$$

Where:

$f(\theta)$ = vertical radiation characteristic

G = electrical height of the antenna in electrical degrees

θ = elevation angle of the observation point measured up from the horizon in degrees.

The vertical radiation characteristics in Eq. [A-3] are graphed in Fig. A-7.

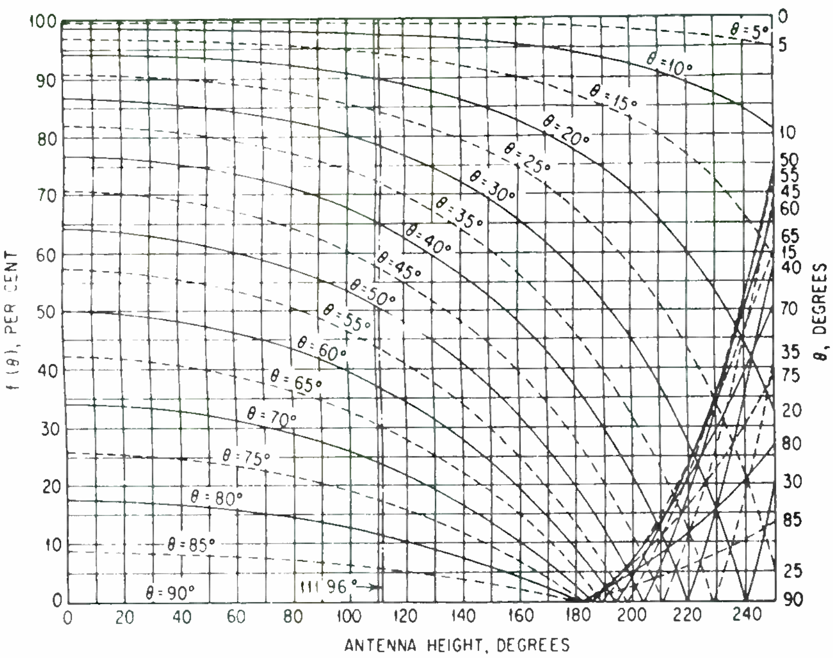


Fig. A-7. Vertical-radiation characteristic as a function of electrical tower height for various values of elevation angle.

For top-loaded tower the formula is,

$$f(\theta) = \frac{\cos B \cos (A \sin \theta) - \cos G - \sin B \sin \theta \sin (A \sin \theta)}{\cos \theta (\cos B - \cos G)} \qquad \text{[A-4]}$$

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

For a two section top-loaded tower as shown in Fig. 5 the formula is,

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

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, such as shown in Fig. 6.

Theoretical Self-loop and Base-radiation Resistance

It is useful to know the theoretical loop and base resistance of a vertical radiator. This information is presented graphically in Fig. A-8 along with the theoretical inverse field strength at 1 mile.

Mutual-impedance Curves

The value of mutual impedance for most tower heights and spacing is given in Fig. A-9. The loop mutual impedance between quarter-wave towers is shown in Fig. A-10.

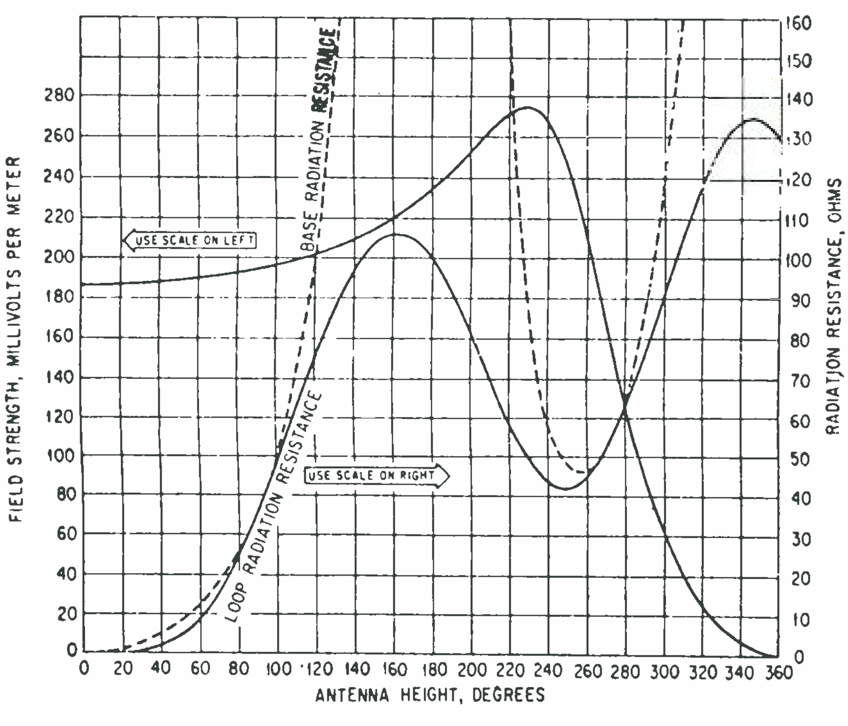


Fig. A-8. Inverse field strength at 1 mile for 1 kw, loop and base radiation resistance as a function of tower height over a perfectly conducting earth.

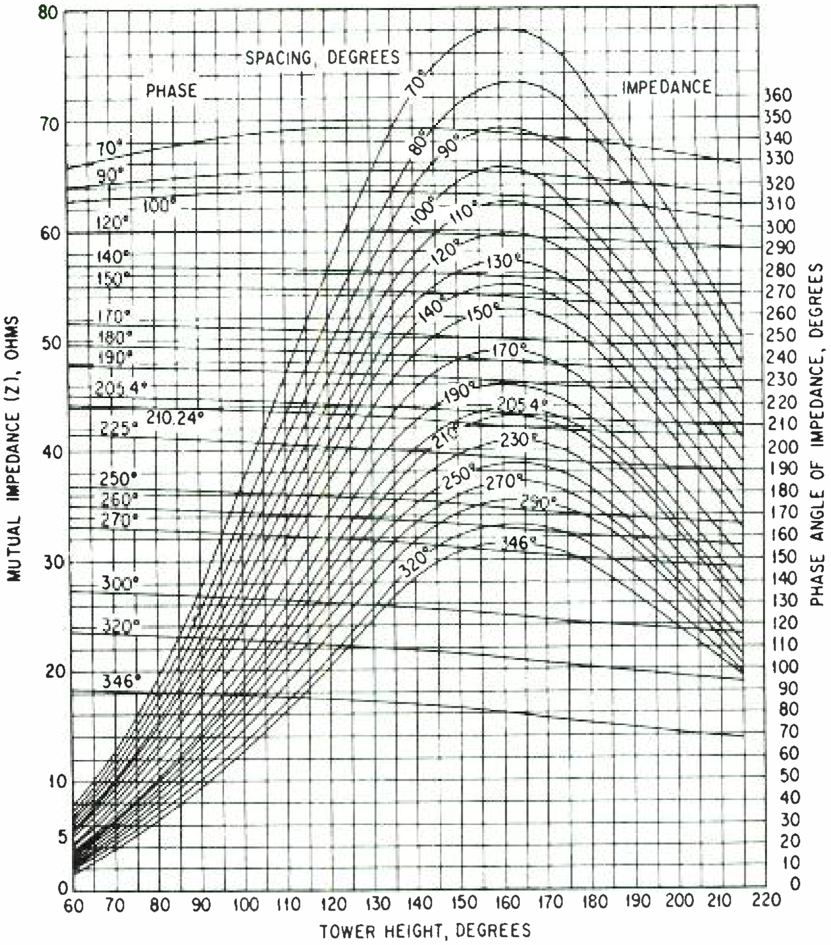


Fig. A-9. Loop mutual impedance and phase angle between two towers of equal height.

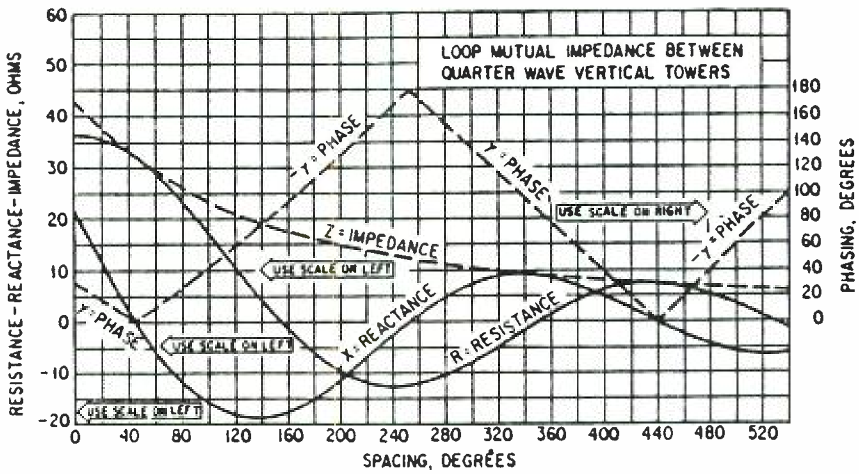


Fig. A-10. Loop mutual impedance between quarter-wave vertical towers.

Horizontal RMS Field Strength

The field-strength gain or loss of a two-tower array for various values of phasing and spacing is shown in Fig. A-11.

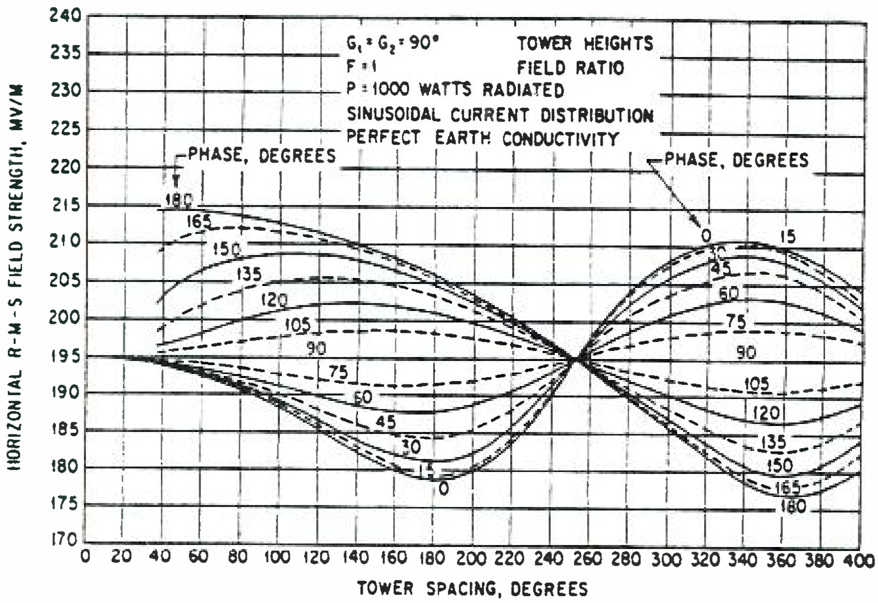


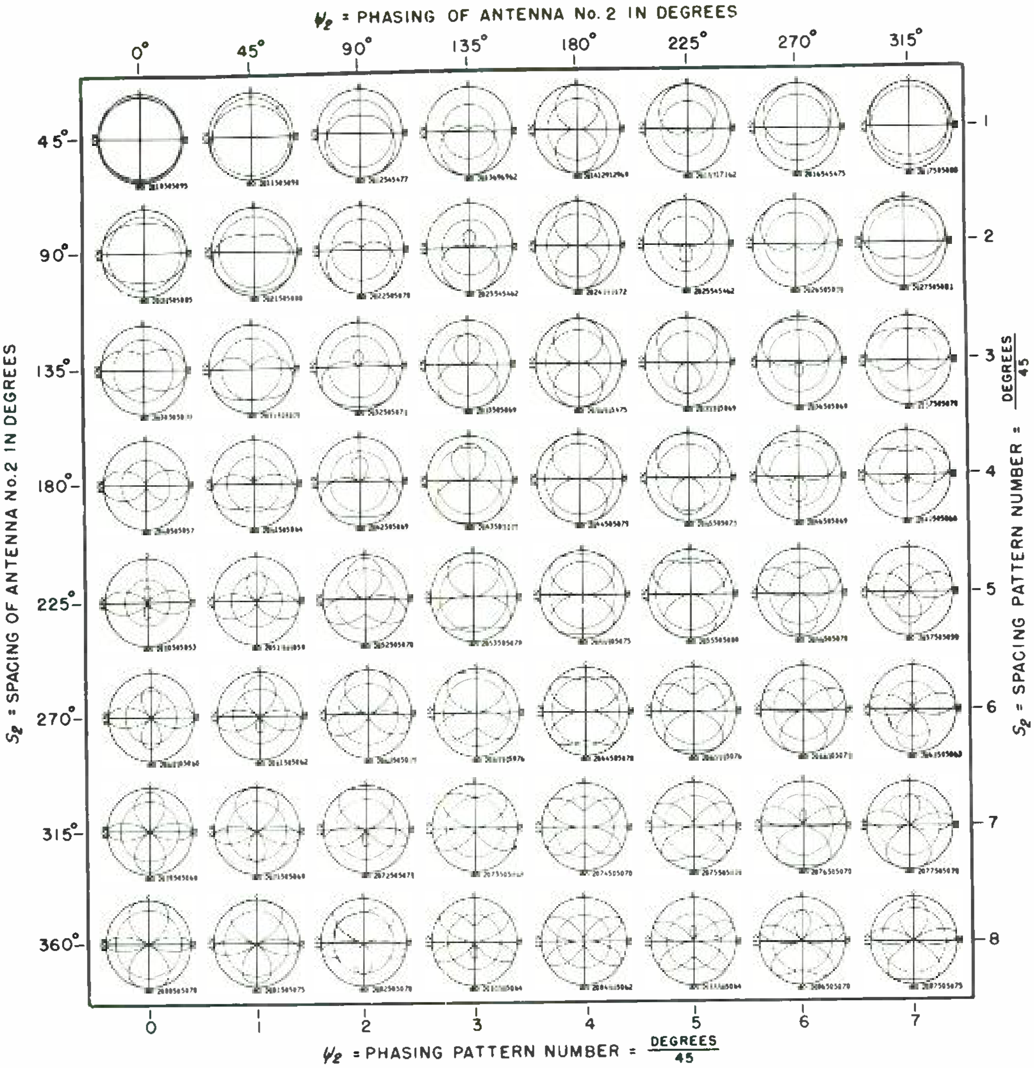
Fig. A-11. Horizontal rms field strength of two-tower directional antenna.

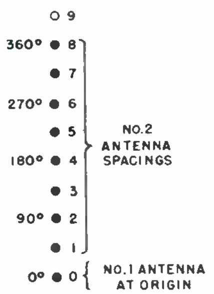
APPENDIX B

SYSTEMATIZATION OF TWO TOWER PATTERNS

The pattern numbering system has been devised to furnish the antenna parameters in an orderly fashion as described at the bottom of each page. To simplify the numbering system the spacing and phasing of each antenna is shifted in steps of 45 degrees. The spacing varies from 45 degrees on page B-1 to 1440 degrees on page B-4 while the phasing varies from 0 degrees to 315 degrees on each page. The field strength of each antenna, E_1 and E_2 is expressed in percent of the maximum lobe field strength (50%) of the horizontal pattern and finally the last two digits specify in percent the RMS field strength in the horizontal plane of the two tower directional antenna array.

The detailed patterns on pages B-5 through B-10 are for spacings in steps of 15 degrees up to 360 degrees. The phasings are only presented from 0 degrees to 180 degrees since the same patterns, oriented 180 degrees, results for phasing from 180 degrees to 360 degrees.



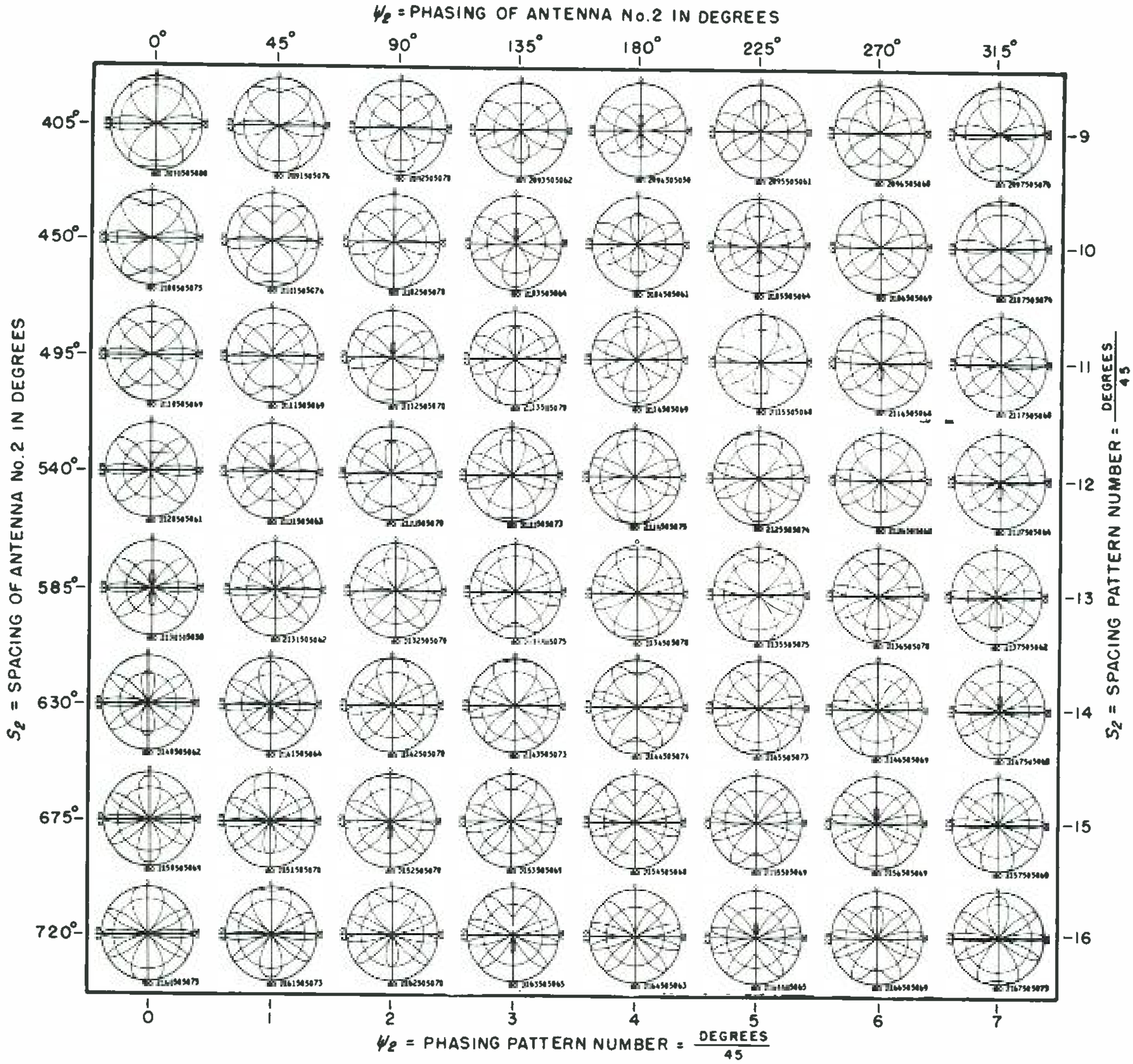


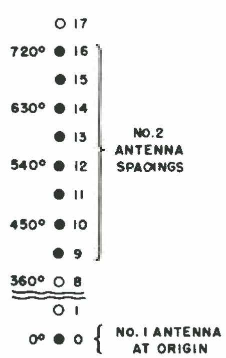
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS.

NUMBER OF ANTENNAS IN THE SYSTEM.	SPACING OF NO. 2 ANTENNA = DEGREES / 45	PHASING OF NO. 2 ANTENNA = DEGREES / 45	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA.	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 2 ANTENNA.	% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM.
NO.	S_2	ψ_2	E_1	E_2	E_0
2	01	0	50	50	95

PATTERN NOMENCLATURE

Appendix B-1.



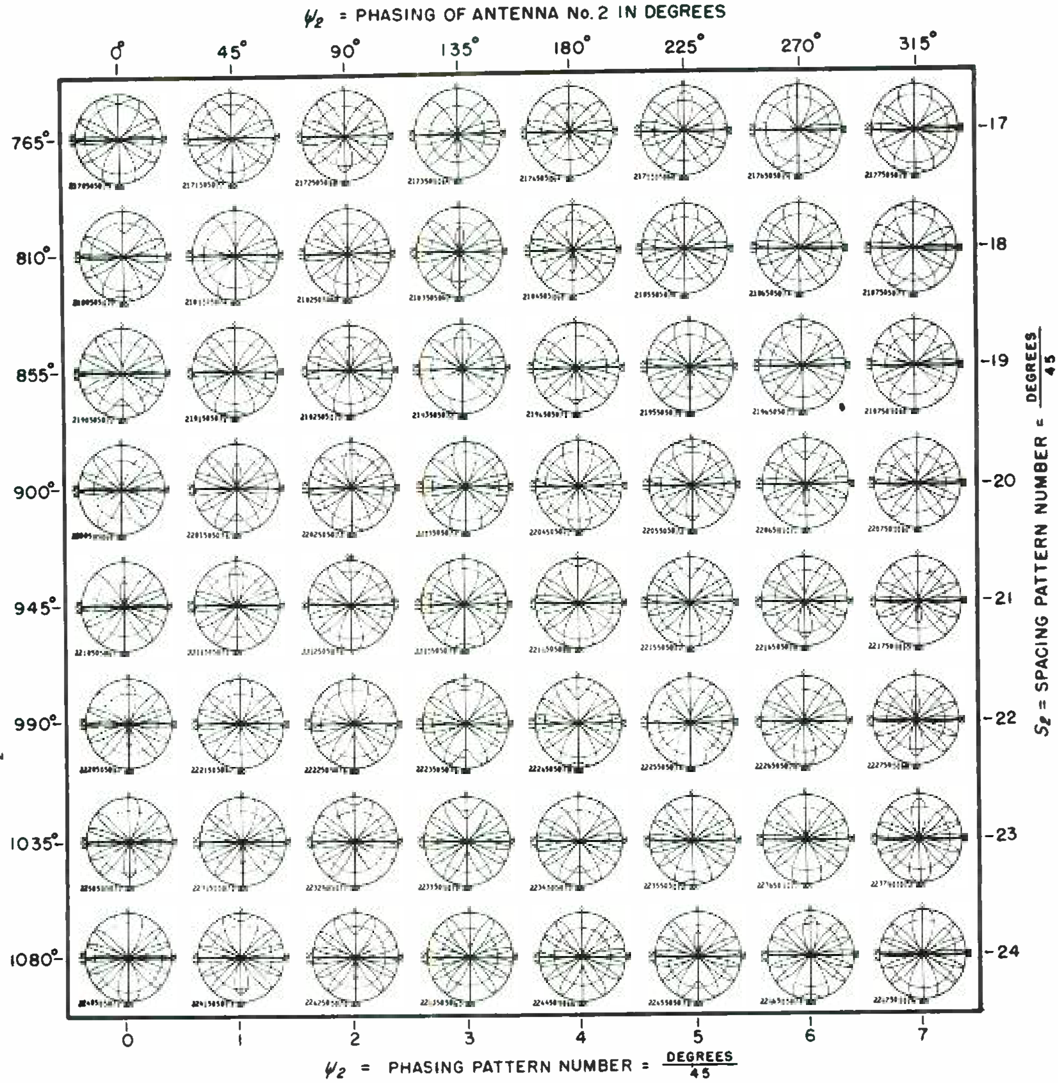


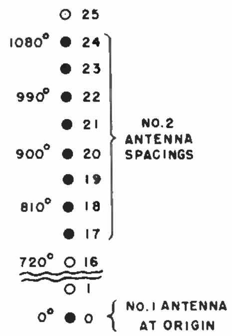
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS.

NUMBER OF ANTENNAS IN THE SYSTEM.	SPACING OF NO. 2 ANTENNA = DEGREES/45	PHASING OF NO. 2 ANTENNA = DEGREES/45	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA.	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 2 ANTENNA.	% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM.
NO.	S_2	ψ_2	E_1	E_2	E_0
2	09	0	50	50	80

PATTERN NOMENCLATURE

Appendix B-2.



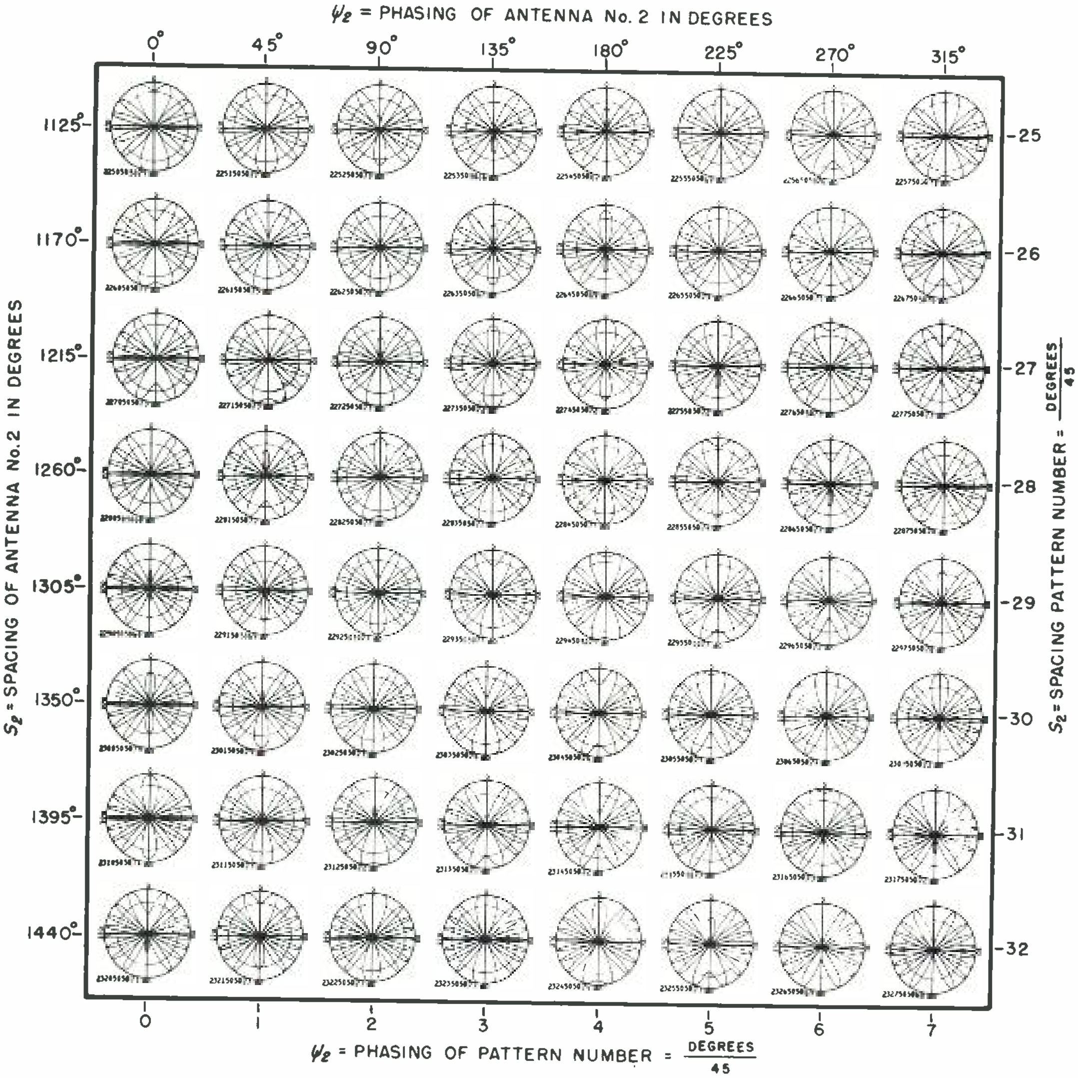


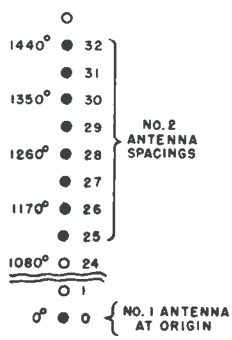
SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS.

NUMBER OF ANTENNAS IN THE SYSTEM.	SPACING OF NO. 2 ANTENNA = DEGREES/45	PHASING OF NO. 2 ANTENNA = DEGREES/45	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA.	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 2 ANTENNA.	% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM.
No.	S_2	ψ_2	E_1	E_2	E_0
2	17	0	50	50	79

PATTERN NOMENCLATURE

Appendix B-3.



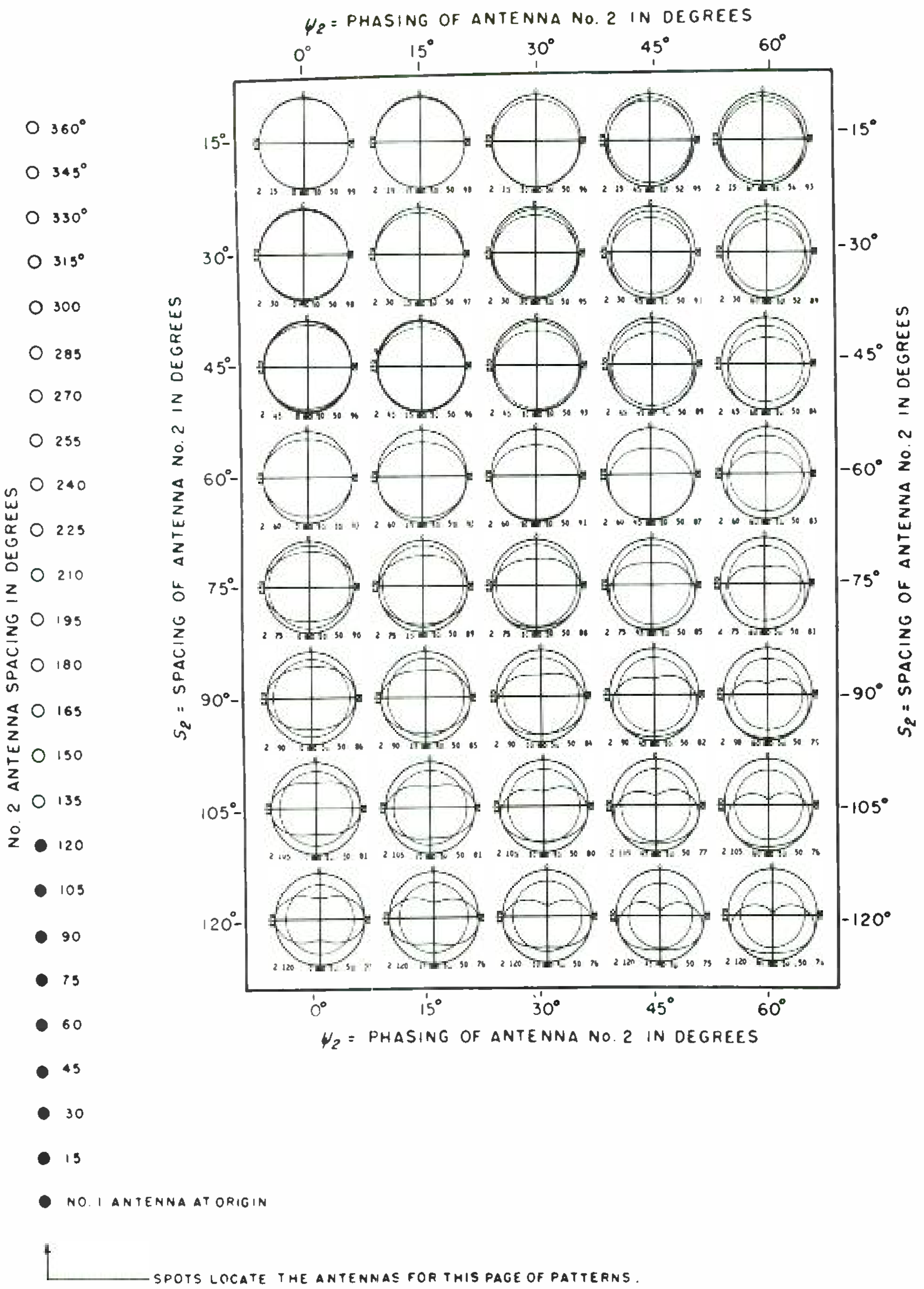


SPOTS LOCATE THE ANTENNAS FOR THIS PAGE OF PATTERNS.

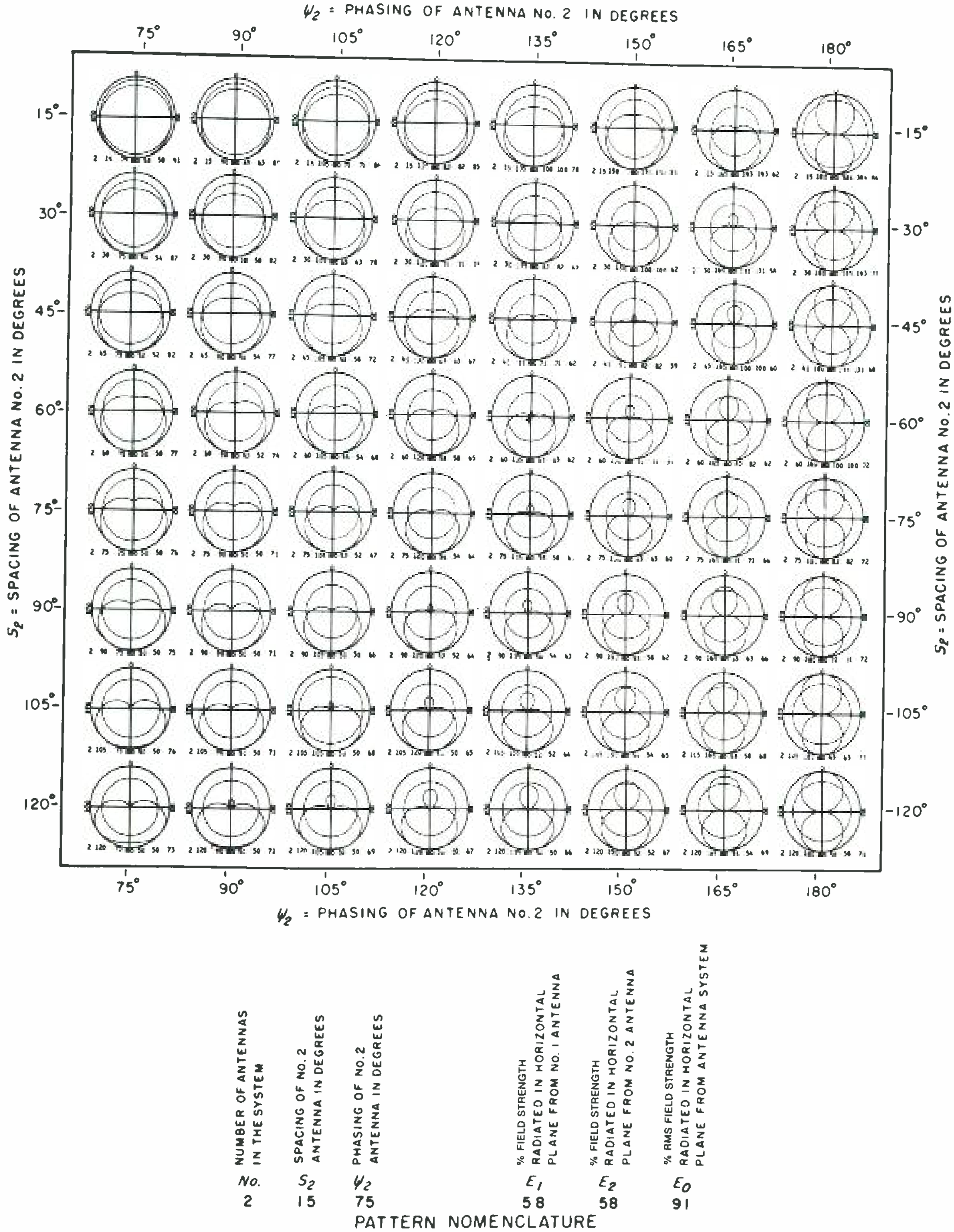
NUMBER OF ANTENNAS IN THE SYSTEM.	SPACING OF NO. 2 ANTENNA = DEGREES / 45	PHASING OF NO. 2 ANTENNA = DEGREES / 45	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA.	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 2 ANTENNA.	% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM.
No.	S_2	ψ_2	E_1	E_2	E_0
2	25	0	50	50	79

PATTERN NOMENCLATURE

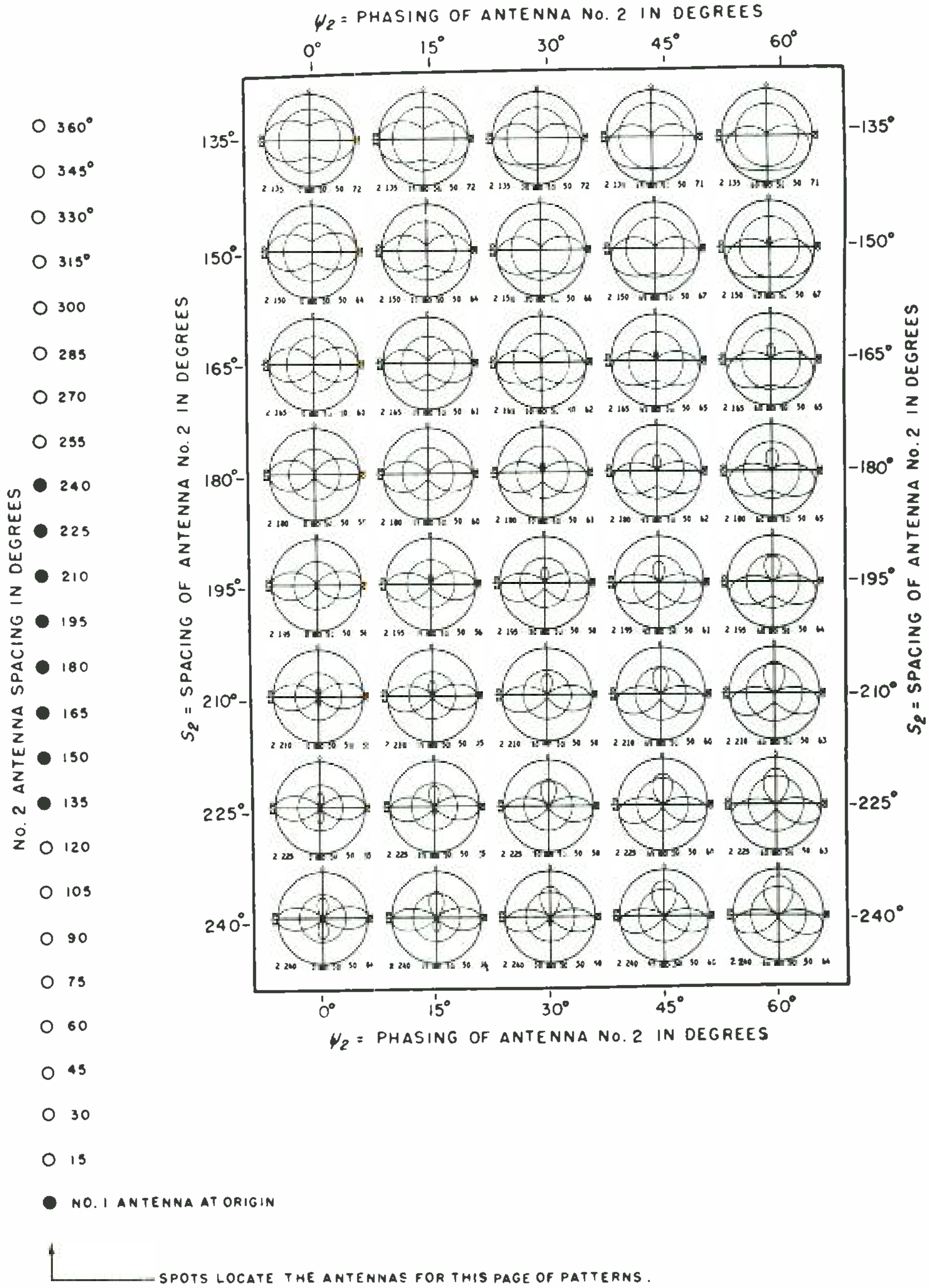
Appendix B-4.


ψ2 = PHASING OF ANTENNA No. 2 IN DEGREES
0° 15° 30° 45° 60°
15° 30° 45° 60° 75° 90° 105° 120°
-15° -30° -45° -60° -75° -90° -105° -120°
S2 = SPACING OF ANTENNA No. 2 IN DEGREES
No. 2 ANTENNA SPACING IN DEGREES
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.

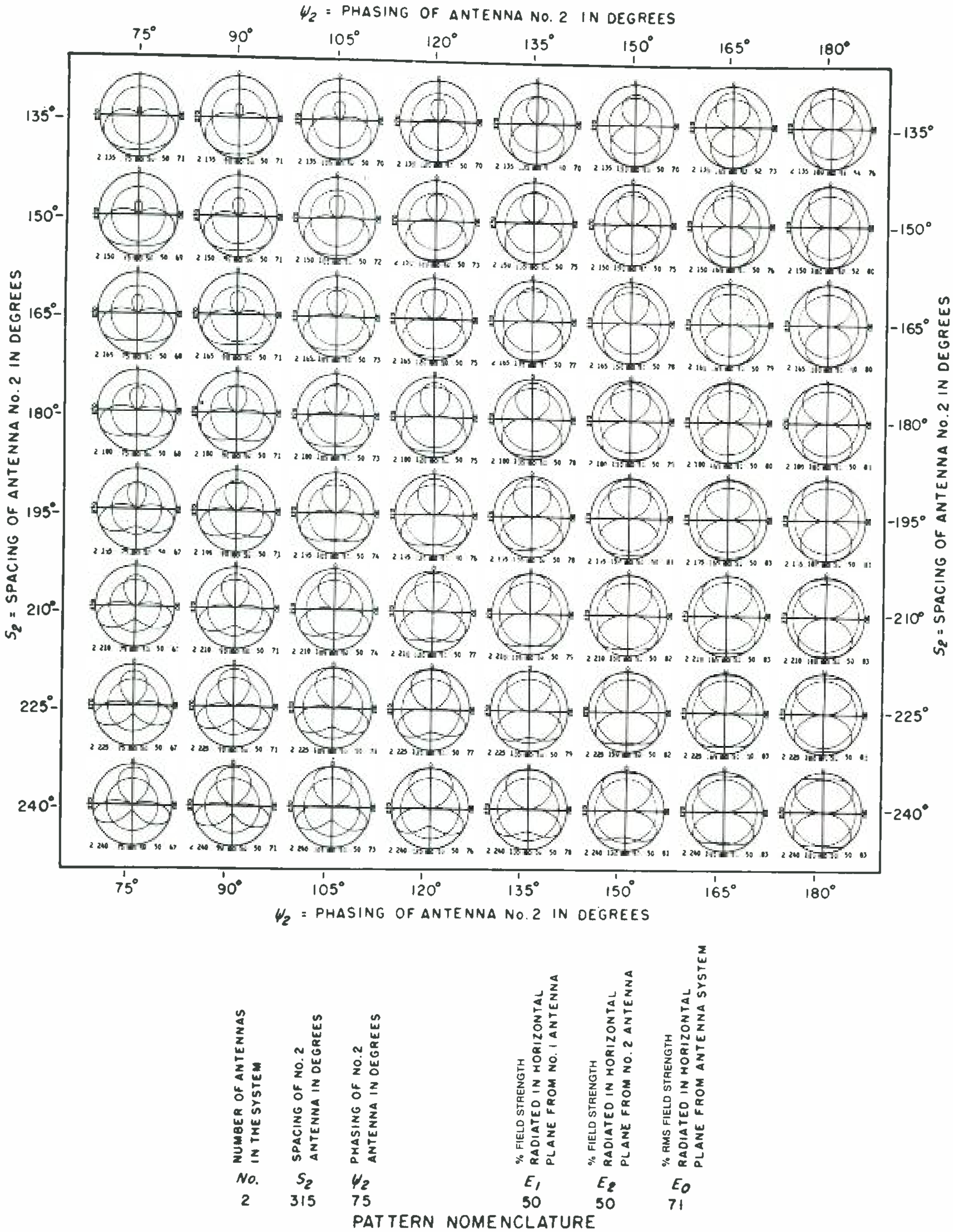
Appendix B-5.


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°
NUMBER OF ANTENNAS IN THE SYSTEM
SPACING OF NO. 2 ANTENNA IN DEGREES
PHASING OF NO. 2 ANTENNA IN DEGREES
% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA
% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 2 ANTENNA
% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM
No. S_2 ψ_2 E_1 E_2 E_0
2 15 75 58 58 91
PATTERN NOMENCLATURE

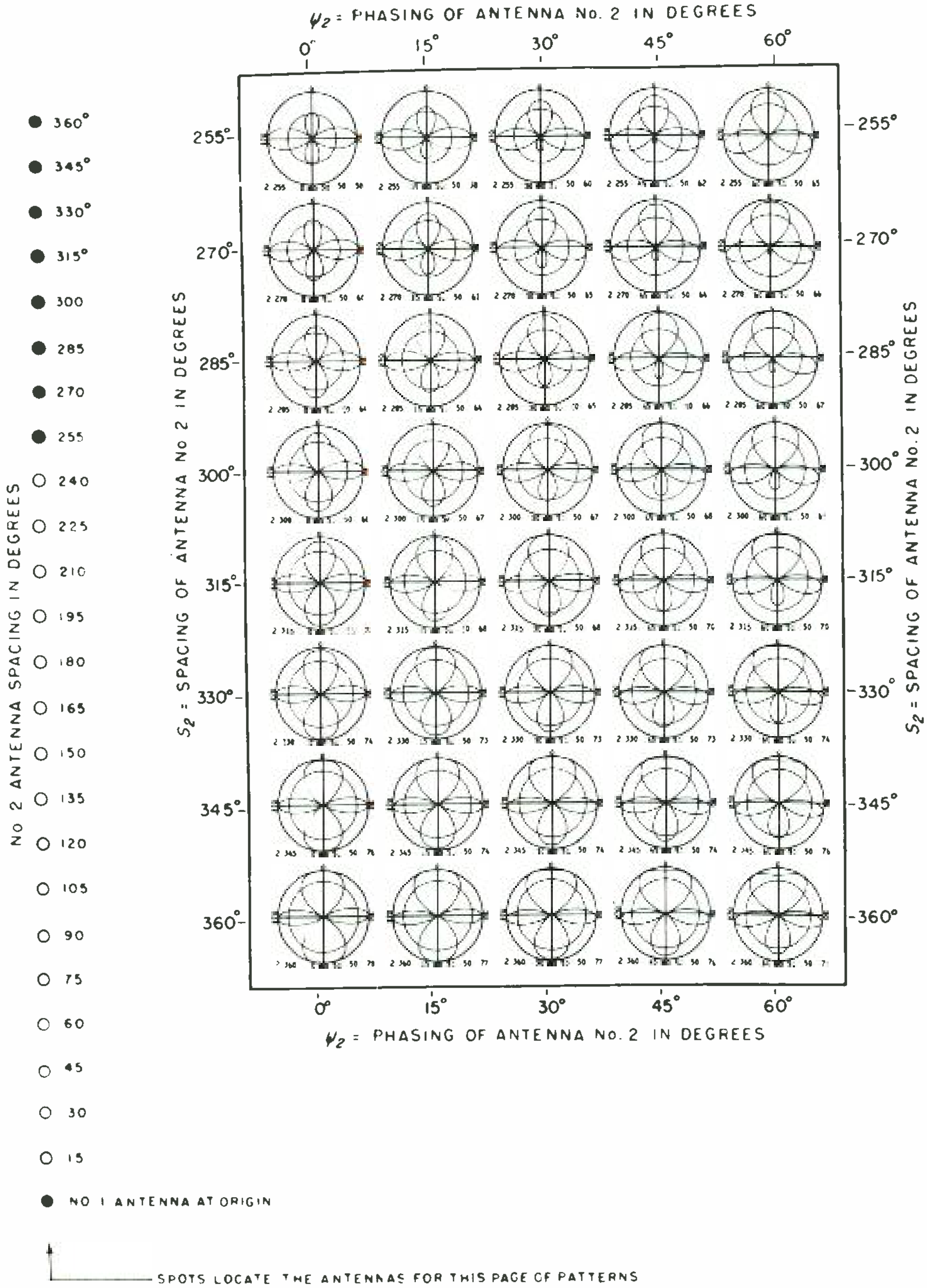
Appendix B-6.


ψ2 = PHASING OF ANTENNA No. 2 IN DEGREES
0° 15° 30° 45° 60°
135° 150° 165° 180° 195° 210° 225° 240°
S2 = SPACING OF ANTENNA No. 2 IN DEGREES
No. 2 ANTENNA SPACING IN DEGREES
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.

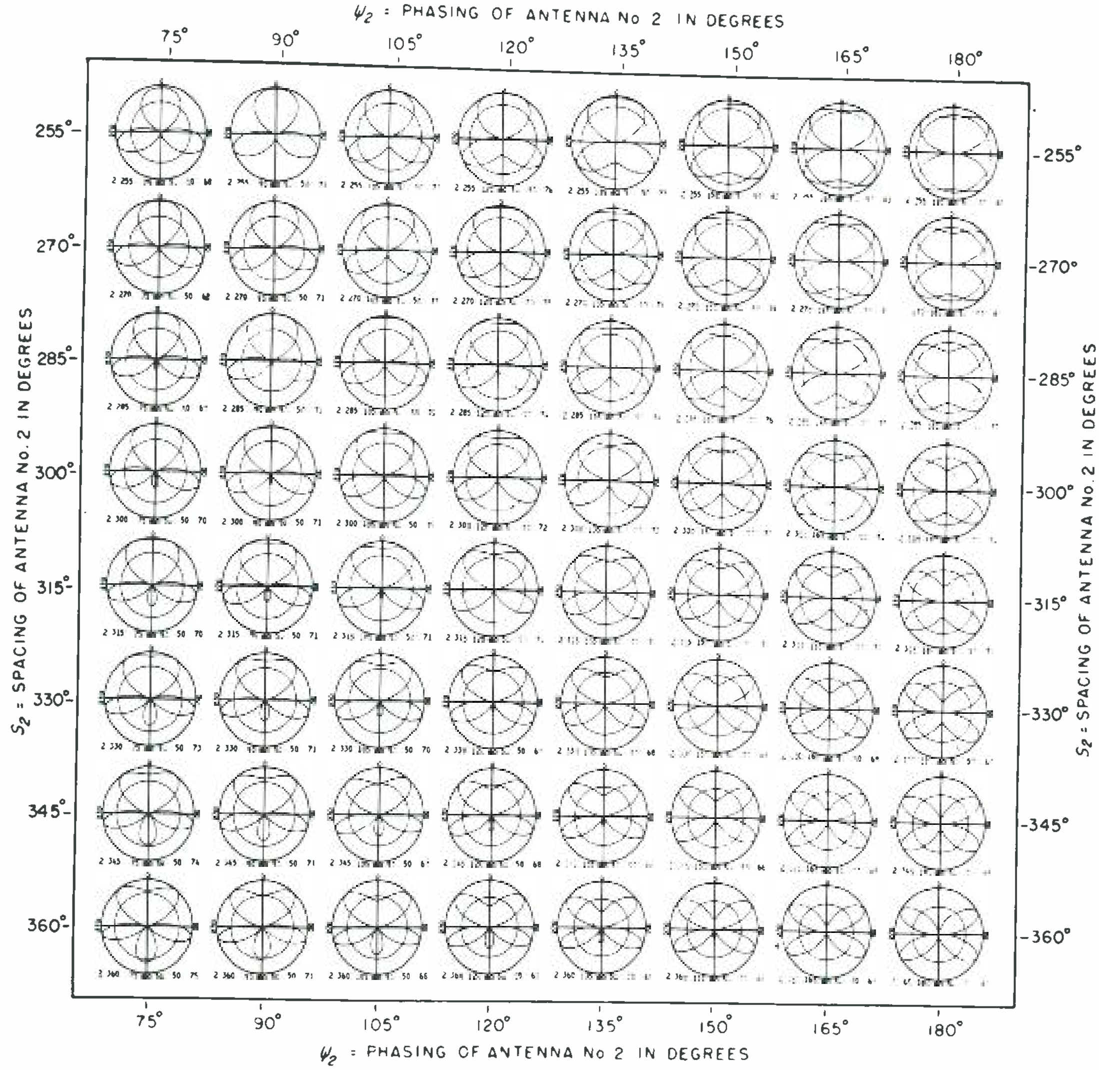
Appendix B-7.


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°
NUMBER OF ANTENNAS IN THE SYSTEM
SPACING OF NO. 2 ANTENNA IN DEGREES
PHASING OF NO. 2 ANTENNA IN DEGREES
% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA
% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 2 ANTENNA
% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM
No. S2 Ψ2 E1 E2 E0
2 315 75 50 50 71
PATTERN NOMENCLATURE

Appendix B-8.


ψ_2 = PHASING OF ANTENNA No. 2 IN DEGREES
0° 15° 30° 45° 60°
255° 270° 285° 300° 315° 330° 345° 360°
S_2 = SPACING OF ANTENNA No. 2 IN DEGREES
NO 2 ANTENNA SPACING IN DEGREES
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

Appendix B-9.



No.	S_2	ψ_2	E_1	E_2	E_0
NUMBER OF ANTENNAS IN THE SYSTEM	SPACING OF NO. 2 ANTENNA IN DEGREES	PHASING OF NO. 2 ANTENNA IN DEGREES	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO. 1 ANTENNA	% FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM NO 2 ANTENNA	% RMS FIELD STRENGTH RADIATED IN HORIZONTAL PLANE FROM ANTENNA SYSTEM
2	255	75	50	50	68

PATTERN NOMENCLATURE

Appendix B-10.

APPENDIX C

DIRECTIONAL ANTENNAS PATTERN DEVELOPMENT

Theoretical Pattern Equation

The theoretical pattern equation of Appendix A can be written as follows by changing the k^{th} tower to the i^{th} tower to conform with FCC, thus

$$E(\phi, \theta)_{th} = \left| k \sum_{i=1}^{n} F_i(\theta) \angle S_i \cos\theta \cos(\phi_i - \phi) + \psi_i \right| \quad [C\text{-}1]$$

where k = multiplying constant which determines pattern size *Standard Pattern Equation*

The standard pattern equation is obtained from Eq. [C-1] by adding the quadrature Q term to fill minimums and increase the size by five percent, thus

$$E(\phi, \theta)_{std} = 1.05\sqrt{[E(\phi, \theta)_{th}]^2 + Q^2} \quad [C\text{-}2]$$

where:

Q is the greater of the following quantities:

$$0.025\, g(\theta)\, E_{rss} \quad [C\text{-}3]$$

or

$$10.0\, g(\theta)\sqrt{P_{kw}} \quad [C\text{-}4]$$

where:

$g(\theta)$ is the vertical plane distribution factor, $f(\theta)$, for the shortest element in the array (see Eq. [C-2] above; also see FCC Rules Section 73.190, Figure 5). If the shortest element has an electrical height in excess of 0.5 wavelength, $g(\theta)$ shall be computed as follows:

$$g(\theta) = \frac{\sqrt{\{f(\theta)\}^2 + 0.0625}}{1.030776} \quad [C\text{-}5]$$

$$E_{rss} = \sqrt{\sum_{i=1}^{n} E_i^2} \quad [C\text{-}6]$$

As an example, consider a two tower array, the theoretical pattern in Eq. [C-1] becomes,

$$E = E_1 f_1(\theta) \angle 0° + E_2 f_2(\theta) \angle S_2 \cos(\phi_2 - \phi) + \psi_2$$

Now for 5 kw with 90° towers for the following parameters:

Tower No.	Height G°	Field Ratio	Spacing S°	True Bearing ϕ°	Phase ψ°
1	90	1.0	0	0	0
2	90	1.0	90	0	−90

the computer gives

E_{rss} (theoretical pattern) = 429.96 mV/m
Q (quadrature term) = 13.42 mV/m
E_{rms} (standard pattern) = 451.68 mV/m

A plot of the theoretical and standard patterns are shown in Fig. C-1.

The minimum horizontal field strength (at one mile) when the theoretical field strength goes to zero is given by Eq. [C-2] for a standard pattern along the ground, using Eq. [C-4] with $g(\theta)$ = 1.0. For 1 kw and under, the Q is 6 according to FCC Rules. For various FCC licensed values of power the minimum field strength values are as follows;

P_{kw}	Q	$E_{mV/m}$
0.25	6.0	6.3
0.50	6.0	6.3
1.00	6.0	6.3
2.50	9.49	9.96
5.0	13.42	14.09
10.0	18.97	19.92
25.0	30.00	31.50
50.0	42.43	44.55

The minimum field strength (at one mile) for any elevation of a standard pattern, by Eq. [C-5] is

$$g(\theta) = \frac{\sqrt{0 + 0.0625}}{1.030776} = 0.2425$$

Augmented Pattern Equation

The augmented pattern equation is obtained by adding an augmentation quadrature term to the standard pattern as given in the following equation,

$$E_{(\phi,\theta)\,aug.} = \sqrt{\{E_{(\phi,\theta)std.}\}^2 + A\{g(\theta)\cos(180\frac{D_A}{S})\}^2} \quad [C\text{-}7]$$

where:

$E_{(\phi,\,\theta)\,aug}$ = Augmented Radiation Value at Azimuth/Elevation

$E_{(\phi,\,\theta)\,std}$ = Standard Pattern Radiation Value at Azimuth/Elevation

$A = \{E_{(\phi',\theta)\,aug}\}^2 - \{E_{(\phi',\theta)\,std}\}^2$

Augmentation Constant

$g(\theta)$ = lSame As In Standard Pattern [Eq. C-5]

S = Span of Augmentation In Degrees

D_A = Angular Distance from Center of Span

The principle of augmentation is illustrated in the cardioid pattern of Fig. C-2.

The FCC has converted all augmented directional patterns to a table for each station as shown in the example of Fig. C-3. In this case there were 6 augmentations as tabulated in Fig. C-4 and shown on the polar chart of Fig. C-5.

It should be noted that where the spans overlap Eq. [C-7] is applied repeatedly, once for each augmentation, proceeding clockwise from true north.

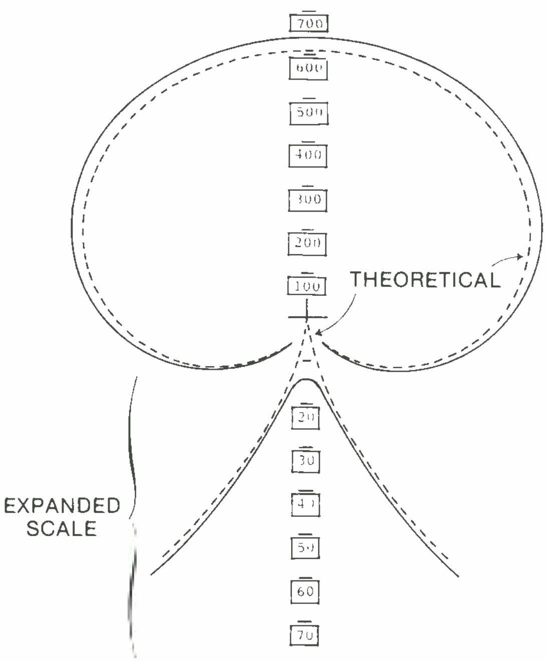


Fig. C-1. Theoretical and standard pattern.

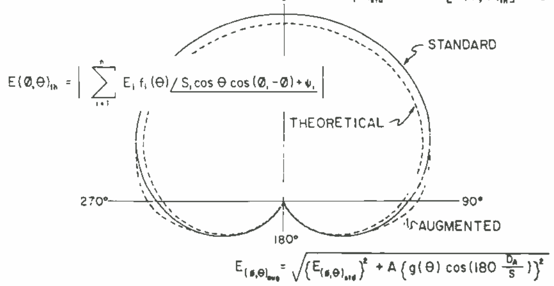


Fig. C-2. Theoretical, standard and augmented pattern.

TECHNICAL PARAMETERS RESULTING FROM CONVERSION
OF AM BROADCAST STATIONS TO STANDARD PATTERNS

STANDARD PATTERN CONVERSION NO.: 1280-22

FREQ. KHZ	CALL LETTER	CITY	STATE	HRS.	PATTERN STATUS	CLASS
1280	WHVR	HANOVER	PA	N	LIC.	3

POWER KW	LATITUDE	LONGITUDE	PAT-MULT MV/M	TH-RMS MV/M	STD/AUG RMS-MV/M	PAT-RSS MV/M	Q-FACTOR
.500	39-49-11	77-00-25	131.27	143.00	150.54	185.65	6.0000

TOWER NO.	PHYS-HT (A)-DEG	TL-HT (B)-DEG	TOT-HT (C)-DEG	TL-HT (D)-DEG	FIELD RATIO	PHASE DEG.	SPACING DEG.	ORIENT DEG-TR	REF FLG
1	91.0	.0	.0	.0	1.000	149.5	.0	.0	
2	91.0	.0	.0	.0	1.000	.0	90.0	178.0	

-----------AUGMENTATION DATA----------

CENTRAL AZIM. DEGREES TRUE	SPAN DEGREES	FIELD AT AZIM. MV/M
64.0	12.0	17.0
260.5	55.0	103.0
288.0	14.0	7.5
288.0	10.0	21.2
295.0	14.0	30.0
295.0	10.0	43.3

-----------HORIZONTAL PLANE STANDARD/AUGMENTED RADIATION VALUES-----------

AZ. DEG	FIELD MV/M	AZ. DEG	FIELD MV/M	AZ. DEG	FIELD MV/M	AZ. DEG	FIELD MV/M	AZ. DEG	FIELD MV/M	AZ. DEG	FIELD MV/M
0	136.8	60	29.1	120	174.0	180	239.4	240	163.9	300	42.2
10	132.8	70	9.0	130	196.3	190	237.0	250	136.2	310	71.0
20	123.1	80	43.5	140	213.5	200	231.2	260	104.7	320	95.4
30	107.5	90	80.0	150	225.9	210	221.4	270	69.3	330	114.4
40	86.3	100	115.0	160	234.0	220	207.2	280	31.3	340	127.7
50	59.8	110	146.7	170	238.4	230	188.0	290	20.4	350	135.1

CONSTRUCTION PERMIT LIMITS

AZIMUTH DEG.TRUE	PRESENT MV/M	NEW MV/M
64.0	17.0	17.0
231.0	179.0	185.8
288.0	33.0	21.2
352.0	131.0	135.9

--PATTERN MINIMA--

AZIMUTH DEG.TRUE	FIELD MV/M
68.5	6.8
284.5	17.3
290.0	20.4
299.0	40.9

--PATTERN MAXIMA--

AZIMUTH DEG.TRUE	FIELD MV/M
178.0	239.4
288.0	21.2
296.0	44.2
358.0	136.9

-FCC-

Fig. C-3. FCC method of specifying augmentation.

CENTER AZIMUTH OF AUGMENTATION	SPAN DEGREES	EXTENT OF SPAN	FIELD AT CENTER SPAN
64°	12°(±6°)	(58°-70°)	17.0
260.5°	55°(±27.5°)	(233°-288°)	103.0
288°	14°(±7°)	(281°-295°)	7.5
288°	10°(±5°)	(283°-293°)	21.2
295°	14°(±7°)	(288°-302°)	30.0
295°	10°(±5°)	(290°-300°)	43.3

Fig. C-4. Table of augmentation data.

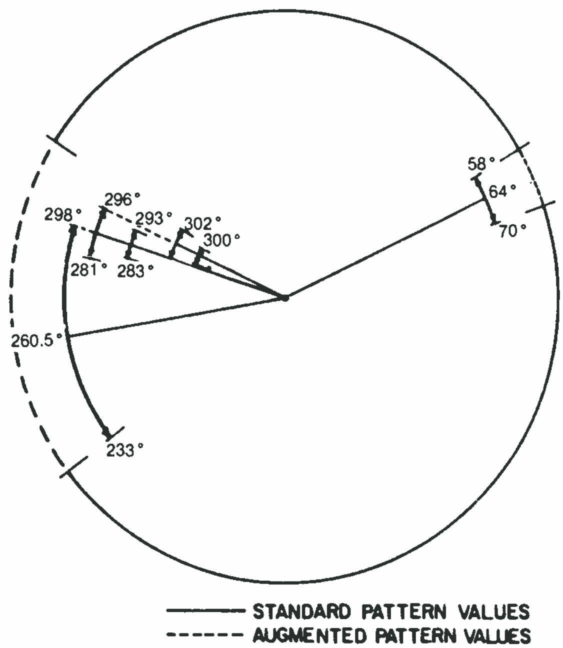


Fig. C-5. Augmented pattern flow chart showing overlapping spans.

2.4

AM Broadcast Antenna Systems

CHAPTER 2.4:
Part I: System Design
Part II: Phasing, Coupling
Part III: Maintenance

Part II: Antenna Coupling and Phasing Systems for AM Broadcast

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AM broadcast antenna coupling and phasing systems consist principally of passive networks of coils, capacitors, transmission lines and of auxiliary components such as lightning gaps, meters, jacks, and relays. This equipment can range from simple (such as nondirectional station having the transmitter building located adjacent to the tower base) to complex (such as a multi-tower directional array requiring different patterns day and night). To understand antenna systems and their environment, we must consider the function of such systems and their performance objectives as well as the basic networks, power dividers, transmission lines, sampling systems, detuning systems, and transmitter load optimization.

THE FUNCTION OF A DIRECTIONAL ANTENNA PHASING SYSTEM

The function of a directional antenna phasing system is to distribute current to each tower with controllable phase and amplitude to generate the desired directional pattern. This function is accomplished typically by means of the following:

1. A network at each tower matches each tower load to its transmission line. (See Fig. 1) This network is typically in a box termed an antenna coupling unit or ACU. The remaining equipment, usually housed in one or more indoor cabinets, is termed a phasor.
2. Phasing networks provide control of the phase of each tower current (relative to the reference tower).
3. Power divider circuits control the relative current amplitude in each tower.
4. A common-point matching network adjusts the input impedance to a desirable resistive value without disturbing the phase or amplitude of the tower currents.

Fig. 1 shows a system with only two towers; each additional tower requires its own antenna coupling unit, transmission line, and phasing network, as well as additional components in the power divider.

PHASOR PERFORMANCE OBJECTIVES

The essential performance objective is to have both the phasor input impedance and the directional antenna radiation pattern remain essentially constant at all frequencies within the channel. The performance may be disappointing if the design process proceeds by a piecemeal block-by-block approach, where the networks are independently designed for each of the functions as illustrated in Fig. 1 and then merely connected together. A

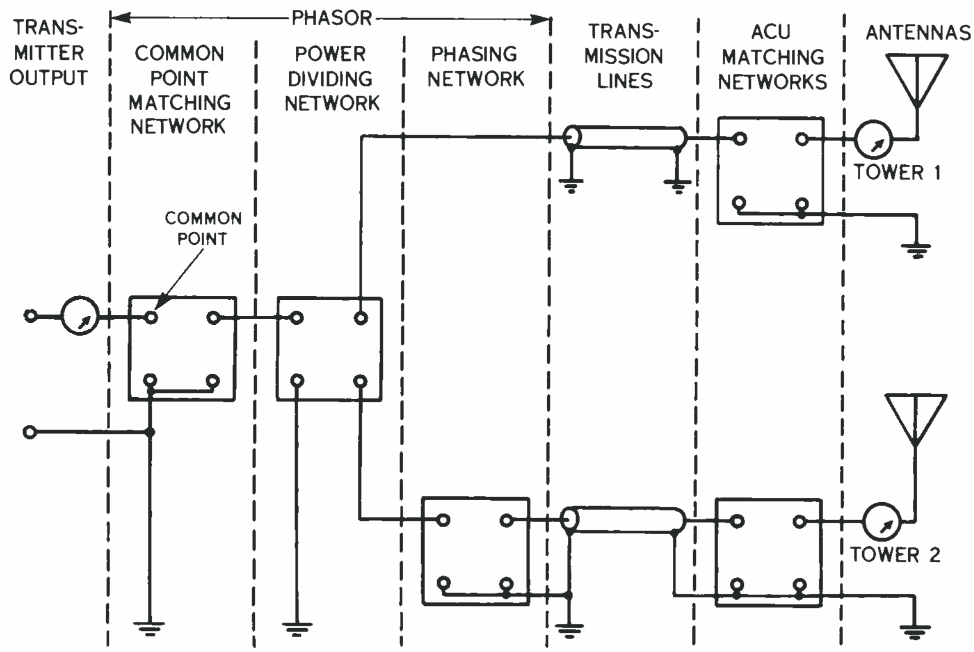


Fig. 1. Block diagram of a directional antenna system.

better approach is to use a systems design that considers the entire collection of components between the transmitter and the towers as a whole rather than by the "building block" approach implicit in Fig. 1.

Phasor Input Impedance

An ideal phasor would present a load to the transmitter that is purely resistive and unchanging at all sideband frequencies. However, phasors consist of coils and capacitors, whose reactance varies with frequency; therefore, this ideal cannot be achieved. The term "impedance bandwidth" is used to describe the degree of constancy of the phasor input impedance across the entire range of sideband frequencies. A useful figure-of-merit to express the impedance bandwidth as a single number is the worst-case voltage standing wave radio (VSWR) existing at either of the two 10 kHz sideband frequencies when the system is perfectly matched at the carrier frequency. This approach yields a VSWR number that is related to antenna performance just as television and FM transmitting antenna performance is described by VSWR limits at various sideband frequencies.

Bandwidth requirements change greatly across the broadcast band. At 1600 kHz, a total bandwidth of 20 kHz corresponds to about one percent of the center frequency, whereas at 540 kHz, 20 kHz corresponds to nearly four percent of the center frequency. Comparatively, an AM station at the lower frequencies has a more stringent bandwidth requirement than is needed for acceptable visual transmitter performance on television channels 7 through 13 or on any of the UHF channels.

The VSWR at 10 kHz above and below carrier often is better than 1.1 to 1 in good phasor designs. Poor designs can be worse than 2 to 1. Poor phasor designs manifest themselves by poor audio quality, which is most obvious in the minimum radiation sectors of the antenna patterns of stations on the lower-frequency channels. The sideband VSWR can be determined by analysis of common-point impedance measurements. The resistance and reactance at each sideband frequency of interest are expressed as a percentage of the measured carrier frequency resistance and are then plotted on a Smith Chart. (A Smith Chart depicts the relationship between the load impedances at sideband frequencies and the matched load established at the carrier frequency.) The distance from the center of the chart for each sideband frequency is a measure of the VSWR at that frequency.

Radiation Pattern

An ideal phasor would produce an antenna radiation pattern that remains unchanged across the channel. Any variations in the phase and ratio of tower currents at the sideband frequencies can result in changes in the location and depth of the intended pattern minimums. The frequencies for which the pattern remains useful describe the "pattern bandwidth". Pattern bandwidth cannot be described by simple numbers, but the concept is useful in comparing alternative designs.

The example of poor pattern bandwidth below (Fig. 2) shows the three-tower daytime pattern of an actual station at its carrier frequency and at the 10 kHz sideband frequencies. The sideband patterns were calculated from the actual measured ratios and phases of tower currents at both sideband frequencies. This directional antenna system did not adequately protect an adjacent channel station even though conventional field strength measurements indicated proper operation. A spectrum analyzer displaying the received signal confirmed the extreme sideband asymmetry in critical directions.

BASIC NETWORKS

The networks used for matching impedances or for shifting phase are typically "T" or "L" configurations. "Pi" networks having shunt elements at the input and output and a central series element can be made electrically identical to any T network; but T networks are easier to adjust.

The networks at the left in Fig. 3 offer large phase shifts, while the configurations on the right offer small phase shifts. Intermediate between these two conditions are L networks which can be considered as T networks with one zero-reactance arm. L networks do not permit independent adjustment of impedance match and phase shift; however, the resulting phase delay or advance can be calculated easily, with the result often being a desirable value compatible with the overall phasor design. The formulas for these networks are all based on matching into resistive loads.

Antenna tower loads usually have a reactive component; therefore, the output arm of the matching network is modified to cancel the tower reactance. When this modification is made, the output arm will occasionally assume the opposite reactance sign as shown in the parentheses in Fig. 3.

T Networks

The reactances of the input, output, and shunt arms of a T network can be calculated quickly, once the desired input and output resistances and the phase shift (β) are specified, by using the formulas shown in Fig. 4. The formulas are equally applicable for leading ($+\beta$) and lagging ($-\beta$) networks.

L Networks

Conventional L networks can provide a match between any two resistance values. The formula for such networks is shown in Fig. 5, which presumes a non-reactive load. If an L network is used to match a tower to a transmission line, the reactive component of the tower impedance must be considered. If the tower resistance is lower than the line impedance, the series arm of

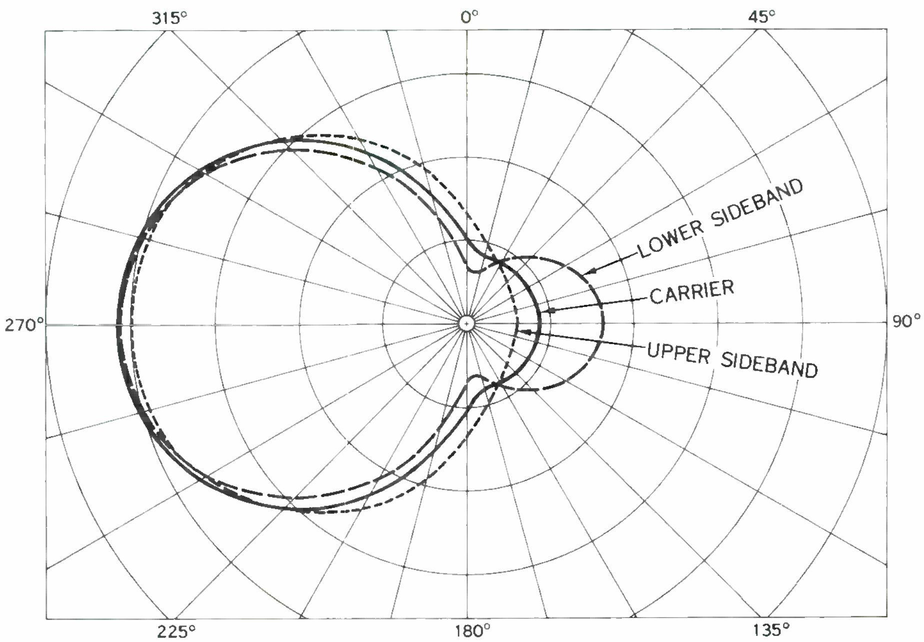


Fig. 2. Example of poor pattern bandwidth.

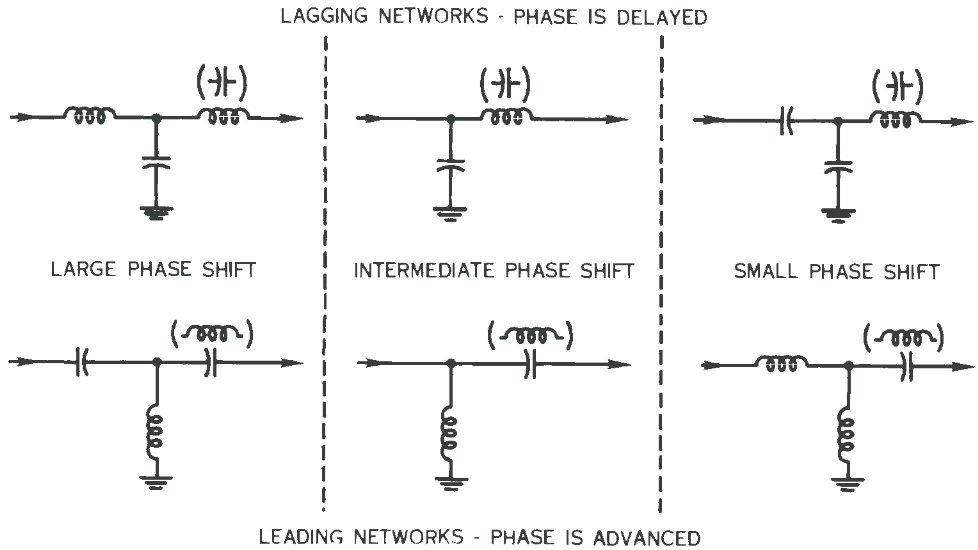
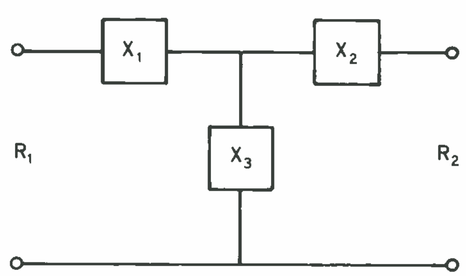


Fig. 3. Conventional "T" and "L" networks.

the L network is connected to the tower. This arm can then be modified from the value calculated by the formula so as to also cancel the tower reactance.

An L network can also be used to match a tower having a resistance higher than the transmission line impedance, but in this case the formula in Fig. 5 does not apply unless the tower impedance contains no reactance. In the usual case, where the tower impedance is reactive, an L network cannot be so easily calculated. The shunt arm (which is in parallel with the reactive tower load) must be one which makes the resistive component of the parallel combination equal to the transmission line impedance. Then the resulting reactance of the parallel combination is cancelled by the series input arm of the L network. Such networks are easy to adjust; the shunt arm of the L network is adjusted to make the input resistance match the transmission line characteristic impedance, and the series arm is then adjusted to cancel the resulting reactive component. The two adjustments are substantially independent of each other. If the tower is one element of a directional array, an operating impedance bridge (hot bridge) at the network input must be used and the phase and ratio parameters must be approximately correct in order for the tower operating impedance to be that which will exist when the directional antenna array is operating normally.

When the tower resistance is higher than the line impedance, there are two different values of shunt arm reactance (one capacitive and one inductive) that can satisfy the conditions necessary for a match with an L network. If the shunt arm



$$X_3 = \frac{\sqrt{R_1 R_2}}{\sin \beta}$$

$$X_2 = \frac{R_2}{\tan \beta} - X_3$$

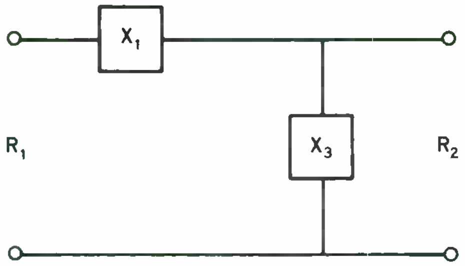
$$X_1 = \frac{R_1}{\tan \beta} - X_3$$

R_1 = INPUT RESISTANCE

R_2 = OUTPUT (LOAD) RESISTANCE

β = PHASE SHIFT BETWEEN INPUT AND OUTPUT

Fig. 4. "T" network formulas.



R_2 MUST BE GREATER THAN R_1

X_1 IS INDUCTIVE (+J) FOR LAGGING NETWORK

X_1 IS CAPACATIVE (−J) FOR LEADING NETWORK

X_3 MUST HAVE SIGN OPPOSITE TO X_1

$$X_1 = \pm \sqrt{R_1R_2 - R_1^2}$$

$$X_3 = \mp \frac{R_1R_2}{X_1}$$

$$\beta = \cos^{-1}\sqrt{\frac{R_1}{R_2}}$$

Fig. 5. "L" network formulas.

is of the same sign as the tower reactance, the required series arm will be of opposite sign and the phase shift will be small. If the shunt arm is opposite in sign to the tower reactance, the required reactance in the series arm will have the same sign as the tower reactance and the phase shift will be large.

An alternative way to design such L networks (rather than by calculating the shunt arm reactance necessary to produce the desired resistive component for the parallel combination), is to think of them as T networks in which the output arm is represented by the reactive component of the tower load. As such, these networks can be described as "Phantom T Networks".

Phantom T Networks

A phantom T network utilizes the tower reactance itself as the output arm (X_2) of the network. It is electrically similar to a conventional T network but requires one less circuit element. Because it has only two adjustable elements, the phase shift of a phantom T cannot be independently selected but two choices are possible, corresponding to T networks with small and large phase shifts. When the input resistance and reactance are properly adjusted, the resultant phase shift is then defined. Phantom T networks can be calculated quickly by the T network formulas and cut-and-try variation of the phase shift until X_2 exactly equals the tower reactance. The phantom T networks with small phase shifts, exhibit excellent bandwidth. Those with large phase shift are only slightly poorer.

POWER DIVIDERS

In most phasors, separate components are used to accomplish the power-division function; but the same networks that control phase shift can also control the division of power, if desired. It is important to remember that the power delivered to a tower bears no direct relationship to the base current. A high current tower having a very low base resistance may consume very little power (I^2R) because the resistance is so low. The actual power division is defined by the required base-current ratios and the base resistances. An example of power-division calculations is shown in Fig. 6.

Tank-Type Divider

In a tank-type power divider, as shown in Fig. 7, roller coils L2 and L3 (termed "jeep" coils in this configuration) adjust the power; the combination of L1, L2, and L3 is tuned close to resonance by capacitors C1 and C2. The input tap on L1 adjusts the common point resistance; L4 adjusts the common point reactance. This system is no longer popular because it is difficult to adjust and the bandwidth is limited by the excessive stored energy.

Ohms-Law Divider

A common type of divider is the "Ohms-Law" design shown in Fig. 8, which uses several adjustable (roller) coils in parallel, each of which controls the current to an individual tower. The reactance of the L1, L2, L3 combination is then tuned to resonance with C1. Component values are selected so that the impedance at point A is in order of 400 ohms. A conventional T network then matches this load to the desired common point impedance. This design is easy to adjust; however, the rollers on the variable coils may tend to bind and develop intermittent contacts after several years of use.

Given: Total power is 1000 watts with base current ratios and resistances as shown. I = Current in Tower 3.

Tower No.	Base Current Ratio	Base Resistance	Power
1	0.20	25 ohms	$(0.20\ I)^2 \times (25) = 1.0\ I^2$
2	0.70	130	$(0.70\ I)^2 \times (130) = 63.7\ I^2$
3	1.00	40	$(1.00\ I)^2 \times (40) = 40.0\ I^2$
4	0.50	10	$(0.50\ I)^2 \times (10) = 2.5\ I^2$
			$107.2\ I^2 = 1000$ watts; $I = 3.054$ amps

Tower No.	Base Current	Base Power
1	0.20 x 3.054 = 0.611 amps	$(0.611)^2 \times (25) = 9.3$ watts
2	0.70 x 3.054 = 2.138	$(2.138)^2 \times (130) = 594.2$
3	1.00 x 3.054 = 3.054	$(3.054)^2 \times (40) = 373.1$
4	0.50 x 3.054 = 1.527	$(1.527)^2 \times (10) = 23.4$
		1000.0 watts

Fig. 6. Example of power division calculations.

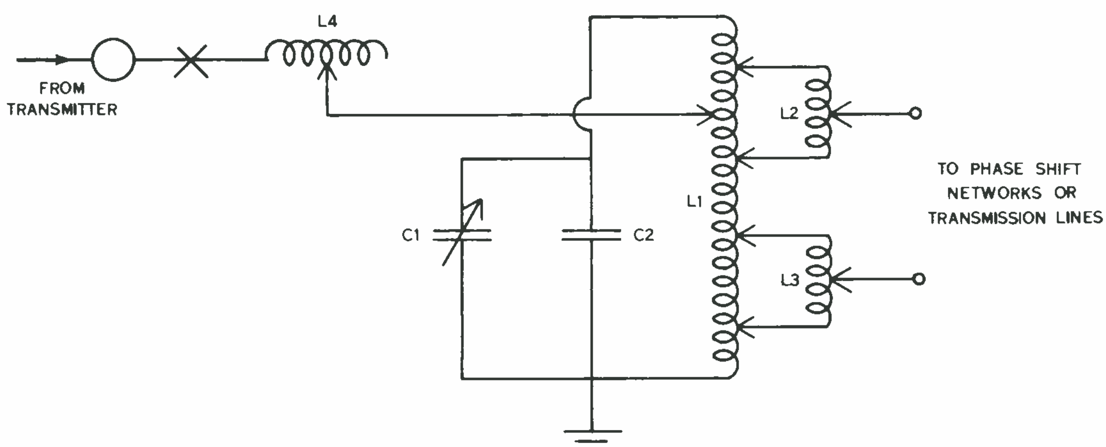


Fig. 7. Typical tank-type power divider.

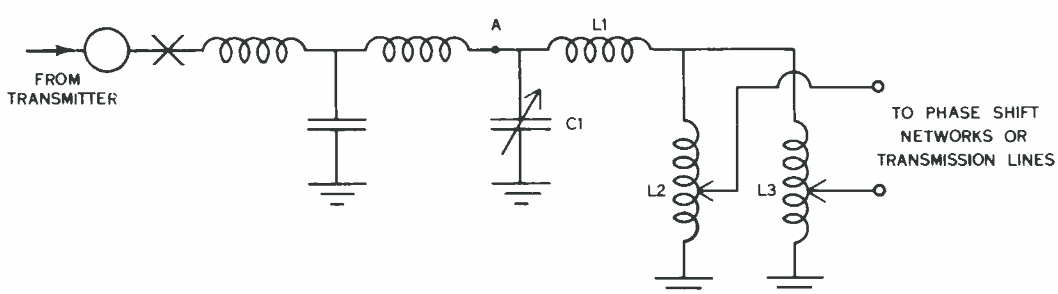


Fig. 8. Typical Ohms-Law power divider.

T Network Power Division

A phasor can be designed to exploit the input impedance of conventional T networks to achieve control of both power division and phase, as shown in Fig. 9. In such a system, each T network presents a load to the input junction which is appropriate to divert the required power to its corresponding tower.

Once such a phasor is properly adjusted, the small changes in phase and ratio that may later be required to maintain an array within tolerances are easily accomplished with very small adjustments in only the input and shunt arms of each individual tower network in the phasor. Although the phase and ratio adjustments interact (as with all phasors, due to the mutual coupling between towers), the shunt arms tend mostly to control power division, whereas the series input arms tend mostly to control phase. By noting which parameters are farthest out of tolerance, it is a simple matter to make small adjustments in the networks, observe the results of each change, and expeditiously restore such a phasor to the desired parameters.

Simplified Power Division

For two-tower directional systems, some very simple configurations can permit adjustment of both power division and phase shift with only two circuit elements. One such simplified system is a so-called "back-to-back" phasor; an example is shown in Fig. 10.

Components "C" and "L" are connected "back-to-back" at the output of the common-point matching network. In this example (which assumes matched transmission lines with resistive inputs), reducing L to zero would yield a current into transmission Line 2 that is in phase with the applied voltage, Eo. As L is increased, the current into Line 2 diminishes and lags the applied voltage. As L is varied from zero to infinity, the locus of all possible Line 2 currents is the semicircle on the lower half of the diagram. Similarly, as Capacitor C is reduced, the amplitude of the current in Line 1 is reduced and its phase is advanced relative to the applied voltage. The locus of all possible currents into Line 1, as C is varied from infinity to zero, is the upper semicircle of the vector diagram. The ranges of adjustment of C and L need only be sufficient to reach the desired phase and ratio parameters, not the entire semi-circular gamut.

Independence of adjustment of phase and ratio is completely lacking in a back-to-back design; yet the phasor is easy to adjust. If one wants to change the ratio, an arbitrary change is first made in either component, phase is restored to the initial valve by adjustment of the opposite component, and then the direction of ratio change is noted. It becomes a very simple cut-and-try process, not unlike that required to maximize transmitter plate efficiency by adjusting transmitter plate tuning and loading.

It is not always necessary to employ one coil and one capacitor in a back-to-back phasor.

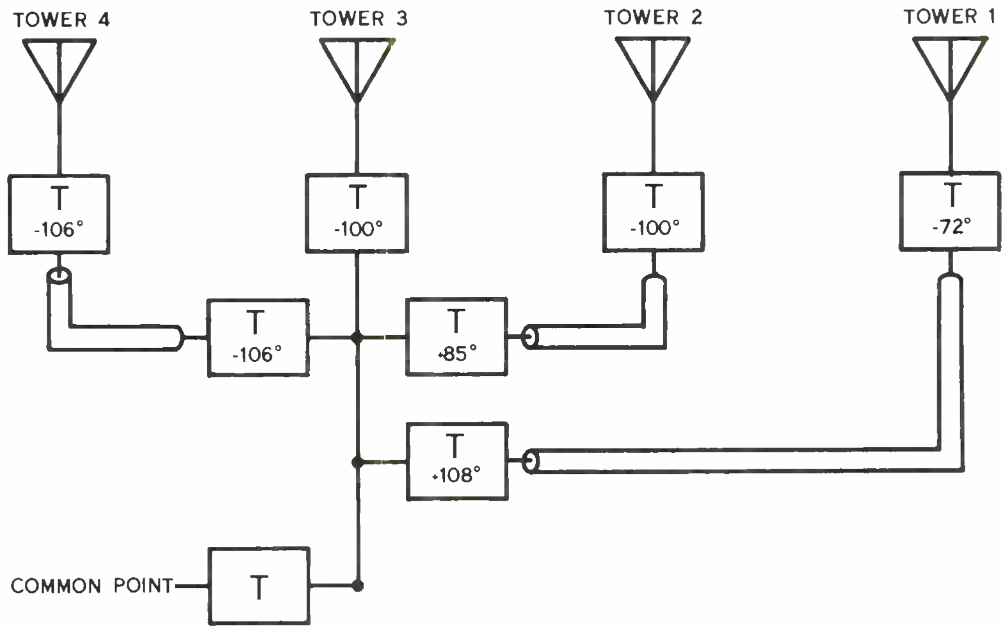


Fig. 9. Typical phasor with "T" net power division.

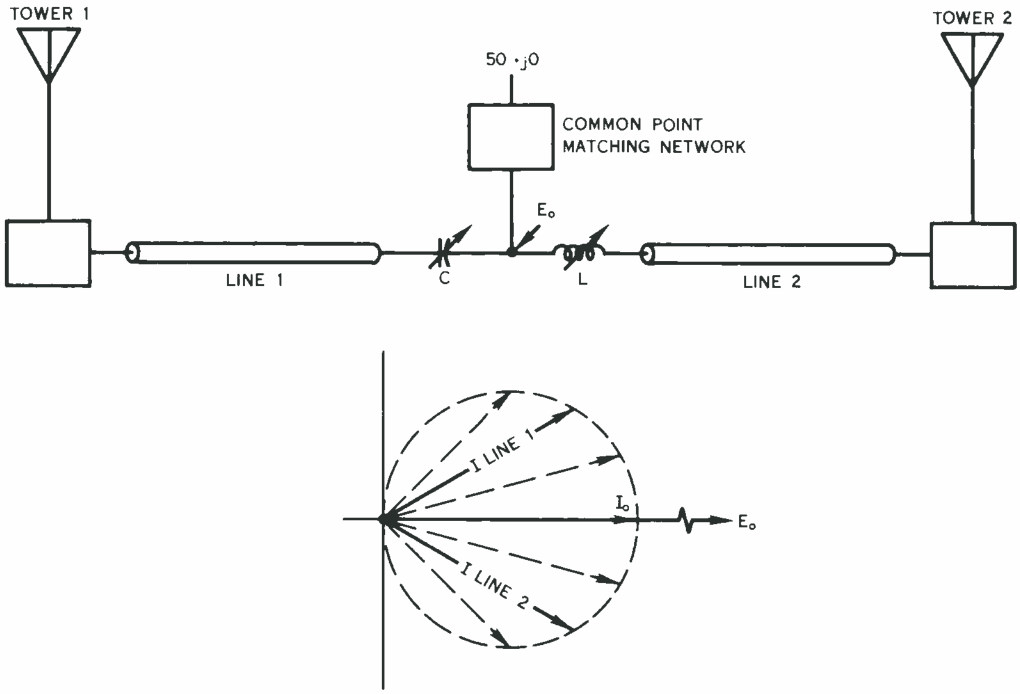


Fig. 10. Example of back-to-back phasor.

Often, the phase shift in the transmission lines and ACU networks can be tailored to provide the desired parameters with a series capacitor on the input to each line, rather than one capacitor and one coil. This arrangement permits a two-tower phasor in which both power division and phase adjustment are accomplished by only a pair of variable vacuum capacitors offering excellent stability and resetability. This arrangement also provides excellent impedance bandwidth.

TRANSMISSION LINES

Some of the requirements for AM broadcast transmission lines differ from those used in FM and TV installations; the similarities and differences are discussed below.

Line Losses

The losses in transmission lines at AM broadcast frequencies are largely in the copper, not in the dielectric. For this reason, and for mechanical convenience, semi-flexible foam-filled lines are the most popular. Air dielectric lines are needed only when power levels exceed the ratings of available foam-filled lines.

Jacketing

All lines should include a black polyethelene outer jacket. Unjacketed lines can result in inadvertent poor contacts to other metallic conductors, which can be a source of minute arcs that can cause spurious emissions. Jacketed lines are particularly suitable for direct burial. Burying the lines greatly reduces the daily and seasonal temperature extremes they encounter, yielding greater stability relative to above-ground installations.

Characteristic Impedance

A characteristic impedance of 50 ohms is the industry standard for transmission lines. Such lines can be expected to be more easily available than other impedances in future years, should a replacement line be needed. The velocity of propagation in transmission lines is less than the velocity in air. Therefore, the electrical length of any line is somewhat greater than its physical length. This increase must be considered in any phasor design. Typical values of transmission line velocity constants are listed below:

Obsolete solid-dielectric flexible lines	68%
Original foam-filled lines	79%
Low-density foam (LDF) lines	88%
Semi-flexible air dielectric lines	90-93%
Modern rigid copper lines	99.8%

Phase-Stabilized Line

In its first year, a new directional array will usually experience small drifts in phase and ratio parameters in directions that will not be repeated seasonally thereafter. This initial drift is caused by the minor mechanical stresses remaining in the line following manufacture and installation; these stresses are slowly relieved with temperature cycling. The result following installation is a small initial change in characteristics that will not be repeated. "Phase-stabilized" lines, which will reduce the initial drift, are available. Such lines have been temperature-cycled in an oven to relieve residual mechanical stresses. Within a year following installation, no observable difference in characteristics exists between regular lines and those that were initially phase-stabilized.

Transmission Line Fittings

All modern transmission lines can be equipped with EIA-standard flanged fittings to mate with connecting equipment. Although the impedance continuity of such fittings is essential at FM and TV frequencies, such fittings are unnecessary for antenna feeds at AM broadcast frequencies. However, adequate electrical bonds are essential between the transmission line conductors and the adjoining equipment.

Line Mismatch

At AM broadcast frequencies, the effects of a transmission line mismatch are quite different from the electrically-long transmission lines used for FM and television antennas, where mismatches can be reflected into a transmitter and cause crosstalk or ghosts. At broadcast frequencies, transmission lines are rarely longer than a wavelength. A mismatched transmission line yields an input impedance that is dependent on both the load impedance and the length of the line. Thus a transmission line can act as a simple impedance transformer and can be designed to exhibit a desired input impedance through proper choice of load impedance.

Perfect transmission line matches are not critical to overall system bandwidth. As long as the transmission line matches do not yield an input VSWR greater than approximately 1.5:1 at carrier frequency, the additional line losses due to the mismatch are usually trivial and the effect on overall system bandwidth is negligible. An exception occurs when the mismatch is on an unusually long line handling the greater part of the total power.

ANTENNA MONITOR AND SAMPLING SYSTEM

A directional antenna sampling system consists of current sampling transformers or sampling loops on each tower to provide a sample of the tower current, the transmission lines which return the samples, and an antenna monitor which measures the amplitude and phase of each sample relative to that of the reference tower.

Sampling Loops

A sampling loop consists of a rigid single-turn coil permanently attached to each tower. Because sampling system stability is essential, the loops are typically made of galvanized angle iron or rigid copper water pipe. The loops must be at least ten feet above ground and may be insulated from the tower and kept at ground potential. However, it is more common practice to use loops at tower potential and return the sample to ground potential through an isolation coil (iso coil) formed by coiling up the sampling coax so as to form a high impedance across the tower base insulator while not disturbing the current sample carried within the coax.

Sampling Transformers

An alternative method of obtaining tower current samples is to use shielded sampling transformers. These have much to recommend them if the tower heights do not exceed approximately 130 degrees. Although a transformer will sample both the current going up the tower and a lesser component that flows to ground through the base insulator capacitance, the sampling error is usually inconsequential. The advantages to using sampling transformers are extreme stability, a sampling device that is protected inside the ACU instead of being exposed to the weather, and the elimination of the iso coils that are otherwise usually required at each tower.

Sampling Lines

The transmission lines in sampling systems are usually cut to equal length and are buried. The surplus line from the closer towers is also buried so that a uniform environment for all lines minimizes the effects of temperature variation. Most sampling systems employ 3/8" diameter semi-flexible foam transmission lines. Although smaller diameter line is available, it is usually thought to be not sufficiently rugged for the hazards of direct burial and the wear and tear to be expected on those portions above ground.

Sampling System Stability and Accuracy

Sampling system stability is vital, but accuracy is not critical because the proper directional antenna pattern is determined by means of field strength measurements. The sampling system is required to detect changes from the original adjustments of indicated phase and ratio. The accuracy of a sampling system in measuring the absolute amplitude of radiation from each tower is inherently poor. Even though the sampling loops may be carefully adjusted so that each has exactly the same area in its single-turn coil and all are mounted at the same height, the samples will not be a measure of the relative radiation from each tower. The mutual impedances between towers seriously distort the sinusoidal current distribution which would otherwise exist throughout the height of each tower. Thus the indicated antenna monitor ratios are not an absolute measure of the relative radiation from each tower. The monitor ratios may also differ substantially from the base current ratios, particularly when the loops are a considerable distance above ground level. The indications of phase from a good monitoring system are relatively more accurate than the ratio indications.

DETUNING AND DECOUPLING SYSTEMS

Tower Sectionalization

Occasionally when it is necessary to use a tower that is too tall, sectionalization of the tower is

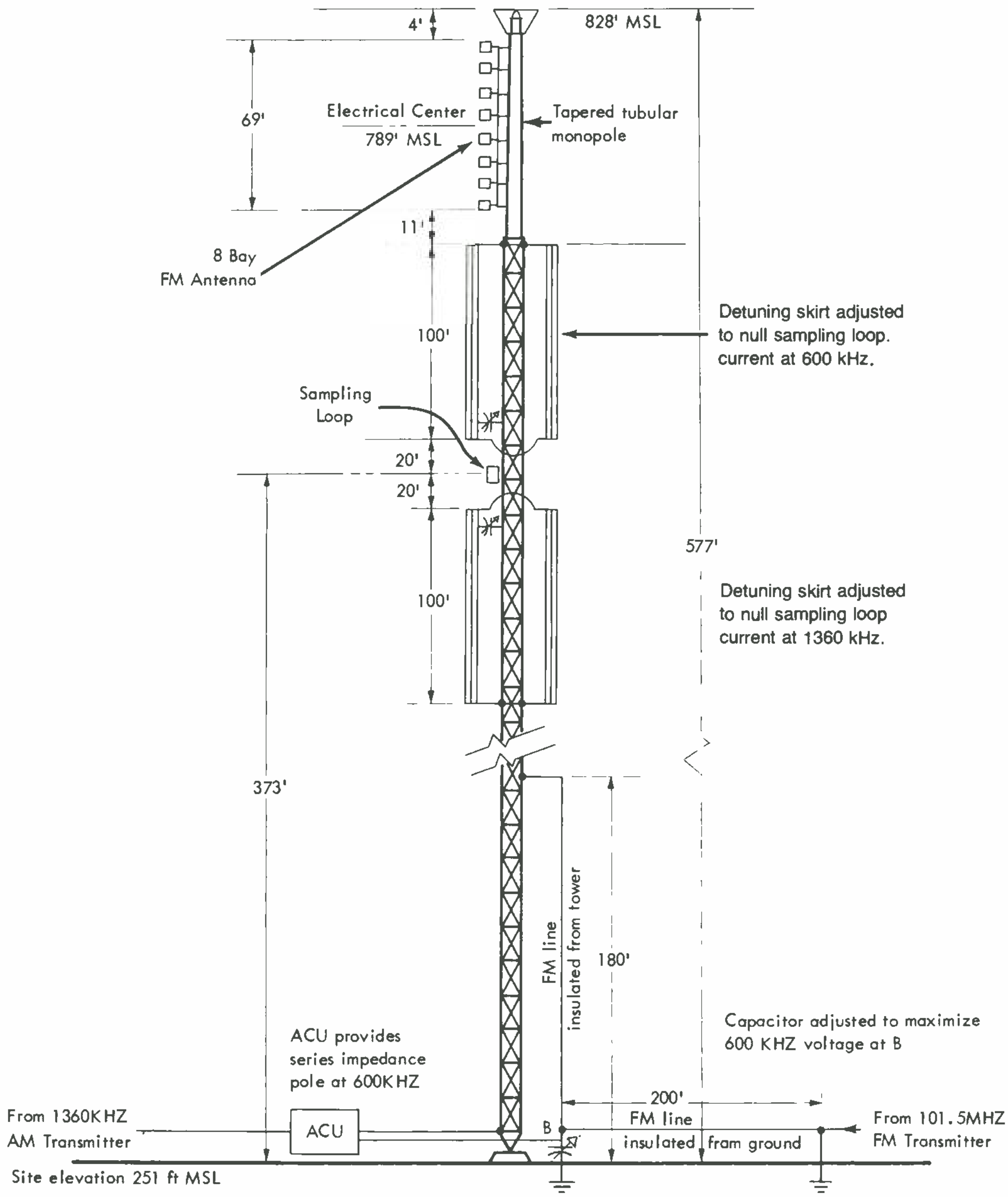


Fig. 11. FM tower sectionalized to make an efficient 1360 kHz radiator simultaneously detuned at 600 kHz.

required. For example, it may be desired to share an FM tower with an AM station. If the overall tower height were to exceed about 225 degrees at the AM frequency, the tower would be a poor radiator, putting more AM signal up into the sky than along the ground. The preferred solution for such a tall tower is to include insulators in the tower legs (and an isocoupler in the FM feedline at the same height) so as to open-circuit the tower at the height needed to make it a good AM radiator. A parallel resonant circuit (an impedance pole) across the insulators can then resonate the insulator and stray capacitances to effectively decouple the upper portion of the tower. In certain cases where structural considerations prevent the sectionalizing of a tower by means of insulators, a workable solution can be to use detuning "skirts" to decouple the top portion of the tower (Fig. 11).

A tower skirt, which is an insulated wire cage outside a tower, can be thought of as a shorted quarterwave coaxial transmission line which is slightly foreshortened and loaded with a capacitor at its open end for easy adjustment. The center conductor of the transmission line is the tower itself, with the outer conductor comprised of the skirt wires. All skirt wires are bonded to the tower at one end and can be connected in parallel at the other end so as to be tuned with a single capacitor. Adjustment of the skirt tuning places a high impedance at the open end of the skirt with the result that the tower is effectively open-circuited at the elevation.

The effectiveness of such a tower skirt in open-circuiting the tower is determined by the characteristic impedance and the losses in the transmission line section formed by the tower and the skirt wires. The most effective skirt will necessarily have a high Q, which will best decouple the top of the tower only at or near the carrier frequency. As a result, the tower base can exhibit a steep impedance versus frequency characteristic which can seriously impair the bandwidth.

Detuning Power Lines

The detuning techniques described above can also be applied to steel power line towers or to other tall metallic structures in order to reduce the radio-frequency currents in them, currents that would otherwise cause reradiation and distort the desired directional antenna pattern of a nearby radio station. Fig. 12 shows such an arrangement with each skirt wire on each tower leg separately tuned. In effect any radio frequency currents flowing up the power line tower are effectively balanced by the currents that are on the length of the skirt section and the number, diameter, and spacing of the skirt wires.

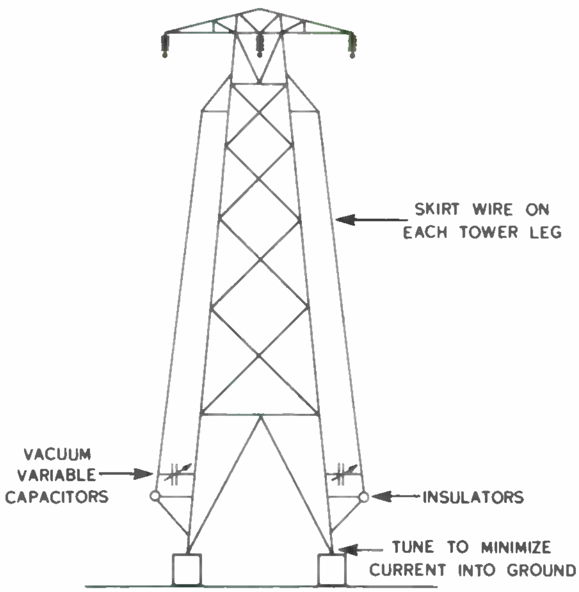


Fig. 12. Skirts used to detune power-line towers.

Floating Unused Towers

When stations operate with different tower combinations day and night, any unused towers must be placed in a nonradiating (floating) condition. If not adequately detuned, these towers will be parasitic radiators. Unused, insulated guyed towers a quarterwave high or less, can often be adequately detuned by simply disconnecting them at the base. More critical situations

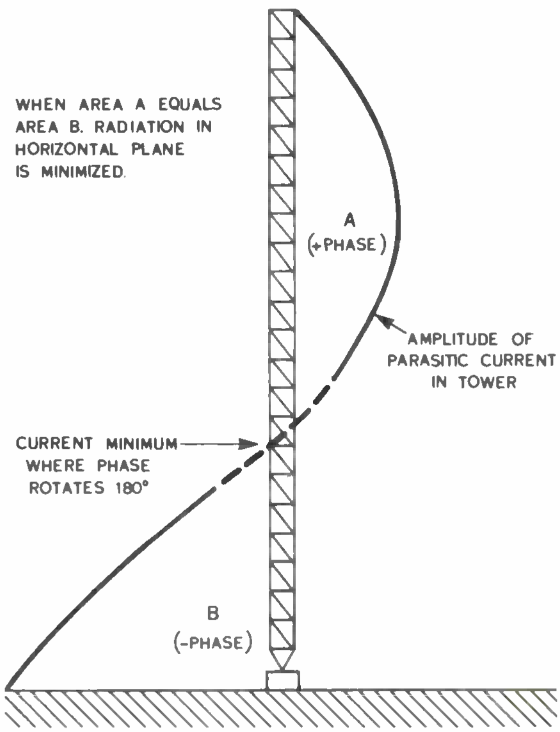


Fig. 13. Current distribution on detuned tower.

require a detuning inductance across the base to cancel the current to ground through the capacitance of the base insulator. Towers of any height can be effectively detuned (for reradiation in the horizontal plane) by placing a reactance across the base to achieve a tower current distribution as shown in Fig. 13.

Because there is a phase reversal at the elevation of minimum current, it is simply necessary to position a current minimum on the tower so that Area A equals Area B. In the horizontal plane, the radiation from the portion of the tower above the minimum will then cancel that from the portion below the minimum. Such a detuning method may still leave substantial amounts of reradiation departing the tower at high elevation angles. The most practical way to eliminate almost all reradiation is to subdivide the tower height into insulated sections (or skirted sections), each considerably less than 90 degrees high.

Filter Systems

If it is necessary to control the current distribution on a tower at a different frequency in order to avoid disturbing the pattern of a nearby directional station, a filter system is needed to permit control of the impedance shunting the tower base at the other station's frequency. The control should be independent of routine phasor adjustments. Such an arrangement is shown in Fig. 14 for each tower of a station operating on 630 kHz. The 630 kHz station must control tower current distribution at 950 kHz in order to protect the directional antenna operation of the nearby station on that frequency.

For filters in series with antenna feeds (such as the C3/L7, C4/L8 combination) it is important to provide an impedance zero at the pass frequency as well as the impedance pole at the reject frequency. Even when the pass and reject frequencies are widely separated, failure to provide the impedance zero with a reasonably low L/C ratio often results in excessive losses and impaired bandwidth.

Tower Current Minimums

For reasonably thin guyed towers of uniform cross-section, the required location of a current minimum on the tower to minimize reradiation (detune) in the horizontal plane can be calculated. Fig. 15 shows the proper null location to detune guyed towers of various heights. Placing current nulls at the proper height on towers to be detuned is a more straightforward process than attempting to achieve a detuned condition through analysis of field strength measurements.

Intermodulation

Filters to control spurious emissions resulting from intermodulation products generated within the final stage of a transmitter can have the same configuration as filters used to control tower-current distribution for a nearby station. Before such filters are designed, a knowledge of the frequencies that generate the intermod is essential. The second and third harmonic frequencies of a station can be involved in intermod products even though these harmonics themselves are suppressed to acceptably low levels when measured at the transmitter output. In the general case, an unwanted incoming signal from some other station can be coupled into the final amplifier through the antenna system to produce a spurious output frequency.

Effective filters can take the form of either traps to prevent an unwanted signal from getting

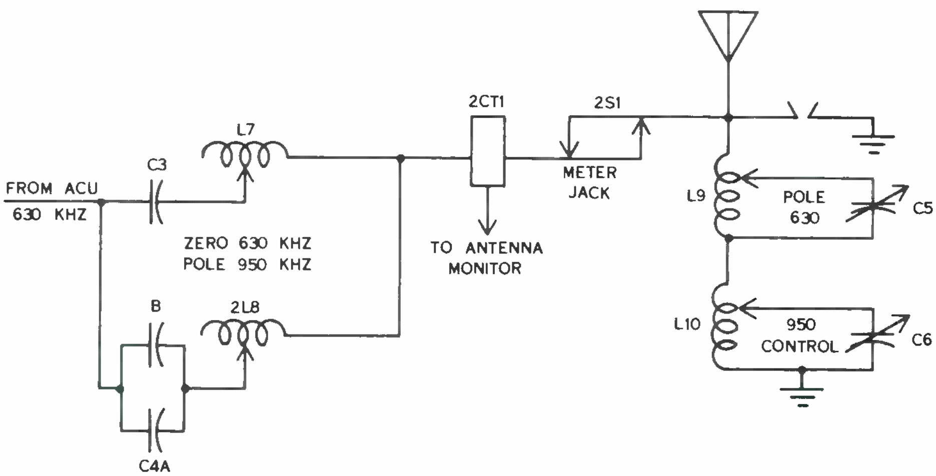


Fig. 14. Independent control of tower current distribution at a second frequency.

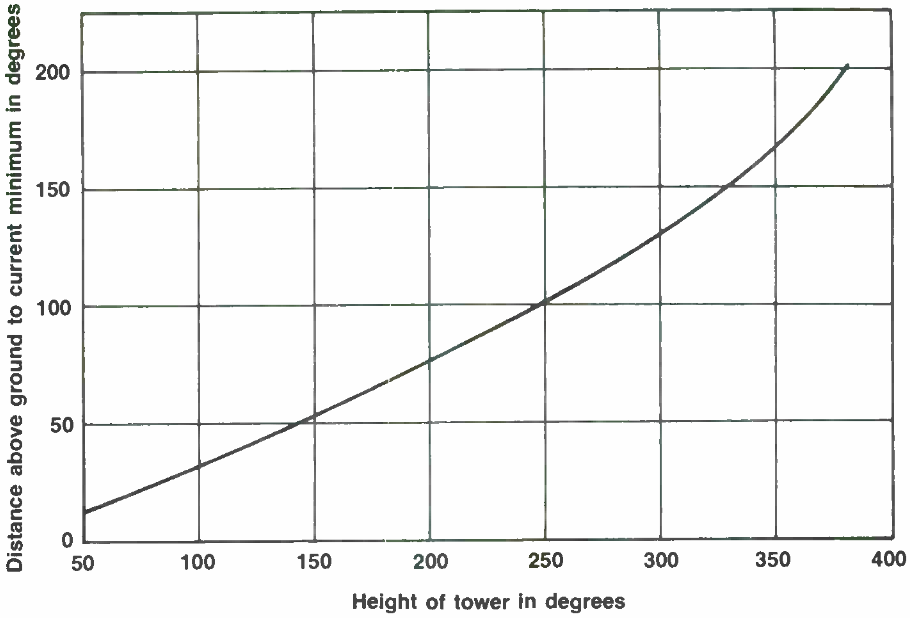


Fig. 15. Approximate height of required current minimum to detune guyed towers.

into the transmitter or traps to prevent the resulting spurious emission from getting out (or both). Filters can be series-resonant shunt elements that short the unwanted incoming signal (or the spurious emission) to ground, or they can be parallel-resonant elements in series with the transmitter output to present a high impedance to either the unwanted incoming signal or the spurious emission.

One clever and expeditious arrangement, when a single spurious frequency must be eliminated, is to modify the shunt arm of the common point matching network to consist of a series-resonant L/C circuit that simultaneously has a low impedance at the undesired frequency and the proper reactance at the station carrier frequency.

TRANSMITTER LOAD OPTIMIZATION

A transmitter will deliver equal power to both sidebands only if the sideband load resistances are equal. If the transmitter load VSWR at ±10 kHz from carrier is rather good (perhaps 1.2:1 or better), further adjustments to improved load symmetry may not be warranted. However, if the ± kHz sideband loads are rather poor (e.g., 1.5:1 or greater) sideband load symmetry can become a critical matter. Symmetry is achieved by adjusting the phase shift in the common-point matching network so that the load resistances at the ±10 kHz sideband frequencies are equal and the reactances are equal but opposite in sign as measured at the anode of the transmitter output stage.

Because different manufacturers use different output circuitry with different phase shifts and many have not published information as to optimum load orientation at the transmitter output terminal, the necessary measurements usually must be made on the load seen by the final amplifier plate. Fig. 16 shows the Smith Chart orientation for the two conditions that satisfy symmetrical loading requirements. The lower curve shows equal sideband resistances which are higher than at carrier; this orientation tends to emphasize the high frequency response. The upper curve also shows equal sideband resistances, but these are lower than at carrier; this orientation tends to show reduced 10 kHz distortion. Either of the two conditions is preferable to the intermediate conditions that yield asymmetrical load resistances at the two 10 kHz sideband frequencies.

DIPLEXERS AND MULTIPLEXERS

Two, three, or more AM stations can be combined on a single tower provided sufficient frequency separation exists between the channels and the electrical height of the tower is not unreasonably short or tall at any of the channels. Depending upon the transmitter characteristics, only 40 dB of isolation or less is typically required between the transmitters to avoid generation of spurious emissions and to permit completely independent operation. Diplexer adequacy is assured when each station

1. Has no objectionable spurious emissions.

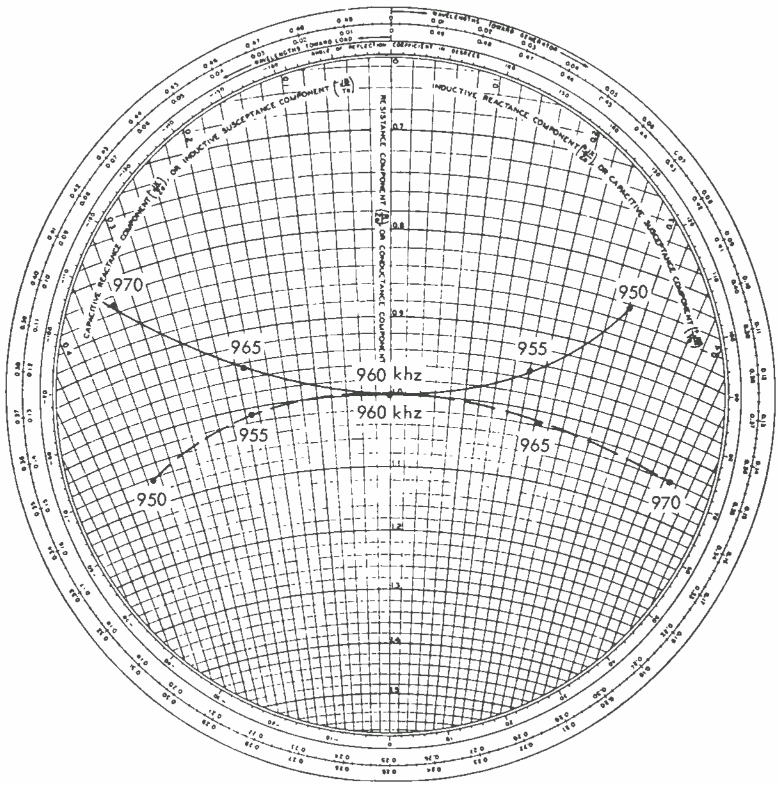


Fig. 16. Proper load impedance at final amplifier plate.

2. Can conduct an acceptable audio proof, including distortion and noise measurements, while the other station is in operation, and
3. Has no observable change in its indicated antenna current when the other station's transmitter is turned on and off.

The losses in diplexing and multiplexing filters can become crucial to a successful design. Since the tower impedance and required tower current at each frequency are known, the losses can be calculated with good accuracy. Capacitor losses are negligible. Coil losses can be calculated using an assumed coil Q of 200, which is a reasonable approximation for typical silver-plated RF inductors in shielded enclosures. Diplexer losses can be minimized if the reactive component of base impedance can be eliminated by means of shunt networks connected directly across the tower base. Then the shunt elements in the diplexing filters operate at lower voltage levels.

OVERALL SYSTEM PERFORMANCE

Directional antenna pattern design and phasor design go hand in hand. Given a poor pattern design, no amount of clever circuit design in the phasor can provide an excellent system. Following are considerations that can lead to an excellent antenna system.

In the Pattern Design

1. Avoid broadside minimums without ample spacing between towers; otherwise the driving point impedances can become very low.
2. Check to see that the individual tower radiation vectors add in-phase (or very nearly in-phase) in the pattern maximum; otherwise excessive circulating currents, poor bandwidth, and pattern instability can result.
3. Choose tower heights in the range of 100 degrees to 130 degrees when possible. Shorter towers exhibit lower driving point resistances and poorer bandwidth. Taller towers may require excessively large impedance transformations in the ACU networks; this condition can add another bandwidth limitation.

In the Phasor Design

1. Minimize reactive power (I^2X) in the phasor components. This will avoid high Q circuits

with their attendant frequency selectivity that limits bandwidth.

2. Avoid excessive use of series (trim) coils to adjust the reactance of fixed capacitors. Such coil/capacitor combinations necessarily have a steeper impedance versus frequency characteristic than a capacitor alone of the proper reactance exhibits.
3. Consider alternative phasor designs. The design with the fewest parts usually has the best bandwidth unless specific broadbanding circuits are incorporated.
4. Derate coil current ratings by 40 percent and mica capacitor current and voltage ratings by 50 percent. Remember that RF currents under heavy asymmetrical modulation can exceed 125 percent of the unmodulated current and that peak voltages can exceed 350 percent of the unmodulated RMS voltages. Vacuum capacitors are self-healing and need no derating.

A SIMPLE BANDWIDTH TEST

A simple test can evaluate the performance of the individual towers in an existing directional antenna system. The object is to determine the amplitude of each high-frequency sideband component as radiated by each tower. This test is possible with any common field strength meter because the selectivity of such meters is just sufficient to resolve sideband components that are 10 kHz removed from the carrier. The procedure is as follows:

1. Keep the sampling lines terminated into the antenna monitor, but add "T" connectors to bridge off samples into a field strength meter operating as a linear tuned voltmeter. Be certain the samples do not exceed the safe voltage input for the field strength meter.
2. Modulate the transmitter 50 percent with 10 kHz sinewaves. In a perfect system, this would result in sideband amplitudes equal to 25 percent of the carrier level in each tower.
3. For each tower sample, first adjust the field strength meter gain so as to set the carrier level full scale (100 percent). Then tune in each sideband in turn and log each sideband amplitude as a percent of full scale.
4. Repeat the process for each tower.

In the best antenna systems, all 10 kHz sideband components will range between 23 percent and 27 percent with 50 percent modulation at 10 kHz. Poor systems have been observed to have individual tower sideband components as low as 5 percent or as high as 40 percent in this test.

In the main lobe of a directional antenna pattern, deficient 10 kHz sideband amplitudes do not usually result in measurable distortion because the radiation components from the individual towers add approximately in phase and the sideband deficiencies of any one tower are masked by the sum total of radiation from all of the other towers. However, the test is useful in pinpointing limitations in existing systems.

SAMPLING SOURCE TO FEED A MODULATION MONITOR

The indications of a modulation monitor may be inaccurate at high modulation frequencies if its modulation sample is taken from a less than perfect antenna system. In an antenna system with a high VSWR at the 10 kHz sidebands, the voltage sampled for the modulation monitor may be higher or lower at the 10 kHz sidebands than at low modulating frequencies.

The best measure of 100 percent modulation is at a remote point in the main lobe of the antenna pattern. Various sampling points within the transmitter or phasor can be tried until a sample source is found that matches the percentage modulation at high modulating frequencies observed in the far field of the main lobe.

CONCLUSION

When the complexities in the design of directional antenna patterns and circuitry are considered together, the need for specialists in this field is evident. However, these chapters should have increased the reader's understanding of the complexities and thus assisted in the design and construction of excellent AM directional antenna systems.

2.4

AM Broadcast Antenna Systems

CHAPTER 2.4:
Part I: System Design
Part II: Phasing, Coupling
Part III: Maintenance

Part III: Maintenance of AM Broadcast Antenna Systems

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Many stable directional arrays, being electrically passive devices, operate for 10 or more years without any readjustment. However, maintenance attention will be needed to overcome the normal effects of age and deterioration (routine maintenance), to restore proper operation after catastrophic failures (such as caused by lightning), and to cope with new sources of reradiation that may develop within the environment in which the antenna system operates. Infrequently, readjustment and relicensing with new pattern parameters may be required.

ROUTINE MAINTENANCE

Routine mechanical and electrical maintenance is required to offset the effects of age and deterioration. Mechanical maintenance includes the attention necessary to keep the moving parts functioning and the tower painted and in good repair. Electrical maintenance may involve replacement or recalibration of base current meters; checks on the continuing proper performance of the phasor components, transmission lines, and ground system; and infrequent readjustment of the antenna phase and ratio parameters as necessary to assure operation within licensed limits and to maintain the proper directional antenna pattern.

Mechanical Maintenance

The moving components within an antenna system may include RF relays, meter switches, dial drives, and the rollers on variable coils.

The contacts on RF relays that carry substantial currents may eventually wear out and require replacement. It is vital that such relays be interlocked so they cannot be switched while transmitter power is applied. Relay maintenance problems are greatly reduced when vacuum relays are employed.

Meter switches that disconnect thermocouple-type ammeters from the circuit when not being read are subject to considerable mechanical wear and tear. Occasional lubrication and tightening of the components are necessary if the parts are to function properly. Replacement of thermocouple ammeters with modern transformer-type meters eliminates the need for RF meter switches and their associated maintenance requirements.

Dial drives on variable coils and capacitors, once properly adjusted, require little attention except infrequent lubrication. The thrust bearings on vacuum variable capacitors are factory lubricated and do not require maintenance attention. However, the rollers on variable coils are often a source of mechanical difficulties (particularly in older coils) and periodic maintenance is required if they are to operate smoothly and without arcing. Networks that are designed to utilize variable capacitors instead of variable coils are superior in this regard.

Electrical Maintenance

Thermocouple RF ammeters that measure base currents and common-point currents are a frequent problem due to failure or changes in calibration. If such meters cannot be replaced with modern transformer-type units, an intermediate improvement can be effected by substituting make-before-break meter jacks at the base of each tower (in lieu of the original permanent thermocouple meters and associated protective switches). The meters can then be stored in a dry environment and taken to the towers only when base current readings are required. The effects of calibration errors are reduced if the same meter is used to measure all base currents (provided all currents fall within an acceptable range on the meter scale).

Thermocouple ammeters can be calibrated with 60 Hz current. A useful procedure is to remove all such meters from the system and connect them in series for testing. A high-quality dynamometer or soft-iron-type meter should also be included as a calibration standard. A filament transformer having adequate secondary current rating can be used to drive current through all of the meters connected in series. Current amplitude is easily controlled by supplying the filament transformer from an adjustable ac supply such as a Variac.

Modern current-transformer RF ammeters cannot be calibrated with 60 Hz and, if defective, must be returned to the manufacturer for repair and recalibration. The transformer, meter, and interconnecting cable are calibrated as a unit. The cable length should not be changed without recalibration by the manufacturer.

Occasionally loose connections or deteriorating phasor components will produce abnormal heating. Failures from these causes can be anticipated by simply feeling all RF connections and components for warmth immediately after sign-off.

Transmission Lines

Air or foam dielectric lines in continuous lengths rarely develop troubles, but pressure must be maintained on air dielectric lines in order to prevent the accumulation of moisture. Breaks in the outer conductor of foam-filled lines that are buried may cause obscure symptoms and prove difficult to locate. In extreme situations, a time-domain reflectometer is the best tool to pinpoint the problem.

Ground System

Significant deterioration of a ground system can manifest itself in two ways. The first indications may be unusual changes in the phase and ratio parameters between wet and dry conditions. These changes depend upon the nature of the directional array and the character of the ground. When ground systems are installed in shallow tidewater or saltwater marshes, the inherent ground conductivity is so good that even drastic changes of the ground system may produce negligible effects.

A second, more obvious symptom of a deteriorating ground system is a reduction in antenna radiation and a reduction in base currents. It is not uncommon in older arrays to find that the absolute value of each base current has fallen off since the time of the initial installation, even though the base current ratios remain correct. With the available common-point power remaining constant, any increase in ground system losses must necessarily reduce the base currents.

It is essential that all joints in a ground system be made by brazing or silver soldering. Soft solder consisting only of lead and tin deteriorates quickly when buried.

The existence and continuity of buried ground radials is best checked by using an underground cable locator of the type used by utility companies to locate buried cables and pipes. These devices consist of a transmitter, which can be located at the tower base to place a modulated low-frequency signal on all connected ground wires, and a receiver that detects the unique modulation. While in use, the receiver can be carried in a circle with a radius of 100 feet or more about each tower, so that the radial wires that are intact can easily be detected and counted.

Alternatively, if a cable locator is not available, a shielded pick-up loop held near the ground and connected to the external input of a field strength meter may suffice to detect the current in individual radial ground wires. Even when a radial is broken, the current beyond the break tends to concentrate in the wire instead of the adjacent earth. A most definitive check is to uncover the distant ends of adjacent radials and check for continuity between them with a dc ohmmeter.

Towers

Towers require occasional attention to assure their structural integrity. Periodic inspections by an experienced tower contractor are desirable. Guyed towers should be checked to confirm that they are straight and plumb and that the guy tension is correct. Towers with tubular legs can rust from the inside out; a close inspection is necessary to detect this condition while repairs are still feasible. Towers with solid legs avoid the hazards of internal rust. Galvanized towers must be painted only if required for aeronautical safety. Nongalvanized towers should be avoided, not only because rusting makes the maintenance problem more severe but also because of their inferior electrical conductivity.

Lightning strikes and target shooters may destroy guy-wire insulators. Such failures can usually be discovered with the aid of field glasses or a telescope. The electrical field gradient can be very high adjacent to a tower, particularly near the top. Arc-overs and corona can be avoided by cascading guy-wire insulators (johnny balls) immediately adjacent to the tower. Under severe conditions, fiberglass rod insulators or dielectric guy cables are a preferred solution. In an existing system with marginal insulation, any dirt or salt deposits on the insulators may cause corona and arc-overs. Washing the insulators and coating them with silicone grease may provide a temporary remedy.

SUDDEN COMPONENT FAILURES

The most common cause of component failure in a well-designed antenna system is lightning damage. Ideally, lightning which strikes a tower should be conducted directly to ground through the ball gap that is typically part of each tower installation. However, lightning has been known to destroy components in what appear to be well-protected systems. Such components can most usually be located by a careful visual inspection.

Lightning currents flowing through adjacent coil turns tend to collapse them; therefore, coils should be inspected to confirm that all turns are in their original uniform alignment. The forces generated by lightning traveling through the coil strap and clip on a ribbon coil may dislodge the clip and leave the strap hanging in nearly its original position. Careful visual inspection is needed to locate dislodged coil clips.

Although vacuum capacitors are usually self-healing if subjected to minor over-voltages that cause internal arcing, the extemely high currents from a lightning strike can melt the plates together and short the capacitor, necessitating replacement.

If lightning damage is a recurring problem that warrants additional protection, the following steps are suggested:

1. Check the ball gap at the tower base. The balls should be arranged side-by-side so that dirt and water will not bridge the gap with the first rain of the season. The balls should be on the same radial line through the tower axis because towers tend to twist in high winds; this twisting

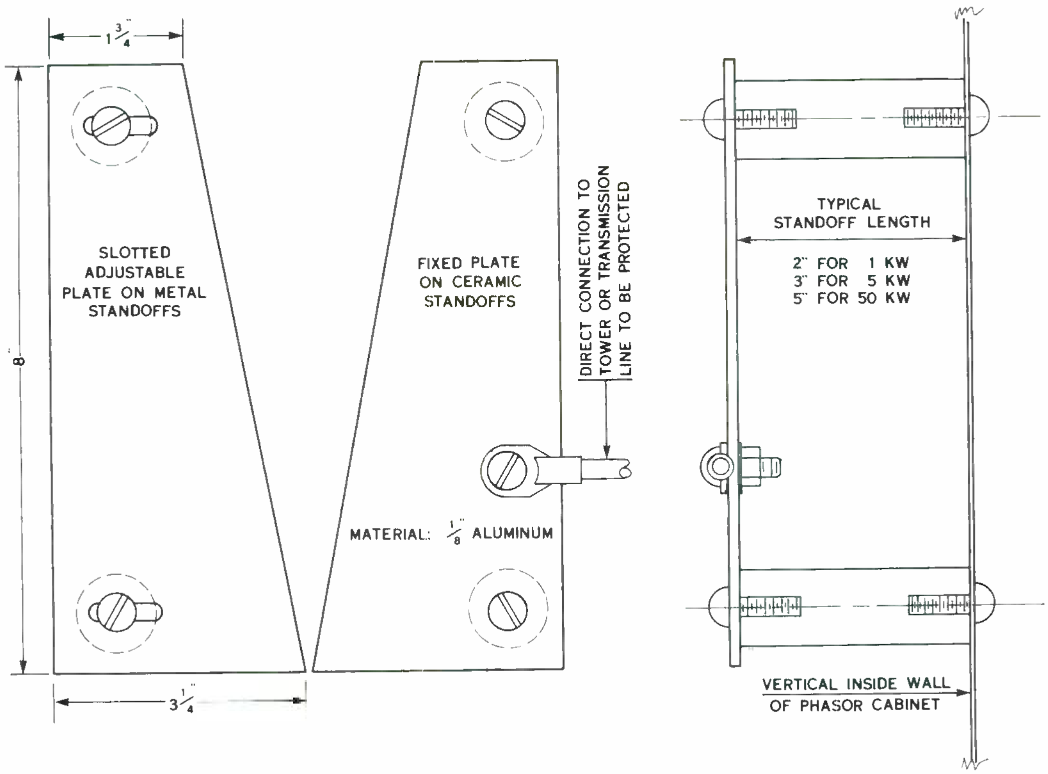


Fig. 1. Suggested lightning gap design.

could otherwise change the gap between the balls. The gap should be as narrow as possible.

2. Provide a two-or-three turn choke coil in the RF feed from the antenna coupling unit (ACU) to the tower if one is not already installed. The coil can be from 3 to 10 inches in diameter depending on the station power level and the feedline size. Its function is to present a high impedance to lightning strikes so they will jump the ball gap rather than enter the ACU. Readjustment of the output arm of the matching network will be required to offset the added lightning choke inductance.
3. Provide a horn-type lightning gap within the ACU similar to the design shown in Fig. 1. The relatively clean, dry, and insect-free environment inside the ACU permits a tighter gap setting and increased lightning protection than can be accomplished with an exterior gap. The path for lightning currents from the tower to the gap within the ACU should be very direct with minimum inductance and no sharp bends.
4. Lightning gaps, similar to those described in Step 3, can be installed at both ends of all transmission lines to help prevent lightning currents from getting into the phasor.
5. Adjust each gap individually by reducing the spacing until it arcs on the heaviest modulation peaks. The spacing should then be doubled for the permanent adjustment. This will be a much smaller gap spacing than is usually encountered on external gaps at the tower base.
6. Check to see that there is a dc path from each tower to ground, either through a phase sampling isolation coil, a separate static drain, a spare winding on a tower lightning choke, or the network circuitry within the ACU itself. Without a static drain, static charges may build up on a tower and will then discharge with small arc that may be sufficient to trip protective circuits and take the transmitter off the air.

ENVIRONMENTAL CHANGES

The ideal environment for a directional antenna system is a flat plane of high conductivity with no tall structures in the general vicinity, such as buildings, power line towers, water tanks, or oil wells. Such structures (or any metallic objects of substantial vertical dimension) will have currents induced in them, currents which are dependent upon the size and shape of the structure, the frequency, and the ambient field with which they are illuminated. The currents in such objects make them parasitic antennas. The resulting reradiation can distort the pattern of a directional antenna array.

Reradiating objects located in the main lobe of an antenna pattern are of greater consequence than those located in or near pattern minimums where their illumination is substantially less. The reradiation from reasonably slim electrically short objects (where the overall height is substantially less than a quarter wavelength) can be calculated with useful accuracy by means of the approximate formula shown in Fig. 2.

If feasible, a more accurate assessment of the reradiation can be obtained by measuring the RF current flowing in the reradiating object. If the object is reasonably thin (such as a guyed communications tower, a cable television headend tower, or the four individual legs of self-supporting power line towers) measurement of the current flowing from the tower to ground is not difficult. For this measurement, a toroidal pickup coil formed by the spiral steel wire in a length of clothes-dryer exhaust hose (or even better, some types of vacuum-cleaner hose) is useful. The hose section should be long enough to encircle the tower or current-carrying conductor to be measured and to have its ends attached to a field strength meter operating as a linear voltmeter. Such a pickup coil can be calibrated by encircling a conductor carrying a known current, such as the base of a radio tower.

It is not necessary to measure the current distribution throughout the height of electrically short objects. The current distribution can be assumed to be triangular, decreasing to zero at the top of the tower if it is freestanding; or the current can be assumed to be uniform throughout the entire height of the tower as a worst-case assumption where power-line towers exhibit heavy toploading due to the capacitance to ground of the conductors they support. Once the current is measured the reradiation can be calculated by relating the "ampere-feet" of current in the reradiator to the ampere-feet of current in a quarterwave tower at the same frequency which typically produces an unattenuated radiation of about 300 mV/m at one kilometer with one kilowatt of power.

The techniques for detuning reradiating objects are the same as those described in the previous chapter for detuning unused towers within a two-pattern directional array.

READJUSTING AN ARRAY

Any readjustment of a directional antenna array should be undertaken only by personnel who have a basic understanding of directional antenna theory and practice. At the minimum, the

$$E_r = \frac{E_i \dfrac{\cos G - 1}{\cos G}}{6{,}282\,(ln \dfrac{2h}{a} - 1)}$$

Where: E_r = Reradiated field in mV/m at 1 km
E_i = Incident field in mV/m at location of raradiator
G = height of reradiator in electrical degrees
h = height of reradiator in meters
a = effective radius of reradiator in meters
ln = natural logarithm

Fig. 2. Approximate formula for calculating reradiation

material in the preceding two chapters should be read and understood. Before any array adjustments are attempted, considerable information needs to be collected and analyzed.

Four conditions to proper array performance are explained below. All of these conditions should be met simultaneously in normal operation.

1. The antenna monitor indications should be within the FCC tolerances of five percent for tower current ratios and three degrees for phase. A special case is a "critical" array which has been assigned tighter tolerances by the FCC.
2. Changes in base current ratios should be consistent with changes in antenna monitor ratios. Although the base current ratios and antenna monitor ratios are rarely in exact agreement (and will differ greatly in arrays with unequal height towers), these ratios should change by essentially the same percentage for incremental changes in the actual base current ratios. In other words, when the monitor indications match those shown in the license or the most recent proof, the base current ratios should also match what is shown in the same license or proof. Discrepancies are an indication of changes in the sampling system or in the base current metering and should be investigated.
3. The reradiation environment must be essentially unchanged from that in which the array was last in proper adjustment. Any substantial structures such as power-line towers or steel-frame buildings constructed recently in the vicinity of the array, particularly in the main lobe of the pattern, can cause trouble. Grounded structures a quarterwave high can distort critical antenna patterns even if located one or two miles away in the main lobe of radiation.
4. The monitoring points should be within the limits shown on the station license. A high monitoring point may result from a changed environment due to the construction of buildings or power lines near the monitoring point. If a high monitoring point does not correlate with observed changes in antenna monitor parameters, the point is suspect and should be checked by measuring and analyzing 10 or more of the other points on the same radial that had been measured and recorded in the most recent proof or partial proof. Readjustment to reduce excessive radiation is indicated only if the analysis of 10 or more points confirms that the radiation is in fact in excess of the standard pattern limit.

Soil Conductivity

The analysis of a radial may be misleading due to changes in soil conductivity. Increased soil conductivity during wet seasons may cause substantial increases in signal strength at distant measuring points when compared to the same measurements during dry seasons. This phenomenon varies with distance, with season, and differing geographical regions. These effects may not exist in some regions, but in extreme cases may show 2:1 changes in field strength at a distance of 20 miles. Soil conductivity variations can be eliminated by comparing the present ratio of directional to nondirectional field strength at each measurement point to the same ratio in previous complete or partial proofs.

Because new nondirectional measurements may be needed at a future date, it is highly desirable to incorporate in the phasing system at least some simple manual switching capabilities to permit reversion to nondirectional operation at those stations which do not normally have a licensed nondirectional mode.

Readjustment Data and Analysis

Directional antenna arrays vary so much in pattern shape, suppression requirements, and phasor circuitry that precise readjustment instructions cannot be described. If possible, the consulting engineer who adjusted the array before its last proof of performance should be consulted on the problem. The following guidelines should prove helpful:

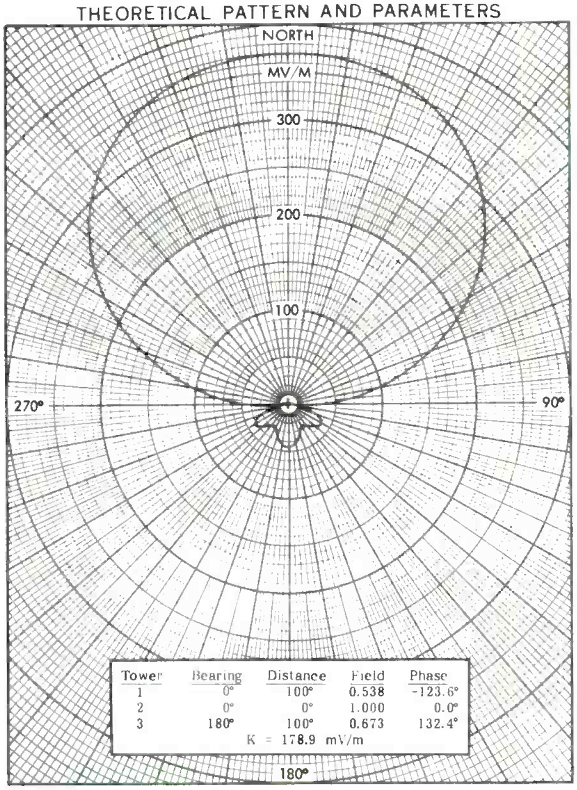
1. Carefully log all dial settings and all coil tap locations before making any changes.
2. Keep in mind what you are trying to accomplish before twisting any knobs or changing any coil taps.
3. Make changes only in small increments, typically never more than about one degree or one percent in phase or ratio.
4. Keep a step-by-step record of each change as it is made so that the array can be restored to initial conditions, if necessary.
5. Remember that even small adjustments of phase or ratio can have a measurable effect on the common-point resistance. The power fed to the antenna system is only correct if the common-point resistance and current are essentially correct. A permanently installed common-point operating impedance bridge is a convenience not only for keeping track of the common-point impedance during adjustments but also for continuing confirmation of the licensed common-point value in day-to-day operation.
6. Construct vector diagrams for each important direction. Samples of such diagrams are shown in Fig. 3. The phase relationships must include both the electrical phase of the currents fed to the towers and the space phase component for each tower relative to the reference tower as viewed in each direction. Such diagrams will assist in visualizing what effect any contemplated changes in phase or ratio for any tower will have on the resultant field in each direction. The vector diagram amplitudes may be in terms of the individual tower field ratios (such as in Fig. 3) or in terms of the theoretical unattenuated radiation. The theoretical unattenuated radiation from each tower (expressed in millivolts-per-meter at one kilometer or one mile) is obtained by multiplying the theoretical pattern field ratio for each tower by the pattern constant K, which is also usually shown in each theoretical pattern.
7. If the pattern includes essentially zero minimums (which need to be as deep as possible), make "talkdown" adjustments at a series of the most distant points on the null radial from which adequate two-way communications can be obtained. At each talkdown location, adjust the phasor for any combination of tower currents and phases that gives the deepest possible minimum. (A deep minimum can usually be confirmed by rotating the field strength meter 90 degrees on a vertical axis and noting that the signal received from scattered reradiators is stronger than that received from the station when the meter is in its normal measurement orientation.)

   Construct the vector resultant for each talkdown on a vector diagram similar to that shown in Fig. 3, but use the antenna monitor indications of phase and ratio instead of the theoretical parameters. The vector resultant will probably not be zero because of errors in the antenna monitoring system, non-sinusoidal current distribution on the towers, and reradiation from objects external to the array. However, the resultants so plotted from a series of talkdowns along a radial will enclose an area in which the optimum adjustment has its vector resultant at its center. Knowing the desired resultant for each critical radial direction, one may then be able to infer a set of phase and ratio parameters to satisfy all conditions simultaneously.

For simple arrays, a more pragmatic, although less scientific approach (but one that often yields effective results), is to station observers with field strength meters at each of the several monitoring points or other critical directions. By using a two-way radio to learn the effect on field strength, cut-and-try adjustments of the phasor can yield a set of phase and ratio parameters that satisfy all conditions simultaneously.

Following readjustment, if any of the new phase and ratio parameters exceed the three degree phase and five percent ratio tolerances permitted by the FCC when applied to the parameters shown on the current station license, a partial proof-of-performance will be required before the FCC will license the new parameters. If the new parameters are within tolerance of the licensed values, a partial proof and application for changed parameters may still be desirable in order to avoid long-term operation uncomfortably close to the tolerance limits.

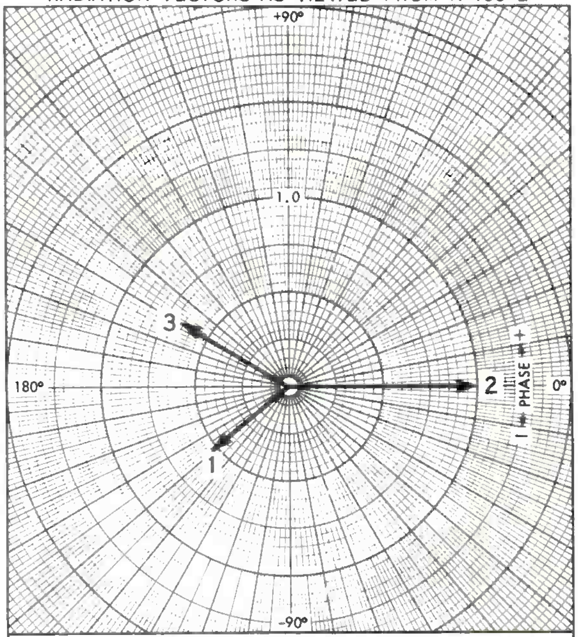
THEORETICAL PATTERN AND PARAMETERS



Tower	Bearing	Distance	Field	Phase
1	0°	100°	0.538	-123.6°
2	0°	0°	1.000	0.0°
3	180°	100°	0.673	132.4°

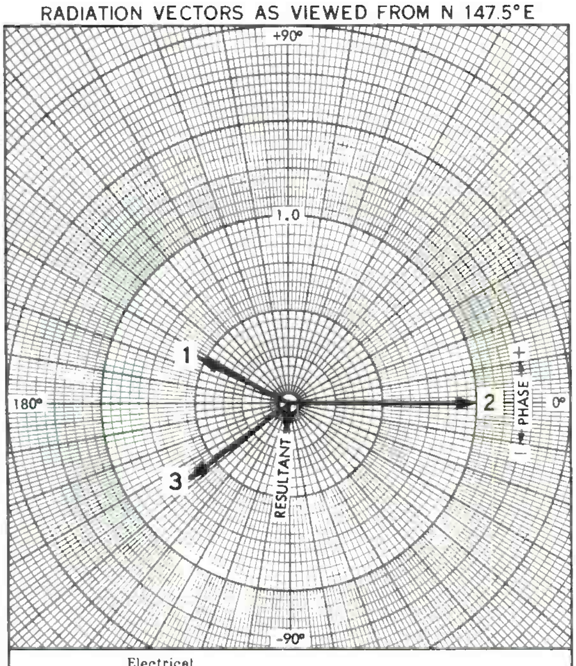
K = 178.9 mV/m

RADIATION VECTORS AS VIEWED FROM N 100°E



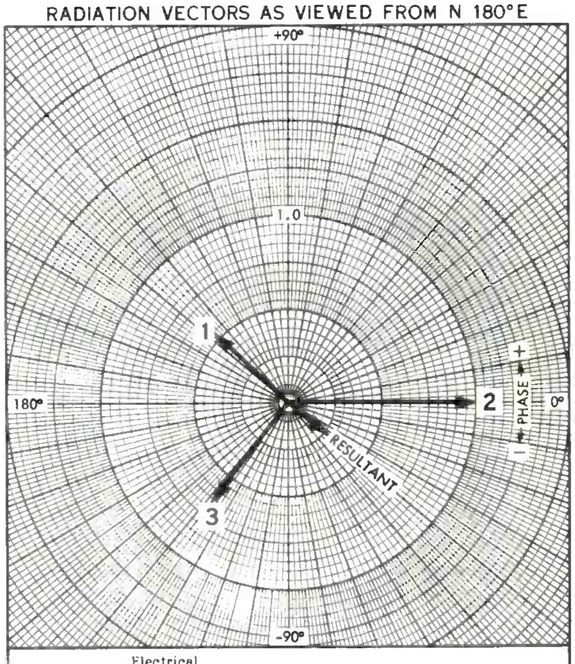
Tower	Field	Electrical Phase	Space Phase				
1	0.538	∠-123.6°	+ 100° cos100°	= 0.538	∠-141.0°	= 0.418	-j0.339
2	1.000	∠0.0°	+ 0°	= 1.000	∠0.0°	= 1.000	j0
3	0.673	∠132.4°	- 100° cos100°	= 0.673	∠149.8°	= 0.582	+j0.339
					Resultant	= 0.0	j0.0
						= 0 ∠0°	

RADIATION VECTORS AS VIEWED FROM N 147.5°E



Tower	Field	Electrical Phase	Space Phase				
1	0.538	∠-123.6°	+ 100° cos147.5°	= 0.538	∠-207.9°	= -0.475	+j0.252
2	1.000	∠0.0°	+ 0°	= 1.000	∠0.0°	= 1.000	j0
3	0.673	∠132.4°	- 100° cos147.5°	= 0.673	∠216.7°	= -0.540	-j0.402
					Resultant	= -0.015	-j0.150
						= 0.151	∠-95.7°

RADIATION VECTORS AS VIEWED FROM N 180°E



Tower	Field	Electrical Phase	Space Phase				
1	0.538	∠-123.6°	+ 100° cos180°	= 0.538	∠-223.6°	= -0.390	+j0.371
2	1.000	∠0.0°	+ 0°	= 1.000	∠0.0°	= 1.000	j0
3	0.673	∠132.4°	- 100° cos180°	= 0.673	∠232.4°	= -0.411	-j0.533
					Resultant	= 0.199	-j0.162
						= 0.257	∠-39.1°

Fig. 3. Tower radiation vectors as viewed from different azimuths.

2.5

Antennas For FM Broadcasting

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This chapter is dedicated to broadcast engineers, technicians, and station managers who must make important decisions regarding FM transmitting antennas. To insure the best possible signal strength in the station's service areas, the site location, antenna height, antenna type and propagation conditions must all be considered.

FM broadcasting was first authorized in the United States in 1940 by the Federal Communications Commission (FCC). The first FM station began operation in 1941. In 1945 the FM service was assigned to the 88 to 108 MHz band and divided into 100 channels, each 200 kHz wide. The projection is that by the first of January, 1986, there will be 5,600 FM stations in the United States, not counting over 1,000 FM translator stations.

About 99 percent of their antennas are nonsymmetrical, that is they are mounted on one side of a steel supporting tower or pole. FM antennas outside the western hemisphere on the other hand are usually symmetrical, that is installed on all faces of a tower. Both methods are capable of providing excellent onmidirectional azimuth patterns.

Antennas for FM broadcasting use horizontal polarization (Hpol), vertical polarization (Vpol) or circular polarization (Cpol)*. Cross polarization is used as a means to prevent co-channel interference in some European countries but not in the western hemisphere. Cpol together with its special form, elliptical polarization (Epol) was introduced in the United States in the early 1960s as a means to provide greater signal penetration into the many different forms of FM receiving antennas, which are now found in the service area. As of this writing, Hpol is standard in the United States, but Cpol or Epol may be used if desired.

Receiving antenna types have proliferated as have receivers. In the 10 year period between 1973 and 1983 there were 276 million FM radios sold in the United States, of which 54 million were automobile AM-FM radios.[1]

Antennas for FM broadcasting must be chosen carefully, in order to cover the service areas properly, with adequate level and quality signals. For economic and technical reasons effective radiated power (ERP) should be produced with a proper balance between antenna gain and transmitter power. It is the purpose of this chapter to provide sufficient technical information for the broadcaster to achieve this.

The height of the antenna over the service area, distances to areas of population, the ERP, and the economics are items that must be considered.

*Hpol, Vpol, Cpol and Epol are unofficial abbreviations used for clarity & brevity in this chapter.

[1]EIA Consumers Electronics Annual Review, 1983. Electronics Industry Association, 2001 Eye Street, N.W. Washington, D.C. 20006.

Antennas currently available in the United States differ considerably from those to be found in Europe. The various American types are discussed so that the engineer will be informed on the subject. Considerable advances have been made in recent years in the design and fabrication of FM antennas. These improvements provide greater penetration of signals into automobile FM radios as well as popular small FM transistor radios of all kinds.[2] The newer FM broadcasting antennas must meet the more stringent requirements for FM stereo and quadraphonic broadcasting.[3]

Circular polarization for FM broadcasting has come of age. About 98 percent of United States FM stations are now using Cpol antennas, while an estimated 75 percent in Latin America use this type.

PROPAGATION

FM broadcasting has some distinct advantages over AM (medium wave) broadcast service. These advantages stem from the propagation characteristics of FM frequencies as well as the modulation system.

There is essentially no difference between day and night FM propagation conditions. FM stations have relatively uniform day and night service areas. FM propagation loss includes everything that can happen to the energy radiated from the transmitting antenna during its journey to the receiving antennas. It includes the free space path attenuation of the wave and such factors as refraction, reflection, interference, diffraction, absorption, scattering, Fresnel zone clearances, grazing and Brewster angle problems.

Propagation is dependent upon all these properties out to approximately 40 miles (65 km). Some additional factors enter the picture with longer service ranges. Radio wave propagation is further complicated because some of these propagation variables are functions of frequency, of polarization, or both, and many have location and time variations.

The technical intent of the broadcaster is to put a signal into FM receivers of sufficient strength to overcome noise and to provide adequate limiting for at least 20 dB signal to noise ratio, which will provide at least 30 dB of stereo separation. The required RF signal level varies from about 2 uV/m (microvolt per meter) for high sensitivity FM stereo tuners in the suburbs to about 500 uV/m for less sensitive transistorized portables, as well as most automobile receivers in urban areas.

FM antenna manufacturers do not guarantee coverage. They supply antennas which radiate a signal meeting certain specifications, including power gain. This is indicated as a free space value for 1 kW of input power and assumes an omnidirectional radiation pattern. These free space values are shown in the catalogs for reference purposes and are achieved in practice only when measured on a good antenna test range.

Some manufacturers in the United States provide azimuth pattern adjustment service to insure a horizontal plane pattern circularity of ±3 dB when mounted on the side of a specific tower or pole. It must be pointed out that this radiation pattern and gain are for free space conditions with no obstructions to propagation. Such conditions are rarely found in actual installations.

The radiation pattern and propagation are two distinctly separate parameters. They should not be confused as one and the same. They are not.

The pattern is the radiation which is transmitted by a given antenna, without any propagation limitations, as measured on a good antenna test range. Propagation depends on conditions existing between the transmitting antenna and the receivers.

The actual service area signal strengths are based upon two probability factors. Contours are not solid signal areas as we would believe. For example, the FCC signal coverage charts are based upon a probability of 50 percent of the locations, 50 percent of the time. This means that at any one given location the signal has a 50 percent chance to measure up to the predicted contour level. Furthermore, half the time at that location, it may reach the level predicted while at other times it may be lower or higher in strength. Signal level prediction is not a fine art.

These FCC charts (FCC Rules, Sec. 73.333) are based upon the assumption that excellent propagation conditions exist. One or more of the conditions mentioned in the second paragraph under this heading may reduce the measured signal strength from those predicted values.

Propagation Loss

The power radiated from a FM transmitting station is spread over a relatively large area, somewhat like an outdoor, bare light bulb on top of a tall pole. The power reaching the receiving antenna is a very small percentage of the total radiated power.

At 100 MHz and a distance of 30 miles (48 km) the figures indicate the free space path loss to

[2]Onnigian, Peter: "A Study Into the Effects of Vertically Polarized Radiation in FM Broadcasting" Technical monogram. Jampro Antenna Company, now a division of Cetec Corp. 1965.

[3]National Quadraphonic Radio Committee, report to the FCC, Nov. 1975. EIA, 2001 Eye Street, N.W. Washington, D.C. 20006.

be 106 dB.[4] Doubling the distance increases the space loss by exactly 6 dB. The path loss does not attenuate the signal with distance as much as some other factors. Path loss between an earth station and a satellite is a classic text book example of a 6 dB loss every time the distance is doubled. But a typical FM station signal travels through a nearly perfect dielectric (air) and over the imperfect earth's surface (ground). Herein lies the FM radio propagation loss problem.

Between the transmitting and the receiving antennas there may occur in the propagation path refraction, diffraction, and reflection from scores of objects such as hills, and buildings. These, along with absorption, scattering, lack of Fresnel zone clearances, and other factors, all reduce the signal strength.

Signal loss due to foliage has been well known to UHF TV broadcasters for many years.[5] This same condition exists to a lesser degree for FM broadcasting. Trees, shrubs, and other foliage on hills or smooth terrain affect the reflected as well as the lateral signal loss with distance. With average values of permittivity and conductivity in both foliage and ground, a loss of about 2.5 dB was found to exist in a ten mile path, at FM frequencies.[6] The height gain factor is increased with heights above the foliage. Considerable depolarization takes place because the transmission through or reflections from ground foliage is a diffracted field contribution.

Multi-path Problems

The ideal reception condition is a strong direct single source signal. When energy from two or more paths (due to reflections) reaches the receiver, a condition called multi-path reception occurs. Poor reception is experienced when there is insufficient strength difference between the direct and the reflected signals.

Nothing is more important in the way of broadcasting facilities than the location of the transmitting antenna. Great care must be exercised to find a suitable site. Poor selection of the transmitter point can result in very unfavorable signal propagation and negate the entire project. One very serious result of poor site selection is multi-path propagation in some directions.

As an example, the transmitter should not be located so that strong reflections take place from nearby hills or mountains. This can happen when

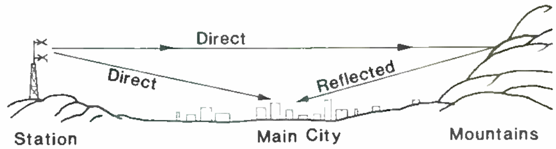

Fig. 1. Example of poor station location causing severe multi-path conditions due to delayed reflections from mountains on the right. Not to any scale.

the transmitter is placed on one side of a large city and the other side of the city has a high mountain range. Radiation into the city directly from the transmitting antenna, as well as reflections from the nearby hills and mountains will create two or more signal paths to many receivers. These reflections can be so strong that only a 10 dB difference may exist between the direct and the reflected, a condition which causes severe multi-path problems.

A TV station at this same location would experience un-usable signals due to heavy ghosting, even with directional receiving antennas, which exhibit moderate signal pickup from their back. This is illustrated in Fig. 1 where a mountain range causes reflections back into a large city.

The multi-path example shown in the sketch was an actual case. The site was chosen by the FM broadcaster, without proper engineering guidance, simply because the hill had a tower, building, power and the road was in. In fact it later developed that the broadcaster learned why the TV people had abandoned the site: the TV station had failed due to extremely heavy ghosting into the principal city.

A much better FM transmitting site was located on the hills between the high mountain range and the city. Using a directional transmitting antenna with very little radiation towards the high mountains, reflections were satisfactorily reduced; and the FM station is now operating successfully.

Multi-path reflections are very easy to identify. On an automobile radio, the signal will drop out, sometimes abruptly, as the car moves. This effect may be rhythmic with distance while traveling slowly. It is sometimes called picketing as it acts like a picket fence alternately blocking and letting the signal pass. A field strength meter will usually reveal great variations of signal when moving, say, 100 feet (30 m) in a line with the transmitter. Cyclic variations over quite uniformly spaced intervals on the ground as great as 40 dB have been observed by the author.

This variation in signal levels is caused by the reflections adding and substracting from direct and reflected signals. This is indeed caused by propagation problems existing in the path between transmitter and receiver. It really has

[4]Freeman, Roger: "Telecommunications Transmission Handbook" John Wiley & Sons, New York. pp 180-186 1975.

[5]Head, Howard: "Influence of Trees on TV Field Strengths" Proceedings of the IRE, Vol. 48, pp 1016-1020, June 1960.

[6]Armstrong, A.: "Study of Electromagnetic Wave Propagation at 112 MHz." Proceedings of IREE Australia, pp 105-110, April, 1969.

nothing to do with the qualities of the transmitting antenna. It is a function of site selection. This should not be confused with a similar effect observed near the base of the tower supporting a high gain antenna. Nulls produced by stacking bays for gain are found near the antenna and may be filled-in if a problem (see "Null Fill" in this chapter).

Ground Reflections

In the elevation plane between transmitter and receiver nearly all FM signal coverage lies within 10° below the horizon. Generally the higher the transmitting antenna above the service area the greater will be this angle. Called the grazing angle, it lies between the horizontal plane and the earth's surface.

The angle of incidence and reflection are not the same, as shown in Fig. 2. The depression angle and the grazing angle are not equal as would be the case for a flat earth. Reflections from these angles play an important part in the strength and the quality of the signal in FM broadcasting with Cpol.

It is quite difficult to predict accurately the reflection co-efficient (efficiency), which varies considerably as a function of polarization, frequency, grazing angle, surface roughness, soil type, moisture content, vegetation growth, weather and the season. There are complex formulas for predicting the ground conductivity at the frequency of interest. For 100 MHz, a value of 10 millimhos per meter ground conductivity is often used, with a permittivity of 25, as being about the average for the continental United States.[6]

The ground which causes reflections at these grazing angles does not treat Hpol and Vpol in the same manner. The Vpol is attenuated considerably more than the Hpol as shown in

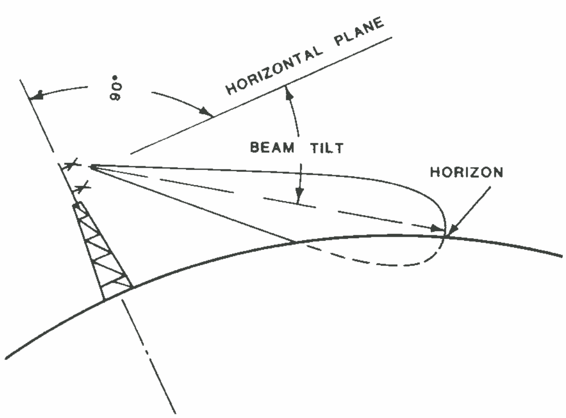

Fig 2. Beam tilt to radiate maximum ERP at the horizon. Not to any scale and exaggerated for illustration.

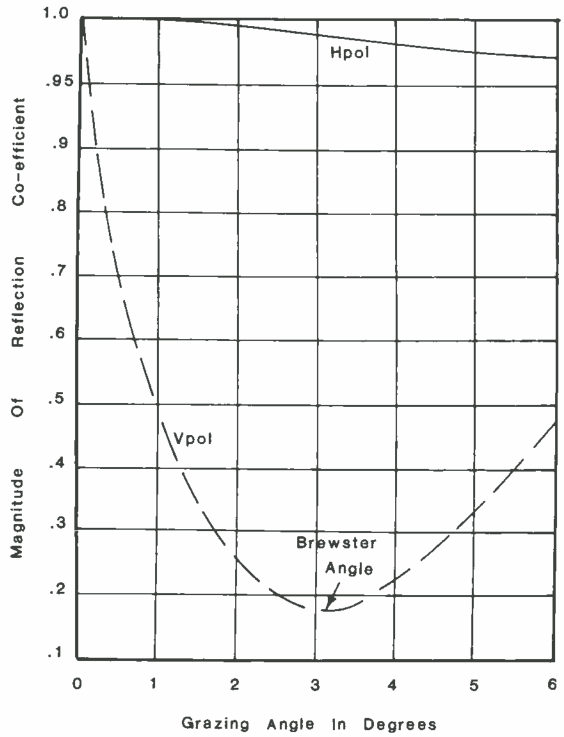

Fig. 3. Magnitude of reflection co-efficients showing differences for Hpol and Vpol, and the Brewster angle.

Fig. 3. The phase of the Vpol changes substantially with angle, while Hpol remains nearly the same. At these useful low propagation angles, there is considerably less Vpol signal reflected than Hpol, when grazing takes place. Field measurements confirm this fact.[7] For this reason, it is impossible to measure accurately axial ratios in the service area. To be meaningful, the Hpol and Vpol ratios must be measured on a good antenna test range.

Brewster Angle

For polarization with the electric field normal to the plane of incidence, there is no angle that will yield an equality of impedances for earth materials with different dielectric constants but like permeabilities. An incident wave with both polarizations present will have some of the second polarization component but little of the first reflected. The reflected wave at this angle is thus plane polarized with the electric field normal to the plane of incidence and the angle is the polarizing angle.

Notice that in Fig. 3 the minimum reflection co-efficient occurs at a grazing angle of about

[7]Moeller, Adolph: "Effect of Ground Reflections On Antenna Test Range Measurements" Microwave Journal, pp 47-54 March, 1966.

2°. Below this angle, the reflection co-efficient rapidly increases to unity. The angle at which the minimum reflection co-efficient occurs is called the Brewster or polarizing angle, after the Englishman who first discovered this phenomenon.

For ground reflections occurring near the Brewster angle, the reflection co-efficient is much smaller for Vpol than the Hpol. Therefore the Vpol signal components of Cpol are attenuated considerably. The greatest attenuation for Vpol from ground reflection occurs at this angle.

Field measurement of Vpol signals will usually show a greater ratio of Hpol to Vpol due to this Brewster angle loss. It must be borne in mind that the Brewster angle is a function of soil conductivity and may change from place to place, as well as from season to season.[8]

It is important, then, that the antenna height above the service area results in grazing angles which are less than the Brewster angle. Otherwise the Vpol will be reduced and the radiation will be much more elliptical than circular in polarization.

Fresnel Zone Clearance

A much neglected consideration in FM transmitting antenna location and height is Fresnel zone radius clearance in the path to the service area. Microwave engineers always make certain that their signal paths have this important clearance.

The effect of clearance above ground or other obstacles was studied by Auguste Jean Fresnel, a French scientist who first discovered this phenomenon in optics. Fresnel zones are circular areas surrounding the direct line-of-sight path of a radius such that the path length to the zone perimeter is a multiple of one half-wavelength longer than the direct path. This is illustrated in Fig. 4. The zone diameter varies with frequency and path length. The greater the path length, the larger the required mid-path clearance required for full signal.

Fresnel also discovered that the entire first zone radius is not required for full signal strength. Six-tenths of the first zone would suffice, which is fortunate since the radius is quite large at the FM frequencies. The equation for determining the first Fresnel zone radius for 4/3rd earth curvature is:

$$R = 1140\sqrt{d/f}$$

where d is the path length in miles, F is in MHz and R is in feet for the first radius.

[8]Reed, Russel: "Ultra High Frequency Propagation" 2nd Edition, Boston Technical Publishers pp 223-238 1964.

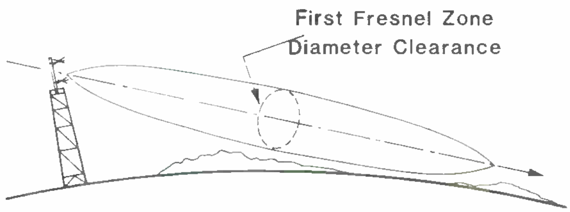

Fig. 4. First Fresnel zone clearance occurs as shown above, but only six-tenths is required for full free space signal level. Not to any scale.

In Table 1 the required 0.6 first Fresnel zone radii clearances at the middle of the path are shown for 98 MHz and service areas up to 52 miles (92 km) from the transmitter. The idea is to raise the height of the transmitting antenna so that the mid-path height is as high as or higher than shown in the Table. Due to the geometry of the Fresnel zone, if the terrain is relatively flat, the mid-path radius will control and be larger than that required elsewhere along the path. If the mid-path clearance is less than the values shown, the FM signal will be attenuated in accordance with the curve shown in Fig. 5.

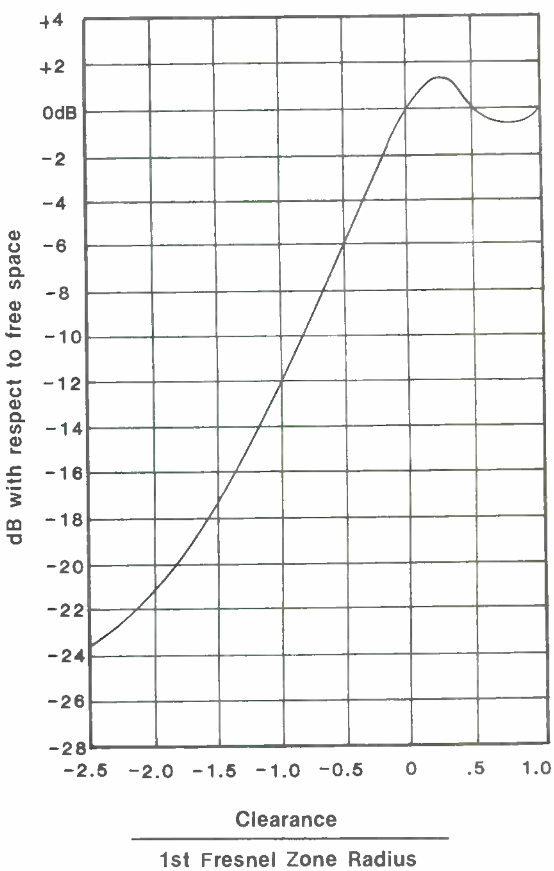

Fig. 5. Attenuation of FM propagation when the path between transmitter and receiver lacks Fresnel zone clearance in the ratios shown.

TABLE 1. Recommended Minimum Antenna Heights (for flat terrain and 98 MHz).

Service Area Radius Required		Fresnel Zone Six-tenths Clearance		Recommended Min. Antenna Height		Probable FCC 80-90 Class
Miles	Km	Feet	Meters	Feet	Meters	
5	8	155	47	310	95	A
7½	12	189	58	378	115	A
10	16	218	66	426	130	A
15	24	267	81	534	167	A,B,C-2
20	32	309	94	618	188	B-1,C-2
25	40	346	105	700	213	B-1
30	48	378	115	756	230	B
35	56	409	125	818	250	B
40	64	437	133	875	267	C-1
45	72	463	141	925	282	C-1
50	80	488	149	975	297	C-1
57	92	522	159	1,043	318	C,C-1

The center-of-radiation heights of the antennas in Table 1 are actual and not height above average terrain (HAAT). Some of these recommended heights will reduce the allowable effective radiated power (ERP) in accordance with FCC 73.211 (b), depending on the class of station and the zone. However, it is better to have the Fresnel clearance than the maximum low height ERP values, as the higher heights will produce stronger signals.

It is a well known propagation axiom that greater heights are more useful in producing higher signal strengths than ERP levels, everything else being equal.

Without the first Fresnel clearance of 60 percent the signal level at the distant point suffers. This reduction will follow the curve shown in Fig. 5 for different values of clearance.

In order for the FCC prediction curves to be valid, the recommended minimum antenna heights should be achieved. These heights not only provide line-of-sight conditions to the service limits but also proper Fresnel clearances. Both conditions are required for the FCC F(50,50) curves to be valid.

The values in Table 1 are for relatively flat terrain but take into consideration the FCC suggested roughness factor of up to ±150 feet (50 m). Where the tower height is limited by HAAT values or other limitations, the signal strength will suffer due to those factors.

Soil Conductivity

The conductivity and permittivity of the soil, together with the vegetation on it, play a part in the attenuation of FM signal strength. Average soil has a dielectric constant of about 15 millisiemens per meter at 100 Mhz.[9]

[9]Skolnik, Merril: "Radar Handbook" McGraw Hill Book Co. New York pp 39-8 to 39-9 1970.

By raising the receiving antenna above the immediate effects of the soil, the signal level will be increased. Actual field measurements have proven a 9 dB increase in signal when the dipole was raised from 3.28 feet (1 m) to a level of 30 feet (9.1 m).

FCC Service Contours

From the FCC coverage prediction charts, it is possible to draw contours of the various grades of service for a given ERP and antenna height above average terrain. These predictions, at 50 percent of the locations, 50 percent of the time, constitute the basis for the service contours. The city grade contour being 70 dBu (3.16 millivolts per meter) and primary service contour which is 60 dBu (1.0 millivolts per meter).

The FCC Section 73.333 charts for these predictions now have a built-in terrain roughness factor, to more accurately predict the distances, as explained above.

CIRCULAR POLARIZATION

Radio waves are composed of electric and magnetic fields at right angles to each other and to the direction of propagation. When the electric component E is horizontal, the wave is said to be horizontally polarized, as shown in Fig. 6-B/D. Such a wave is radiated from a horizontal dipole. References are with respect with the earth plane. If the desired electric component is vertical as in Fig. 6-A/E, a vertical dipole could be used to produce the vertically polarized wave.

When the two plane waves are equal in magnitude, and if one plane wave lags or leads the other by 90 electrical degrees, the field will rotate as shown in Fig. 6, at the speed of the carrier frequency and will be polarized circularly.

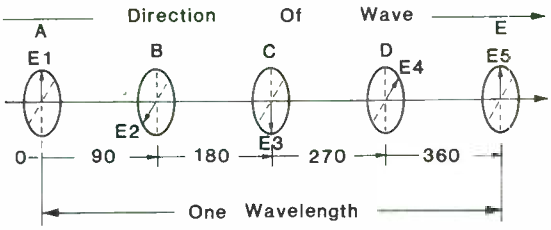

Fig. 6. Circularly polarized wave propagation in one wavelength of travel, showing right hand rotation. Note vector rotation with wave travel.

Only in the special case where the horizontal and vertical components are equal in strength with a 90 degree phase difference is the radiation said to be Cpol.

The direction of rotation shown by the vector arrows in Fig. 6 depends on the relative phase of the two components. Thus the polarization of the wave will appear to have either clockwise or counter-clockwise rotation, as shown. The FCC has set clockwise rotation as the technical standard, in order that similar sense of rotation antennas may be used for receiving in the future.

Notice that in Fig. 6 the polarization rotates at any given place during its propagation. Importantly, vertical and horizontal vector polarization does *NOT* occur at the same instant, at the same place of measurement or observation. It is this rotation which gives Cpol its signal penetrating qualities, so useful in FM broadcasting. The rotating polarization of Cpol will find its way into the FM receiving antenna and provide useful signal levels under conditions where Hpol may not.

The axial ratio as shown in Fig. 7 is that between the maximum and minimum voltage component at any orientation of the reference measuring test dipole which is placed perpendicular to the direction of propagation. An axial ratio of 1:1 (0 dB) is perfect. In practice, axial ratios of 2 dB or better are considered to be excellent and commercially available. Axial ratios over 4.9 dB (1.75 to 1 voltage ratio) are considered to be elliptically polarized, a hybrid form and not as good in signal penetrating qualities as Cpol.

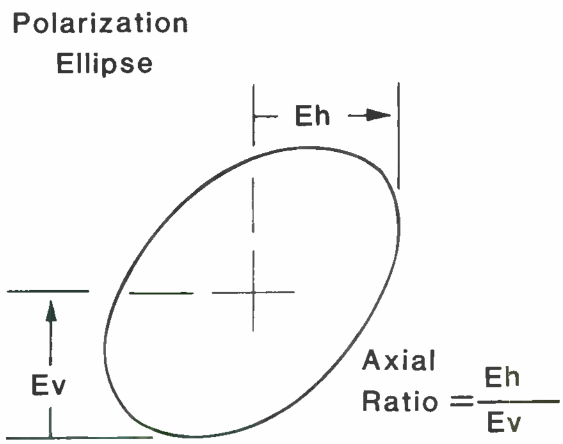

Fig. 7. Axial ratio expressed in dB is the ratio of the larger polarized component divided by the smaller at any reference dipole orientation, where the maximum ratio occurs.

Cpol radiation does not increase the distance to the FCC contours. Interference and allocation contours are not changed when switching from Hpol to Cpol. The service contours are predictions based on the horizontal component of the Cpol radiation only. It must be remembered that the ERP from a Cpol station reaches its maximum Hpol power 90 degrees *after* it reaches its Vpol peak. Hpol and Vpol do not add since they do not occur at the same instance, as shown in Fig. 6.

GENERAL COVERAGE STANDARDS

There are certain height and power levels fixed by the FCC for various classes of stations. The United States has been divided into three different geographical areas based on population density as well as propagation refractive index levels. These ERP and height values have been set to prevent co-channel and adjacent channel interference.

Zone I generally speaking is the northeastern part of the United States. Zone I-A includes Puerto Rico, Virgin Islands and that portion of California lying below the 40th parallel. Zone II includes Alaska, Hawaii and the remainder of the United States not in the above two zones. This is more fully described in FCC Section 73.205.

Under new Rules which resulted from Docket 80-90: "Modification of FM Broadcast Station Rules to Increase the Availability of Commercial FM Broadcast Assignments," in 1983, new ERP levels and additional classes of stations were created. The distance to the 60 dBu (1 mV/m) signal contour is the controlling factor so that the ERP based on the HAAT is adjusted to produce that level and no more at a specific distance for a particular class station.

Table 2 shows for each FM class station, the zone, the maximum ERP, the maximum HAAT and the distance to the 60 dBu contour calculated by using the maximum ERP and HAAT and then rounding to the nearest kilometer and mile. The FCC issued these in that docket and they are currently the standards.

TABLE 2. Docket 80-90 FM station classes, zones, and ERP.

FM CLASS	ZONE	MAX. ERP In kW	MAXIMUM Feet	HAAT Meters	DISTANCE TO Miles	60 dBu km
A	I, I-A	3	328	100	15	24
B	I, I-A	50	492	150	32	52
B-1	I, I-A	25	328	100	24	39
C	II	100	1,969	600	57	92
C-1	II	100	984	300	45	72
C-2	II	50	492	150	32	52

Under these new Rules, Class C stations will be required to have at least 100 kW ERP and an antenna height of more than 984 feet (300 m) above average terrain. Class C-1 stations are now permitted a maximum of 100 kW ERP with an antenna maximum HAAT of 984 feet (300 m), while C-2 stations may go to 50 kW at a maximum HAAT of 492 feet (150 m). Higher HAAT may be used with reduced ERP values, in accordance with equivalent 60 dBu coverage. Class C and C-1 stations may thus share the same community antenna and tower.

Stations may be upgraded using the easiest method which is to increase existing location tower height. Such factors as local zoning laws and aircraft flight patterns may preclude this approach, however.

FM Signal Measurements

The signal strength received at 5 feet (1.5 m) above ground, which is about average for auto whip antennas, is several times lower in level than at the standard FCC measurement height of 30 feet (9.1 m). This fact should be taken into consideration when comparing low height measurements with the FCC Section 73.333 prediction charts, which are made for the higher height. Signals at the higher height are considerably stronger.[10]

Signal levels inside houses, apartments, offices and other structures vary greatly. Levels depend on the type of building construction but in nearly all cases will be lower than those outdoors. Reflections inside the building reduce stereo separation, and cause crosstalk problems with SCA channels. An outside FM receiving antenna is recommended for good reception.

Field strength measurements should not be used to determine the transmitting antenna radiation pattern or efficiency. The propagation factors discussed previously camouflage the true performance. The only technically acceptable way to determine the antenna's characteristics is on an antenna test range.

Elsewhere in the Handbook is an entire chapter dealing with the recommended methods and equipment to make FM and TV field strength measurements. This information may be used to determine the actual quality of service and the areas where useable signal levels in fact exist. Predicted one millivolt-per-meter contours may be considerably different from actual measured values.

Required Signal Strength

What is the minimum satisfactory signal strength? What's the maximum above which it is wasteful? FCC Section 73.315 has indicated some of the following levels:

34 dBu	=	.05 mV/m	For rural areas
60 dBu	=	1.00 mV/m	Suburban areas
70 dBu	=	3.16 mV/m	Principal community
82 dBu	=	12.64 mV/m	Highest useful level

The first three levels were set by the FCC in the early 1950s when tube receivers and Hpol antennas were the vogue. Modern day transistor radios have much greater sensitivity. And Cpol has much greater signal penetrating power than the old Hpol had in the days more than 30 years ago when these levels were first established.

The FCC defines two grades of signal contours on its applications. The first is based on the 70 dBu contour (3.16 mV/m) required to cover the principal community. The second is the 60 dBu contour (1 mV/m) which defines the primary service area.

The FCC also stated that, in rural areas, levels as low as 50 microvolts-per-meter were useful. Indeed current home stereo tuners and FM auto radios operate very well with only 25 microvolts-

[10]Saveski, Peter: "Radio Propagation Handbook" TAB Books Inc. Blue Ridge Summit, PA. pp 148-159 1980.

per-meter. In practice, 50 microvolts-per-meter (0.05 mV/m) is quieting in nearly all automobile and transistor radios receiving a stereo signal from a Cpol station antenna. Therefore 50 microvolts-per-meter should be considered the minimum useful signal level.

If the highest level of 3.16 mV/m is quadrupled, it will be 12.64 mV/m. This is a 12 dB increase, equal to increasing the FCC power level by more than 15 times. It can be safely said that this level of 12.64 mV/m is considerably more signal than necessary by any present day working FM radio. Any signal level higher than this is superfluous and not at all useful.

BLANKETING

Excessive RF signal into a receiver creates a problem of unsatisfactory reception called blanketing. High signal levels overload the front end of receivers and make satisfactory reception impossible. The FCC has defined the 115 dBu (562 mV/m) level as the "blanketing contour" and adopted the inverse distance method to predict how far this contour extends. New or modified FM stations have the responsibility to satisfy all complaints, at no cost to the complainant, of blanketing-related interference inside this contour within one year of commencement of operations.

The distance to the 115 dBu contour is determined using the following equation:

$$D \text{ (in kilometers)} = 0.394 \sqrt{P}$$

$$D \text{ (in miles)} = 0.245 \sqrt{P}$$

Where P is the maximum effective radiated power (ERP), measured in kilowatts of the maximum radiated lobe, irrespective of vertical directivity. For directional antennas, the horizontal directivity shall be used.

ANTENNA GAIN

Antenna gain is expressed in power ratio and may also be stated in dB. For example an antenna with a power gain of 2 is also said to have a gain of 3.0 dB.

The FCC in Section 73.310 (a) of its Rules, defines antenna gain as the square of the ratio of the root-mean-square free space field strength produced at one mile in the horizontal plane, in millivolts per meter for one kW antenna input power to 137.6 mV/m. (In metric units, 1 km and 221.4 mV/m).

Notice that this gain is not in reference to a half wave dipole, nor is it with respect to a Cpol antenna, when the gain is for a Cpol antenna, as is the communications practice parlance.

A two bay Hpol antenna has a power gain of approximately two. But a two bay Cpol antenna in FCC terminology has a gain of about one because the other half of the power is Vpol and is not considered in the gain calculations. Only the horizontal polarization mode is used by the Commission. The vertically polarized energy must not exceed the Hpol however (except for noncommercial, educational FM facilities attempting to minimize interference to TV Channel 6 reception).

The power gain of an antenna is used with the transmitter gain when determining the Effective Radiated Power (ERP). Consider for example a 10 kW transmitter and an antenna power gain of 5. Neglecting transmission line loss, the ERP is 10 kW × 5 = 50 kW ERP. If the antenna gain were 10 and the transmitter power was 5 kW, we would have the same ERP of 50 kW. (5 kW × 10 = kW ERP)

EFFECTIVE RADIATED POWER (ERP)

The FCC defines the term Effective Radiated Power to mean the product of the antenna input power (transmitter output power less transmission line loss) times the antenna power gain. Where circular polarization is used, the term ERP is applied separately to the Hpol and Vpol of radiation. For allocation purposes, the ERP is the Hpol component of radiation only.

BEAM TILT

FM broadcasting antennas are normally mounted on towers which are plumb, so the peak power beam in the elevation pattern is perpendicular to the tower axis. A standard FM antenna without any beam tilt radiates more than one half of the ERP above the horizon. All this power is lost.

The higher the antenna is above its average terrain, the larger the coverage area. It also follows that the higher the antenna above terrain, the greater is the elevation angle down to the earth's horizon. This is shown in graph form in Fig. 8. In order to strike the farthest service area from a high HAAT, the beam may need to be tilted down towards the earth.

Consulting engineers who are familiar with this problem can easily work out the required amount of beam tilt, if it is necessary. Practical values are one-half to three-quarters of one degree, depending on the antenna height, distance to the far service area, and the antenna elevation pattern.

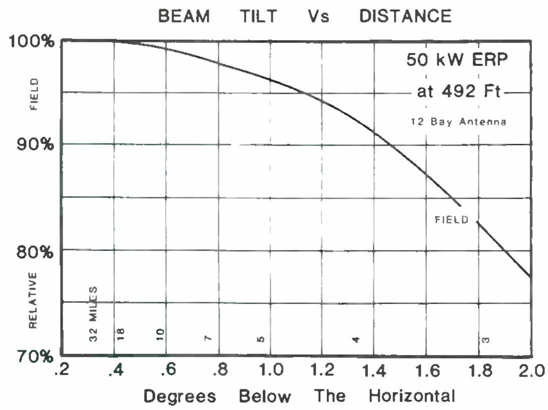

Fig. 8. Twelve bay Cpol antenna with 0.3 degree beam tilt showing ERP distribution with coverage from 492 foot (150 m) tower over flat land. Degrees below the horizon are based on 4/3rd earths curvature. Horizon is — 0.341 degrees at 32 miles (52 km).

Beam tilt is usually accomplished electrically, by delaying the currents to the lower bays, and advancing the phase of the upper bay currents during the design and construction of the antenna at the factory.

NULL FILL

While the beam tilt puts more signal into the far reaches of the service area, it does not solve the problem sometimes caused by high gain antennas within several miles of the transmitter. Elevation angle nulls common to all antennas with two or more bays appear farther and farther away from the antenna as its gain is increased with more bays.

It is a simple matter to determine the existence of elevation pattern nulls from manufacturers literature, to determine where they will fall and the small amount of null fill in power required to produce a useful level of signal strength.

The reader is referred to the TV Antenna chapter for some excellent information on null fill and beam tilt. The matter is essentially the same for FM and TV antenna systems.

TRANSMITTER-ANTENNA COMBINATIONS

Typical Class A Station Coverage

Table 3 shows the FCC predicted signal strengths for a typical Class A facility on a relatively flat plane, with the antenna center 328 feet (100 m) above average terrain (HAAT). The maximum allowable power of 3 kW is used. The first two columns show the distances, with the farthest being the horizon from this height. The third column indicates the true earth angle from the antenna to the distances shown. From the elevation information the ERP from each antenna was determined at each vertical angle. This ERP value was used to find the signal strength from the FCC F(50,50) FM prediction chart, FCC Section 73.333 Fig. 1.

Under signal level in millivolts-per-meter (mV/m) the predicted field strengths are shown in this Table based on the above procedure. From 5 miles (8 km) to the horizon, the signal strengths are identical because the ERP values are very nearly identical. This is due to the shape of the elevation pattern near the maximum.

Departure occurs as the elevation pattern angle becomes larger. At 4 miles (6.4 km) the one bay antenna ERP at 0.92 degrees is 2,982 watts while from the six bay antenna it is 2,912 watts. Anyone who has used the 73.333 charts has found the enlarged versions to be easier to read, but even then a difference of 200 watts between two ERP values is difficult to ascertain, and at best is a calculated guess.

Going towards the transmitter from 4 miles (6.4 km) the field increases in favor of the one bay. This table clearly demonstrates that the high power transmitter-low gain antenna does not improve the signal strength available to the receivers beyond about 4.5 miles (7.25 km) in this example. The signal level starts to increase between 4 and 5 miles (6.4 and 8 km). Any increase above this level is useless because full limiting has certainly taken place in even the poorest FM receiver. (See Required Signal Strength in this chapter)

In Table 3 the signal strengths of 16 mV/m at 5 miles (8 km) are identical coming from either transmitter-antenna combination. This is due to the fact that the ERP power at the vertical angle of -0.74 degrees is about the same from both antennas. The ERP at 0.0 degrees elevation pattern will of course be exactly the same for both combinations. The field does not change measurably until observation is made beyond 1.5 degrees from the peak 100% value in a six bay antenna. This is the nature of things.

The signal strengths in this table were based on relatively flat terrain from an antenna 328 feet (100 m) HAAT. The true earth curvature distance to the horizon is 25.56 miles (41.23 km). Therefore the outer reaches of useful signal drop off very rapidily beyond this point in the typical Class A station.

There are no nulls in the one bay antenna pattern. In the six bay the first null occurs at about -10 degrees, placing it approximately 0.37 miles (0.6 km) from the tower. Antenna arrays are never perfect so the null is never zero power. So assume a minimum radiation of five watts in the

TABLE 3. Transmitter Power Vs Antenna Gain.
Class A 3kW ERP — Zones 1 and 1-A
Maximum HAAT 328 Ft (100 m)

Service Miles	Distance Km	Vertical Angle	SIGNAL LEVEL IN mV/m 7.5kW Transmitter 1 Bay Antenna	1kW Transmitter 6 Bay Antenna
1	1.6	3.58	275	210
2	3.2	1.80	88	81
3	4.8	1.21	42	40
4	6.4	.92	24	22
5	8.0	.74	16	16
6	9.6	.63	11	11
7	11.3	.55	8.5	8.5
8	12.9	.49	6.2	6.2
9	14.5	.44	5.0	5.0
10	16.1	.41	3.7	3.7
12	19.3	.36	2.5	2.5
14	22.5	.33	1.8	1.8
16	25.7	.31	1.4	1.4
18	28.9	.29	1.1	1.1
20	32.2	.28	.85	.85
22	35.4	.28	.70	.70
24	38.6	.27	.55	.55
26	41.8	.27	.40	.40

first null. The predicted signal would be 31 mV/m and the second null with the same five watts ERP would be even stronger in this example. So in practice there would be no need to fill in the nulls of the six bay antenna.

Another consideration is that the nulls fall very close to the tower and the number of people occupying the null areas is small. So any problems resulting from these close in nulls would be very minor.

Typical Class B and C-2 Station Coverage

The same comparisons of transmitter-antenna combinations can be made for Class B and the new Class C-2 stations, operating with a HAAT of 492 feet (150 m) with 50 kW ERP. This is shown in Table 5. With 55 kW transmitters now available, a 2 bay Cpol antenna would provide the 50 kW ERP, with high efficiency coaxial lines. It is compared with a 10 kW transmitter feeding a 10 bay Cpol antenna. The terrain flatness is assumed not to exceed ±150 feet (50 m).

Table 5 indicates that the signal levels are the same from 4.6 miles (7.4 km) out to 35 miles (56 km) under similar columns as for the Class A station comparisons. The FCC uses a receiving height of 30 feet (10 m) so the horizon is a bit further away, at 31.3 miles (50.5 km).

From the transmitter out to about 2 miles (3.2 km) the signal rises much more rapidly in the two bay antenna than in the 10 bay, the latter being somewhat similar to a cosecant curve. There is surplus signal close in and more than is needed or can be tolerated.

Therein lies one of several problems with low gain antennas as seen in Table 5. With the two bay antenna there is 900 mV/m at one mile (1.6 km) and 562 mV/m as far out as 1.55 miles (2.5 km). This is above, or at, the blanketing level of 562 mV/m. (See Blanketing in this chapter) The high gain antenna does not cause this type problem under identical conditions.

The signals from both combinations are much more than necessary for present day FM receivers out to about 10 miles (16 km). There is no practical difference technically in USEABLE signal strengths presented to receivers in the entire market area, from either antenna. There is, however, a great deal of savings in capital costs as well as operating expenses between the two combinations.

One antenna factor is not clearly indicated in Table 5. The two antennas have elevation pattern nulls. The two bay antenna null at -30° falls 852 feet (260 m) from the foot of the tower and can be disregarded. The ten bay antenna nulls can be filled to as little as 2½% field, which will not affect its gain. This would represent a minimum ERP at the nulls of 31 watts. Although seemingly very small, it is very effective as can be seen in Table 4.

It is obvious that the 10 bay antenna nulls can easily be filled to produce signal levels in excess of those required. If the transmitter is located in a populated area, these high levels prevent the loss of stereo separation and noise in the SCA, if there are reflections from high level lobes in the built up areas. This problem is common to

TABLE 4. 2½% Null fill in — 10 bay antenna.

Null	Angle	ERP	Distance	Field
First	−5.75°	31 w	4,800 Ft	31 mV/m
Second	−11.50°	31 w	2,240 Ft	70 mV/m
Third	−17.25°	31 w	1,512 Ft	109 mV/m

TV transmitters which produce ghosts from high signal level lobe areas reflecting into null areas. This problem is greatly and satisfactorily reduced with null fill in as shown in Table 4.

ANTENNA SITE SELECTION

The transmitter location must be carefully chosen. Site economics should be secondary to the technical advantages of a particular site. Fresnel zone clearances, and other factors outlined in this chapter should be considered. A site with an operating FM or VHF TV station makes an excellent source of signals to check propagation for a new station. If the existing station is FM, make certain that its antenna pattern has been optimized to provide as much circularity as possible.

A good field strength meter should be used to probe the actual signal from the existing station. Relative readings are important, not the absolute. Check for reflections as well as level changes within a short walking area of about 100 feet (30 m) which would indicate reflections. Check for stereo separation. Using this information, the operation of a new station near the one being checked can be compared and verified before moving or submitting the FCC application. The consulting engineer will want to use this information to insure the suitability of the new site.

TV CHANNEL 6/FM ANTENNA PROBLEM

Television Channel 6 occupies the band from 82 to 88 MHz. The FM broadcast band extends from 88 to 108 MHz. Non-commercial educational FM stations are assigned from 88 to 92 MHz. Interference clearly exists between the two, with the TV station viewers suffering the most. The FM receiver is relatively selective with a response of about 200 kHz, but the TV receiver has a bandwidth of at least 6 MHz. However, more than TV receiver selectivity is involved in this interference problem, which the FCC has been trying to address since 1972. See FCC Section 73.525

Three principal techniques exist to minimize channel 6 interference from FM stations: (1) collocation, (2) where collocation is not feasible, location of the FM station in an area of low population density, and (3) antenna cross polarization.

Collocation

The purpose of collocation is to achieve the same propagation path for both TV and FM stations, thus making possible the maintenance of a nearly constant desired-to-undesired signal ratio in the service area. If possible, both antennas should be mounted on the same tower. If not, a maximum separation of 400 meters between the two has been adopted.

TABLE 5. Transmitter power Vs antenna gain.
Class B, C-2 50 kW ERP
Zone 1, 1-A & C-2

Service Miles	Distance Km	Vertical Angle	SIGNAL LEVEL IN mV/m 55kW Transmitter 2 Bay Antenna	10kW Transmitter 10 Bay Antenna
1	1.6	4.97°	900	140
1.55	2.5	3.25°	562	165
2	3.2	2.49°	310	230
3	4.8	1.67°	153	135
4	6.4	1.26°	92	88
4.6	7.4	1.15°	71	71
5	8.0	1.02°	57	57
7.5	12.	.70°	22	22
10	16	.55°	13	13
15	24	.41°	6.5	6.5
20	32	.36°	3.1	3.1
25	40	.33°	1.9	1.9
30	48	.328°	1.1	1.1
35	56	.332°	.7	.7

The horizontal and vertical plane radiation patterns of both antennas should be similiar because the objective is to maintain a near constant desired to undesired signal ratio. The HAAT should also be similar, thus the desirability of collocating on the same tower. The maximum ERP of the FM stations operating on this basis is in Section 73.525(b) of the FCC Rules.

Alternate Locations

The FM station may not be intended to serve the same community as the TV station, or collation may not be possilbe. In this event the FM broadcasters should locate in an area of relatively low population density by imposing a limit on the population which may be included within that area where a particular undesired-to-desired protection ratio is exceeded.

Two ratios were proposed by a committee which studied this problem in 1983.[11] Their recommendation varied according to the educational station frequency separation from the Channel 6 aural frequency of 87.75 MHz. In any event, the interference area should not have more than 3,000 people living in it.

Alternate Polarization

Several organizations have made discrimination tests in the United States and in Europe with cross polarized antennas. It has thus been well established that discrimination of 16 dB is to be expected in rural areas and 10 dB in urban areas between two stations one using the Vpol and the other using Hpol, and the receiving antenna being similarly polarized. This is sufficient in most cases to resolve the problem.

While technically cross polarization will help solve the problem, the Commissions Rules will not require it. This is left as an option for the FM applicant to use. Most TV channel 6 receiving antennas will remain Hpol while automobile FM antennas will stay Vpol. So if the TV station remains Hpol, this interference problem may be cleared up if the FM station will switch to Vpol.

Rejection Filters

The FCC believes that rejection filters installed at the TV receiver would be helpful, while others think this is not a satisfactory solution. Unfortunately, many viewers do not sufficiently understand this problem and are thus not motivated to have the necessary filter installation made.

[11]Cohen, Jules: "Proposed Solutions, Channel 6-Educational FM Broadcast Interference Problem" Preceedings 38th Annual Broadcast Engineering Conference, NAB, Washington, D.C. 20036.

It is further complicated by the fact that the majority of the existing TV receivers still have balanced antenna inputs (300 ohms) and filters designed for them do not usually provide the necessary amount of rejection. As more TV receivers with coaxial inputs are purchased by the TV viewing public, this situation could change dramatically. Unbalanced coaxial (75 ohm) filters are excellent, and 20 dB of attenuation of the FM signal is readily available.

VSWR BANDWIDTH

According to theory, the bandwidth of an FM signal is actually infinite if all the sidebands are taken into account. It is also interesting to note that at certain modulation indices, the carrier amplitude goes to zero and all the transmitted power is on frequencies other than the carrier frequency. Practical considerations in the transmitter and receiver circuitry make it necessary to restrict the RF bandwidth to less than infinity of course.

Prior to 1984 the maximum deviation for FM stations was 75 kHz, representing 100% modulation. In that year the FCC changed the maximum deviation to 82.5 kHz (110%) for those stations with 10% injection of subcarrier channels. This additional deviation requires greater antenna system bandwidth than previously needed.

System bandwidth is measured at the point in the antenna system where the transmitter is connected. This usually includes the harmonic filter, all the main coaxial transmission line, and, of course, the antenna itself.

The significant sidebands are usually considered to be those whose amplitude exceeds one percent of the unmodulated carrier. With 110% modulation (82.5 kHz deviation) these side bands require a bandwidth of 260 kHz.[12,13]

The bandwidth is considered to be the VSWR points in the system under consideration having a reflection coefficient of less than five percent which corresponds to a VSWR ratio of 1.1:1

Intermod and AM Distortion

Intermodulation distortion and synchronous AM noise are caused by narrow VSWR bandwidth in the antenna system, as well as from final amplifier circuitry all the way to and including the antenna.[14]

[12]Gray, Lawrence: "Radio Transmitters" McGraw Hill Book Co. New York pp 181-186 1961.

[13]Mendenhall, Geof: "Study of RF Intermodulation Between FM Broadcast Transmitters Sharing Diplexed Antenna Systems:" Technical monogram. Broadcast Electronics Inc. Quincy, IL 62301 1983.

[14]Mendenhall, Geof: "The Composite Signal - Key to Quality FM Broadcasts" Technical monogram. Broadcast Electronics Inc. Quincy, IL 62301 1984.

Synchronous AM is AM modulation of the carrier caused by frequency modulation of the carrier frequency in the VSWR notch. At the notch the reflected energy is the lowest. As the deviation takes place, the greater the frequency swing, the greater will be the reflections, due to the VSWR notch. With a flat VSWR curve, this AM does not take place. If the VSWR curve is skewed, synchronous AM will also take place, intermod and stereo crosstalk will also increase.

Checking System VSWR

From time to time, the VSWR of the narrow band antenna system should be checked and adjusted, if necessary, to ascertain VSWR compliance. If the exciter has thumb wheel exciter frequency adjustability in 10 or 50 kHz steps, it may be used to change the frequency to check VSWR on different frequencies, with the transmitter operating at low power during the FM test period. The reflectometer may be used as the indicator.

Alternately one of several methods of checking VSWR in coaxial line systems using test equipment may be used. These include a signal generator with a high directivity directional coupler, sweep generator test setup, or an impedance test set.

The VSWR should be plotted to insure that the reflection response is balanced to 130 kHz on each side of the carrier frequency. With transmission lines longer than 300 feet (100 m) it is suggested that the 260 kHz VSWR bandwidth be under 1.08:1 all the way out to ±130 kHz. The additional delay due to increasing line length becomes more of a problem, so the amplitude of the reflection must be reduced, for best operational results.

Low VSWR Importance

The VSWR shown by the transmitter reflectometer does not increase or decrease the range of the signal. It has nothing to do with coverage. But VSWR values above 1.1:1 may decrease the final amplifier efficiency. Other definite negative effects of VSWR are increased intermodulation products and AM synchronous noise. Stereo separation is also degraded with increased VSWR.[15]

COMMERCIALLY AVAILABLE ANTENNAS

There are several basic classes of antennas available for use from 88 to 108 MHz. These and variations of them are made by several American manufacturers in different models, gains, and input power ratings. They may be broken down into the following general classes:

1. Ring stub and twisted ring
2. Shunt and series fed slanted dipole
3. Multi arm short helix
4. Panel with crossed dipoles

These antennas have many things in common. For example, all the non-symmetrical antennas are designed for side mounting to a steel tower or pole. Radiating elements are shunted across a common rigid coax line. This has eliminated the problems associated with the older corporate feed system using semi-flexible solid dielectric low power cables.

Shunting elements every one wavelength across a transmission line makes impedance matching simple. Bandwidth is limited by the VSWR of the individual elements and the use of an internal transformer.

With more than about seven bays, the first three of the above antennas have a more difficult task in being matched and there is undesirable beam squint, since the elevation beam angle changes with frequency deviation by the transmitter. Antennas with more than seven bays are fed from or near the center, thus dividing the phase change in one-half and effectively eliminating the beam squint. Center feeding also simplifies the VSWR matching.

A means for tuning out reactances after the antennas have been installed on the tower is also common with all the antennas. Located at the input to the antenna, the VSWR tuner consists of adjustable location dielectric or metal slugs on the inner conductor of the main coax line. Several fixed position variable capacitors spaced one eight wavelength along the main feeder near the antenna input are also used on some side mounted antennas, to adjust the VSWR to very small values.

Another variety has curved radiating elements, around a circumference whose diameter is determined by the number of element arms. Each radiator consists of two, three or four such circular arms, depending on the model. Each element is fed thru a shunt arrangement, and then shunted across the vertical rigid feed coaxial line.

Wideband panel antennas are becoming popular where high buildings, favorable mountain sites or high towers are available. Several firms make wide band panel antennas. Some have very wide band VSWR features in each radiators. Others with not so broad VSWR, use phase impedance compensation similiar to the European scheme, which uses 90 degree phase quadrature impedance compensation.

[15] Onnigian, Peter: "Stereo Degradation as a Function of Antenna System VSWR" Audio Engineering Society Annual Meeting, AES, New York City, NY. 10017 1976.

Phase quadrature compensation makes it possible to cover the entire 88 to 108 MHz band with a VSWR under 1.1:1 while maintaining excellent elevation, and azimuth patterns, together with very good axial ratios. Power ratings up to several hundred kW are offered so that many FM stations can be diplexed into one such antenna.

Only the wideband community FM antenna design now uses a corporate feed system, while the others are shunt fed from a common rigid coax line. This corporate feed system, using air dielectric semi-flexible line at the lower power levels, is very successful. It splits the input power to many different dipoles at the correct amplitude and phase.

These four basic antenna classes are described in greater detail on the following pages.

SLANTED DIPOLE FM ANTENNAS

Shunt Fed Antennas

The slanted dipole antenna in its present configuration was developed and patented in 1970.[16] It consists of two half wave dipoles bent in 90 degrees, slanted and fed in phase.

Fig. 9. Three bay Cetec model JSCP-3 non-symmetrical FM antenna mounted on the tower leg. The guy cables are insulated fiber glass rods near the tower legs. (Photo courtesy Cetec Antennas)

The slant angle is critical as it is this factor which determines the ratio of vertically and horizontally polarized radiated power. The phase point center is at the feed insulator on the dipole support arm as seen in Fig. 9. When fed thru a vertical support pole on which the antenna sat during initial development tests, the axial ratio was excellent varying less than 1 dB.

The commercial adaption uses a horizontal boom containing a step transformer. This boom supports two half wave dipoles, in which the included angle is 90 degrees. The two sets of dipoles are rotated 22.5° from their normal plane. Two opposite arms of the dipoles are delta matched to provide a 50 ohm impedance at the radiator input flange. All four dipole arm lengths may be adjusted to resonance by mechanical adjustment of the end fittings. Shunt feeding when properly adjusted provides equal currents in all four arms resulting in excellent azimuth circularity.

Series Fed Antennas

A similiar arrangement of arms supported by a T arrangement may be series fed. That is, part of the outer end is insulated from the rest of the dipole and fed across the insulated break. To allow for adequate power handling capacity and to increase the VSWR bandwidth, 3 inch (75mm) diameter tubing is used.

Both antennas have VSWR bandwidths of about 1 percent, so they make excellent single channel FM antennas. They are usually mounted on the side of a supporting tower or pole, and stacked vertically to achieve required power gain. This antenna has much greater wind loading due to its larger element diameters necessary to achieve useable VSWR bandwidth. It presents considerable torque on its mounting structure and requires large amounts of AC power for electrical de-icing. Plastic radomes also present additional wind loading.

Short Helix — Multi-Arm

The number of arms may be increased to four instead of the two in the slanted dipole variety. To provide Cpol, the arms are curved to form a one wavelength circumference. These short multi-arm helices are also stacked in the conventional manner, like the others in this series for power gains as desired.

The azimuth pattern of all these non-symetrical antennas is affected by the supporting steel structure. With pattern optimization, the pattern can be made quite omni-directional. See Pattern Optimization in this chapter.

[16] Onnigian, Peter: Circularly Polarized Antenna, US Patent 3,541,570.

RING STUB AND TWISTED RING ANTENNAS

There are several antennas that are simple adaptations of radiators that were designed and manufactured in the 50s and 60s for horizontal polarization. By adding vertical stubs to the ends of the radiator or twisting the ring, elliptical polarization of sorts is achieved.

Both the ring and the ring stub suffer from temperature variations which tend to change the spacing between the ring openings and thus the electrical capacitance and resonant frequency. The ring stub and the twisted ring are not really circularly polarized because the axial ratio varies considerably with azimuth. At best they may be said to be elliptically polarized.

The radiation patterns are strongly affected by the tower mounting environment. Being of relatively high Q design, they are more susceptible to detuning because of icing. Radomes and electrical deicers are available to overcome this problem. While the icing problems may be overcome, pattern optimization is not offered for these antennas.

The Ring Stub Antenna

The Hpol radiation from these antennas comes from the ring portion whose plane is parallel with earth. There is a minor lobe from each radiator, which is strengthened with vertical stacking for additional power gain. This nadir-zenith lobe is the result of 360° degree stacking on the rigid coax feed line. It reduces the gain and presents a lobe at the tower base which may be detrimental if low level audio equipment is located in a building at the foot of the tower.

In order to keep the cost down, like the twisted ring antenna, the ring-stub is manufactured in several radiator to radiator spacings across the FM band. This results in some minor beam tilt up or down depending on the frequency. The higher priced slanted dipole and helix antennas are spaced exactly 360° and are usually tested to assure this spacing during production.

The Twisted Ring Antenna

This type consists of one or more rings, which have been partially twisted so that the open ends of the ring are about 10 inches (25 cm) apart. One semi-circular arm of the ring is fed with a small loop or by a direct tap on that arm. A number of these rings are fed in the same manner as the ring stubs, and have the same zenith-nadir lobe problem.

The mechanical twist is not the same when viewed in all the azimuth directions. Therefore the current is not the same, with the end result that in some directions there is much more elliptical radiation than in others.

These antennas are very simple and relatively inexpensive for single frequency use, but have some serious operational limitations for Cpol operation. They do not have the same signal penetrating affect as the slant dipole, short helix or the community antenna type of Cpol antennas.

Short Helix

A relatively recent asymetrical radiator is the four arm shunt fed helix. By using four dipoles, curved so that their circumference is about one wavelength, a Cpol antenna can be had.[17] Each dipole is about one half wavelength and is shunt fed. These are supported on a four arm structure, one end of which is tied to the supporting structure. The dipoles overlap so that the current flow around the circumference is circular. The four feed arms are connected in shunt and the feed impedance is quite low, but may be brought up to useful values with an internal step transformer.

The Cpol quality of the four arm side fire short helix is good. Three and two arm models are also available, but their axial ratio is not as good as the four arm. Pattern circularity is ± 1dB for the four arm, together with an axial ratio of about 3 dB.

These radiators are stacked about one wavelength apart on a rigid coax feed line, to obtain the necessary power gain. Like other asymetrical FM antennas its patterns are strongly affected by the supporting structure. See Pattern Optimization in this chapter for the need and methods to circularize the azimuth pattern.

Electrical deicers using the stainless steel dipole arms as one half of the heating circuit are available. Heat is created by passing a large current at low voltage thru each arm from voltage dropping transformers placed at each bay level. Plastic radomes are also available to keep snow and ice off the sensitive VSWR parts of the antenna.

PANEL ANTENNAS

Panel antennas for Cpol FM broadcasting are relatively new in the Western Hemisphere, although Hpol and Vpol have been used in Europe since the mid 1950s. This antenna was developed there to provide a wide band unit for several government stations without the need to change antennas when a new channel was added or the

[17] DuHamel, Ray: "TV and FM Transmitting Antennas" Antenna Engineering Handbook, Johnson and Jasik, 2nd Edition. McGraw Hill Book Co. New York, NY Chapter 28, pp 8-9 1984.

operating channels were changed from time to time.

Panels are from 7 to 8 feet (2100mm to 2450mm) square in the flat configuration. In the cavity style they are about 8 feet (2450mm) in diameter and about 3 feet (1000mm) deep.

A heavy metal frame is often used over which large diameter wire mesh has been welded. The wire mesh screen openings vary from 4 to 12 inches (100mm to 300mm). Electrically they are considered nearly solid metal. For wind calculations these openings produce relatively low wind loads. The entire flat frame or cavity is strong enough to support a man on its mesh openings. Some manufacturers hot dip galvanize their steel after fabrication; others use stainless steel construction.

For FM use, two crossed dipoles are used as the illuminating source for each panel or cavity. Each dipole is fed in phase quadrature, that is one dipole receives its peak current 90 degrees after the other, to produce Cpol. A typical set of electrical and mechanical specifications for a Cpol eight bay cavity community antenna is shown in Table 6.

Flat Panel Antennas

By pulling the dipole back on its feed support arms, the "arrowhead" shaped dipoles control both Vpol and Hpol azimuth patterns. Rotating the dipoles 45 degrees with the earth-ground reference improves the polarization ratios even further.

Round dipoles made of tubing as large as 6-1/8 inches (155 mm) in diameter are used along with a single line quadrature feed. This combined arrangement makes an excellent wideband Cpol panel to cover the entire FM band. Power splitters, dividers and cables along with a number of these panels completes the antenna.

Cavity Panel Antennas

The cavity antenna also uses the reflective properties of the flat screen panel. In the cavity however, the illuminating dipoles are flat instead of round and all four arms are parallel to the plane of the cavity. Like the flat panel with its round dipole supporting balun, the cavity also holds its flat dipoles with a double dipole coaxial balun.

The dipoles in the cavity get their wide VSWR bandwidth thru the sleeve dipole principle.[18] Capacity is provided by a metallic ring close to all four dipole arms placed between them and the back of the cavity. This antenna has the advantage over some other designs of greater VSWR bandwidth. It is considered closer to state of the art due to better elevation and azimuth pattern control of both planes of polarizations by the shape of the cavity.

Crossed Dipole Theory

Common to the flat panel and the cavity is the operation of the dipoles which generate Cpol. The dipoles are fed currents in phase quadrature, thru a coaxially balanced balun, which provides equal currents to all four arms of the two dipoles. They excite the entire cavity or flat panel with a rotating RF field in a plane parallel to the dipoles. The RF field is thus Cpol and may be ideally represented by a rotating vector of constant magnitude revolving one revolution per wavelength of propagation distance. It is right hand polarized as the field rotation is clockwise as viewed from behind the screen, looking toward the direction of propagation, if the phasing between the two crossed dipoles is properly made.

[18] Bock, E.: "Sleeve Antennas" VHF Techniques, Vol. 1, McGraw Hill Book Co. New York, NY Chapter 5, pp 119-137 1947.

TABLE 6. Typical measured community antenna performance.

Operational frequency range	88 to 108 MHz
Safe RMS input power rating	200 kW
Power gain ratio, each polarization	4.4 (6.43 dB)
Maximum VSWR any frequency between 88-108 MHz	1.1:1
Elevation pattern beam tilt	−0.5°
Polarization	Right hand circular
Axial ratio	Better than 2 dB
Azimuth circularity Vpol or Hpol	Better than ±2 dB
Antenna dead weight, less than	7,000 Lbs (3,183 kgs)
Active wind load, RS-222-C 50/33 PSF	8,000 Lbs (3,636 kgs)
Antenna input flanges, two, size	6-1/8 inch
Number of bays (stacks)	Eight
Radiator type	Circularly Polarized Cavity

Radiation patterns, associated beamwidth and directivity are determined to a large extent by the size of the cavity or flat panel. The geometry of the dipole has less effect than the reflector size. The size and shape of the dipole controls the antenna impedance and the VSWR. The screen panel, be it flat or a cavity fulfills the following five important electrical functions:

a) Isolates the radiating elements from the tower or the mounting structure, and reduces mutual coupling.

b) Provides sharper beamwidth and more gain than achievable with the dipoles alone

c) Furnishes pattern control so that the beam width is nearly equal for both horizontal and vertical plane polarization.

d) With an effective balun feed system, the crossed dipole radiated pattern phase is very uniform as the amplitude changes normally with azimuth.

e) Computer aided designs are easily achieved in production for various width towers because the pattern is simply pure electrical geometry.

WIDE-BAND ANTENNA FULFILLMENT

In order for an antenna to be useful throughout the 20 MHz FM band, its operation must be the same on any frequency. The VSWR on 89 MHz for example, must be just as good as on 108 MHz. The Cpol azimuth pattern should remain the same on one end of the band as the other, as must the axial ratio. This is a much more rigorous requirement than placed on the single channel slanted dipole or the ring stub. In the wide-band antennas, several factors go together in order to meet these severe requirements:

a) Basic wideband dipole radiators

b) Screen-panel pattern control

c) Quadrature phase distribution

By using these three principle parameters in a wide-band antenna the radiation pattern, VSWR, and the gain can be nearly the same on any channel within the FM band.

Several methods are used to make the VSWR of the crossed dipoles as good as possible. The dipoles are usually fed with a folded balun or the

Fig. 10-A. Series fed element of Harris model FMXH non-symmetrical antenna. Typical pole mounting with rigid inter-bay coaxial feed line. (Photo courtesy Harris Corp.)

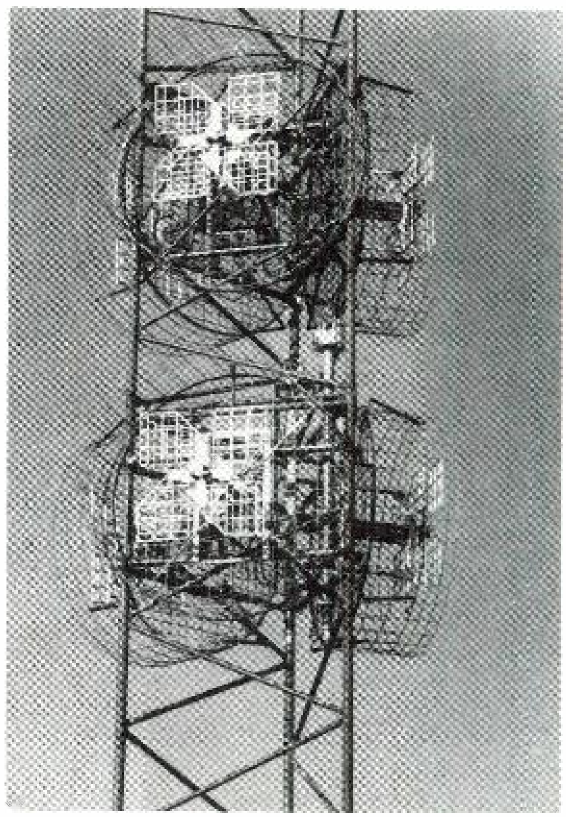

Fig. 10-B. Two bay cavity backed crossed dipole community antenna. Dipoles as well as cavity are made of heavy gauge steel mesh. Typical VSWR is under 1.1:1 across entire FM band. (Photo courtesy Cetec Antennas)

split tube type balun.[19] This improves the impedance match, phase as well as amplitude linearity of the resulting azimuth pattern.

The length to diameter (or width) ratio is usually about three. This not only reduces the Q but also increases the safe power handling capacity by increasing the voltage flash over levels. The low Q also increases the band-width by decreasing the rate of reactance change with frequency.

A natural factor aiding the VSWR problem is the fact that in order to fulfill Cpol from two crossed dipoles, there must be a phase quadrature of the two currents feeding the crossed dipole. The two reflections, as a result of VSWR, return back to the phasing device 180 degrees out of phase with each other. Being the same amplitude, they cancel.

All of the above factors, plus two or three more levels of quadrature reflection cancellations, bring the overall system input at the antenna to under 1.08:1 across the band. This cancellation technique eliminates the need for electrical deicers or plastic radomes, as the VSWR is not affected by moderate ice coatings. However radomes may be necessary with flat panels, to physically protect some radiators from falling ice.

These and other factors all contribute to make the panel-cavity antenna the best possible for either single channel or community antenna use.

Community Antenna Economics

The community antenna fits best in multiple station service. This allows sharing costs so all parties benefit from a superior antenna that each independently could not economically justify.[20]

FCC Docket 80-90 enacted May, 1983, became law in 1984. It requires Class B and Class C stations with less than maximum facilities to upgrade to a minimum facility or face being downgraded. This FCC requirement has widespread impact on existing FM broadcast stations. If a Class C station does not upgrade to the minimum required antenna height of 984 feet (300 m) HAAT within three years of the effective date of those Rules, it will be down graded to a lower classification.

Granted, it is expensive for one station to install its own 1,000 foot (305 m) tower and antenna. But its advantages may be worthwhile depending on the markets served, if it is located on relatively flat terrain with less than required HAAT. The cost is reduced when several stations get together and use one community antenna facility.

Class B and C-2 stations may want to consider putting up their own wide-band antenna at the 492 foot (150 m) level on this same tower. Class A and B-1 stations can settle at the 328 foot (100 m) level, resulting in even greater savings to all tall tower users.

If enough planning is done in advance, it is possible to install all the FM stations of one community on one tower, at considerable savings to all users. Some preclusions are lack of adequate mileage separations, the existence of excellent present facilities, and FAA tower height limitations.

The break-even point appears to be with four stations. When five stations are involved, there is a 20% reduction in cost to each of them, over putting up their own individual single channel antenna and tower at the same height. See Table 7 for a break out of costs for a wide-band community antenna system.

The costs used in Table 7 include the supply of an eight bay Cpol omni-directional community antenna with a gain of 4.40 mounted at the tower top. It also includes a dual run of 6-1/8 inch (155 mm) coaxial transmission line, for upper-lower half feed system. The 1,020 foot (310 m) tower height puts the antenna center at approximately 984 feet (300 m) maximum HAAT level on flat terrain.

The guyed, lighted and painted tower is EIA-RS-222-C spec rated for 85 mph (137 km) ground wind areas. The number of diplexers are equal to the number of stations so there there is always one thru wide-band port left for emergency use if one station loses its diplexer. The dual coax line permits using one half of the antenna in the event of an emergency in one line or one-half of the antenna.

The single channel comparison antenna system also has the same 984 foot (300 m) tower, but with one run of 3-1/8 inch (79 mm) line. Diplexers are not used of course. An eight bay single channel slanted dipole antenna with a power gain of 4.30 is side mounted and has electrical deicers. Its pattern is optimized for a smooth circular azimuth pattern. The VSWR is field adjusted to be under 1.1:1 for ±250 kHz at the station carrier frequency.

TABLE 7. Wide-band panel antenna costs (1985).

Number of Stations	Total Cost of System	% of Single System Cost
4	$1,410,000	Break Even
5	1,460,000	−20%
6	1,510,000	−31%
7	1,560,000	−39%
8	1,640,000	−44%
9	1,690,000	−49%
10	1,740,000	−52%

[19]Rudge, A.: "Handbook of Antenna Design" Vol. 2, Peter Peregrinus Ltd. London, England. pp 917-922 1983.

[20]Onnigian, Peter: "Multi-Station FM Antennas" paper presented at 23rd Broadcast Symposium, IEEE Group on Broadcasting, Washington, D.C. 1973.

All outdoor installation work was included in the costs shown. Both sets of costs have one antenna field technician for VSWR and checking-adjusting the diplexers in the community example. Tower foundations and buildings are not included as this is a variable cost item, and may be done by the owners.

Community Antenna Technical Advantages

Besides the financial advantages cited under the economics heading there may be the competitive advantage of protecting the channel classification under Docket 80-90 and using the same height antenna as the competitor. Other advantages include its emergency upper-lower half feature for transmission line or antenna half backup. The flat VSWR curve is highly useful for SCA and stereo operation. Stations sharing this type antenna will all experience less intermodulation interference than if they had separate antennas, but closely placed.

DIRECTIONAL ANTENNAS

The FCC sometimes requires that the azimuth radiation pattern be directionalized to reduce normally allocated ERP towards a given short spaced station, or for other reasons. See Sections 73.213 and 316 (c) and (d). To conform to these specifications, most broadcasters order antennas which are pattern adjusted, measured, and certified to the Commission's requirements. Directional antennas are licensed for peak ERP values resulting from the azimuth pattern. The Vpol RMS gain may not exceed the Hpol gain in a Cpol directional array, nor may Vpol exceed the Hpol in the protection direction (except in the case of FM protection to TV Channel 6, previously mentioned). The amplitude away from the null cannot climb more than 2 dB per 10° of azimuth.

Directional antennas are usually on poles although some have been tower mounted. Since the support affects the pattern, they are sold with the pole or tower on which they are tested. One firm supplies a choice of four standard patterns, while others will make the antenna meet the specific pattern requirements. There have been some instances of protection to two stations, making the pattern attainment quite difficult.

Directionalizing is a combination of the natural pattern resulting from side mounting and the use of parasitic elements. Using the two factors, any directional pattern specification may be met with sufficient work.

High Transmitter Power ERP Myth

Some people have thought that a high power transmitter with a low gain antenna to yield the required ERP somehow would put a stronger signal into the service area, than a low power transmitter with a high gain antenna. Nothing could be further from the truth.

The ERP is the product of the antenna power gain and the antenna input power. Many different combinations of power gain and input power will yield the same ERP. The azimuth pattern will be quite similiar for many different antenna power gains.

The only difference in various combinations is the elevation pattern. As discussed under Typical Class A and Class B coverage section in this chapter, there is no momentous or important difference in serving listeners from very different transmitter/antenna ratios.

The signal strength at any given location is a direct function of the ERP from the antenna elevation pattern angle to that location, the height of the antenna, and the propagation path. The ERP at the pertinent angle is the product of the elevation pattern amplitude at that angle squared, times the maximum ERP. In practice there is no significant difference between a 3 kW ERP Class A station using a 7.5 kW transmitter and a one bay Cpol antenna, or, one using a 1 kW transmitter and a six bay Cpol antenna, all other factors being equal.

ANTENNA GAIN AND TRANSMITTER POWER

Several available combinations of antenna gain and transmitter power will provide the necessary ERP. But which combination is the best? The choice is further complicated by the nature of the terrain in the service area. Is it all flat, some rolling hills, mountainous or a large valley? What are the regulatory limitations on the antenna supporting tower height?

Important considerations when choosing the transmitter power and the antenna gain combination to produce a given ERP can be listed as follows:

Transmitter	Feed System
Antenna	Transmitter Tubes
Tower	AC power consumption

The transmitter, antenna, tower, and coaxial feed line are one time capital costs for the station equipment. Tube costs and commercial power use, however, are a continuing hour-by-hour cost factor. From the above it is apparent that a low power transmitter is much more economical than a high power transmitter. But is there a difference in signal strength?

It must be remembered that normally all the ERP above the antenna elevation pattern to the horizon is wasted. It is the radiated power below the angle to the horizon that strikes the earth with all its FM receivers. Therefore only the radiated power towards the earth should be considered useful.

The ideal antenna system would put the same signal level from the base of the tower all the way out to the horizon. This requires an antenna whose elevation pattern is a cosecant curve, the normalized reciprocal of sine. It would be the perfect antenna elevation pattern. Although this curve is impossible to achieve, it is approached as the antenna gain becomes greater.

High Gain Antenna Contradictions

The many advantages of high gain-low power transmitter combinations to produce the ERP have been shown. Their superiority in relatively flat land applications cannot be disputed.

There is however the matter of unusual height over terrain to be considered. If the transmitter is located at Mt. Wilson, California for example, or on a very tall building in Chicago, or New York, the elevation pattern problem becomes serious. This is especially serious, when there are listeners near these sites as is the case for all three locations cited.

Mt. Wilson serving the greater Los Angeles metropolitan area is more than one mile (1.6 km) above most of its listeners. In fact coverage is required from 11 miles (17.75 km) out to the horizon which is −0.57 degrees at 105 miles (168 km). Pasadena the city nearest is −13 degrees below the horizon. A high gain antenna tilted down −0.5 degree would serve the far reaches well, but would not lay down a moderate signal at −13 degrees.

Docket 80-90 limits the ERP for overheight antennas such as those on Mt. Wilson which average 2900 feet (884 m) HAAT. New stations using that height must reduce ERP in accordance with the equivalence calculation, so that the predicted signal at the 1 mV/m contour does not extend beyond 32 miles (52 km) for Class B stations.

In these situations a moderate gain antenna should be considered. From Mt. Wilson several existing four and five bay antennas now provide excellent service.

STATION DIPLEXING

Diplexers are used to combine the power of two or more stations and feed the combined power to a common transmission line and/or a common transmitting antenna. This system of utilizing one well-sited high quality antenna has become popular, convenient and economical.

Wide band panel antennas, although expensive for use by one station, are very cost effective for two or more stations. These antennas maintain their omnidirectional horizontal plane patterns and VSWR thru out the FM broadcasting band from 88 to 108 MHz. Thus, they make the ideal antenna for multi-station diplexing.

Diplexers

A diplexer is a passive device used to combine two or more stations into a single master antenna. New channels at any power level may be added in any order by connecting another diplexer in tandem to the previous unit. The first channel may be fed into a wide band antenna without a diplexer, of course. When two stations are to be combined, the first diplexer is put into service. When the third station is added to the system, a second diplexer is required and so forth. Figure 11 shows this arrangement.

Each diplexer contains a thru broadband input port and an injected frequency port. Nearly

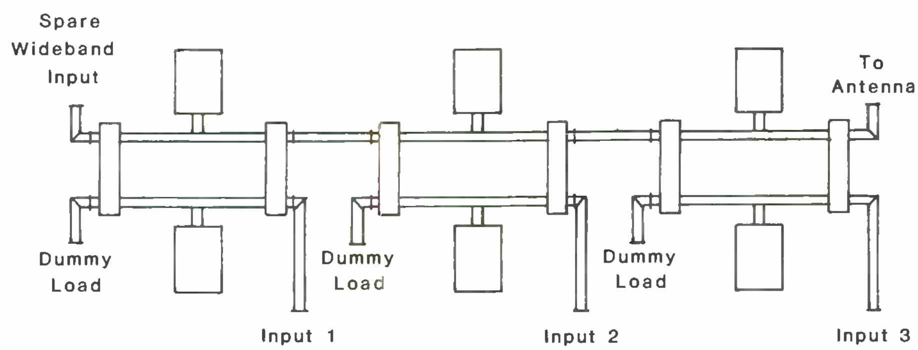

Fig. 11. Three diplexers connected to provide combining facilities for three different stations for one community antenna. Note spare emergency wide band input port.

TABLE 8. Typical measured diplexer performance.
(Three Channels Into One Antenna)

Channel frequency	93.5 MHz	99.3 MHz	100.5 MHz
Input VSWR, plus minus 250 kHz	1.1:1	1.04:1	1.04:1
Isolation: From 93.5	—	−80 dB	−80 dB
From 99.3	−59 dB	—	−50 dB
From 100.5	−80 dB	−50 dB	—
From broad band port	−56 dB	−44 dB	−39 dB
Amplitude Response:			
Carrier plus minus 250 kHz	0.15 dB	0.25 dB	0.35 dB
Group Delay, in nanoseconds:			
Carrier plus minus 250 kHz	25	27	38
Insertion Loss, carrier	0.23 dB	0.24 dB	0.23 dB

all uncombined diplexer power and other undesired products are absorbed by a dummy load connected to the fourth port. The third port goes to the antenna or to the next diplexer's broad input port.

The combining of two different channels must be done without degradation to either of them. The important factors are amplitude, phase delay, VSWR bandwidth, isolation and insertion loss. Insertion loss is a continuing expense item as it consumes RF power that is generated by the transmitter at considerable expense.

Diplexer specifications can be tailored to the specific requirements of the transmitters being used. See Table 8 for a typical three diplexer measured performance. The end user can rest assured in advance of construction that the system will perform to specifications without fear of over or under design of the components within the system.[21]

Constant Impedance Type Diplexers

The constant impedance type takes its name from an operating characteristic of one of its components, namely the constant impedance of the broadband 3 dB hybrid. All of this type use two hybrids and cavities. Because of the use of hybrids the type is sometimes called a hybrid combiner.

An efficient diplexer is not a complicated device, as it consists of two basic components, the two hybrids and two cavities. A terminating absorption load soaks up any rejected power. Coax is used to interconnect these components. Hybrids and cavities either have coaxial flange connections or are directly coupled. Some units are pressurized to keep moisture from tarnishing the cavities which may be silver plated or polished copper, in order to attain high Q.

A terminating load, rated at one half the highest transmitter power being diplexed in that unit is connected to the reject port. In the event of failure of one or both cavities, half of the power will appear in this load, before thermal and other sensors normally turn the affected transmitter off.

The hybrid, sometimes called a 3 dB coupler, is a four port device. When power is fed into one port, it appears split 50/50 percent in two other ports, thus the name 3 dB coupler. Another very useful feature is that the two split powers are 90° apart in their phase relationship. The fourth port is isolated from the input port typically by 26 to 40 dB. If two of these hybrids are connected back to back, nearly all the power entering the first input port will appear in one of the output ports, and a second port will be isolated.

In TV use, a single hybrid is quite useful in feeding a turnstile batwing antenna, which requires split input power with a phase quadrature displacement. The old square quarter wave TV hybrid diplexers are similar in operation, but they are relatively narrow band devices and not suitable for wide-band use in FM community antenna diplexing.

These FM diplexer hybrids are capable of extremely high power as they are usually made of large coaxial components with quarter wavelength coupling bars. Their large physical size and low Q greatly reduces power loss which rarely exceeds 0.05 dB (1.1%).

Many constant impedance diplexers use only reject cavities. Each diplexer contains a thru broadband input port and an injected frequency port. Nearly all uncombined diplexer power and other undesired products are absorbed by a dummy load connected to the fourth port. The third port goes to the antenna or next diplexer's broad input port.

In this approach, such as the band reject diplexers shown in Fig. 13, the signal from TX_1 splits equally in hybrid H_1. It passes by the cavities which are tuned to TX_2 frequency. The two signals of TX_1 combine in the antenna output port of hybrid H_2 since the two inputs to H_2 are equal in amplitude but 90° out of phase, due to the action of hybrid H_1.

[21]Smith, S. and Weirather, R.: "Design Criteria For Multi-Station Combining Systems" NAB Engineering Conference, NAB, Washington, D.C. 20036 pp 125-144 1983.

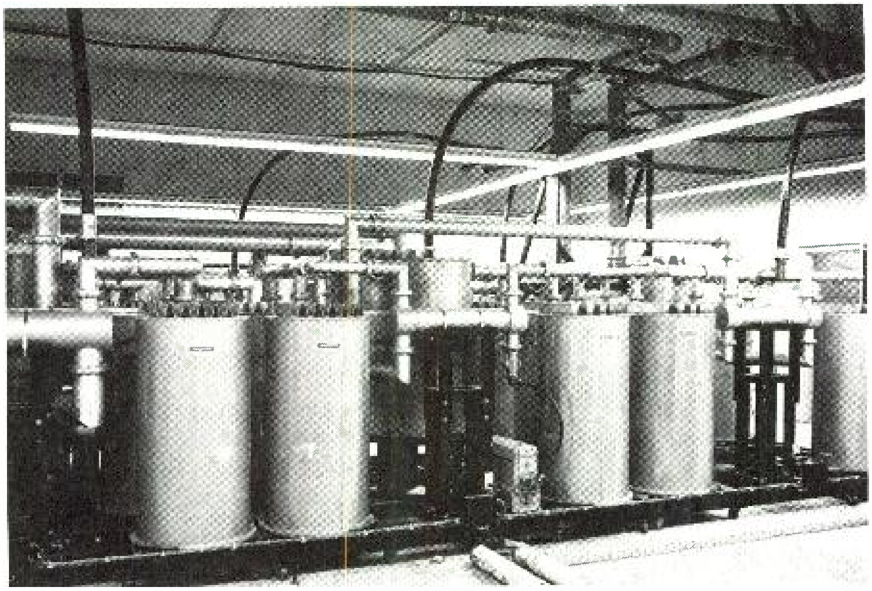

Fig. 12. This Senior Road, Houston, Texas ten port diplexing system, combines nine FM stations into one community antenna. It is capable of 350 kW total input power. (Photo courtesy Harris Corp.)

The signal from TX_2 splits equally in hybrid H_2 and are 90° out of phase with each other. Cavities C_1 and C_2 are tuned to the TX_2 frequency and present a short circuit to it. So the signal is nearly 100 per cent reflected back to the inputs to H_2. These signals are 90° out of phase so they combine only in the antenna port of H_2 and go up to the antenna.

TX_1 frequency is not critical and can be any frequency within the FM band, as long as it is removed from the cavity frequencies by at least 1.0 MHz. However, it will work with some makes of reject diplexers when the separation is a minimum of 800 kHz.

The cavities tuned to TX_2 are not critical in their spacing from hybrid H_2. Because of the nature of the two hybrids, the VSWR remains low and is not affected by temperature variations. The isolation also remains high under these conditions.

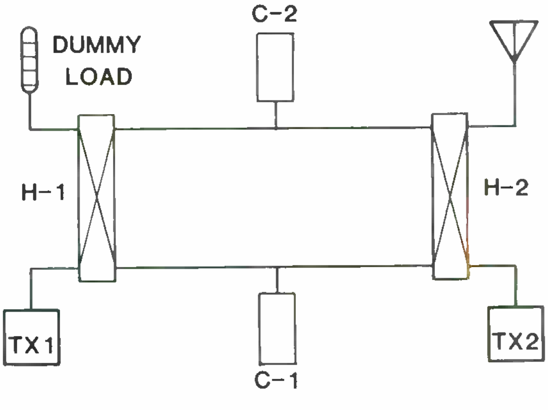

Fig. 13. Basic constant impedance diplexer. See text for explanation of component functions.

Another advantage of the constant impedance notch diplexer is that any beat frequency or intermod product generated in the transmitter TX_2 will be absorbed in the dummy load since only TX_2 will be reflected. This is due to the frequency selectivity of C_1 and C_2.

When more than two transmitters are to be combined, the additional diplexers are merely added in series as shown in Fig. 11. Additional diplexers do not affect the performance of the rest of the system, and can be added at a later time if the need arises. Because of the simplicity of the constant impedance diplexers, they are virtually maintenance free.

Branched Starpoint Diplexers

This type does not use hybrids. Each transmitter feeds into a set of branching filters. In each set there is a bandpass cavity tuned to pass the operating frequency and at least one reject cavity tuned to the frequency of the adjacent channel to sharpen the skirt selectivity. If more than two frequencies are being combined, the middle frequencies have reject filters for both their adjacent frequencies.

All the filter sections connect to one common junction or starpoint which is the combiner's output. Coaxial cable lengths between each diplexer and the starpoint must be a defined electrical length for proper filtering action and low VSWR. This type of diplexer does not use an absorption load, as the small amount of rejected power is consumed by the rejected frequency transmitter and the antenna.

There is no broadband input, so adding channels requires that balanced modules be added on the output. If there is a failure of one branch, it will usually not take the others out of operation. Since there is no broadband port, the affected frequency cannot be switched as would be done with a hybrid diplexer system. However, the transmitter from the failed branch may be operated into one half of the antenna, while the output of the combiner, containing the unaffected channels feeds the other half, for an ERP reduction of 3 dB.

The principal advantages of a branched system are in space and price. There are fewer components, i.e. no dummy loads, no hybrids, and fewer cavities. They are frequently fan cooled, thus permitting the use of smaller cavities. This is all at the price of flexibility and, in the case of some makes, performance.

Cavity Construction

In order for these diplexers to work, a frequency selective electrical short circuit is required to be placed between the two hybrids. This is provided by high Q cavities.

During World War II, low pass and high pass filters were developed for VHF communications and radar. The need for microwave receivers with greater selectivity led to the development of magnetically coupled quarter wave length long cavities. Improvements since the 40s have made cavities with excellent loaded Qs and extremely low insertion loss.

Temperature stability improvement is the result of invar steel, and the high Q resulting from silver plating and polishing the inside of the cavities. Cavity size for FM use varies due to the resonance mode selected by the design. Round cavities as small as 20 inches (508 mm) in diameter and 30 inches (760 mm) long have been used. Square types as long as 60 inches (1524 mm) using waveguide modes have been used. Generally speaking the larger the cavity, the smaller the RF loss thru the cavity.

A very high loaded Q is necessary for close frequency spacing of 800 kHz being the closest assignment in any specific community. Practical values vary from 1,000 to 12,000.,

The power dissipated in heat will expand critical parts of the cavity, detuning it if the heat is not efficiently removed. Air blowers, cooling fins or simple black paint are used, depending on the amount of heat to be removed.

The cavities contribute most of the loss found in a diplexer, due to the ineffectiveness of the cavities. A diplexer with its two cavities tuned to the first possible channel 800 kHz away could have an efficiency of about 95% (0.25 dB loss). Efficiency goes up as the spacing between the pass and the reject frequency increases so that at 1.6 mHz it could be 96% and at 2.3 mHz, about 97%.

An extremely high Q would be excellent on the operating frequency but would not be useful on the FM sidebands. Using twice as many cavities and stagger tuning them increases costs and does not really solve the efficiency problem.

TYPICAL COMMUNITY ANTENNA SYSTEM

In 1984 a group of Houston, Texas broadcasters formed the Senior Road Tower Group, and installed a 2,049 foot (625 m) tower supporting a 12 bay community FM antenna system, with its HAAT at 2,000 feet (610 m).[22] This height permits the maximum ERP under Docket 80-90.

Two runs of 8-3/16 inch (208 mm) diameter coaxial lines are used to feed the antenna in such a manner that power in both the lines causes right hand Cpol from the antenna for all stations.

The nine stations use one diplexer each, all housed in one 2,400 square foot (223 square meters) room. The 10 port modular diplexer has a total power handling capabilty of 350 kW. The insertion loss for each station is 0.80 dB (17% loss). The coupling between the various transmitters does not produce intermodulation products exceeding the Commissions requirements.

All the diplexers are monitored at a central operating rack which indicates each diplexer's forward, reflected, and rejected power. This permits trouble shooting in an orderly and rapid manner. Electrically operated coaxial switching permits each station to be connected to the dummy load for individual testing. Air conditioning and chilled water are used to remove heat produced during operation.

The tower also holds one UHF TV antenna below the FM antenna, in addition to three levels of two way radio communications antennas at the 800, 1,200 and 1,400 foot (244, 366 and 427 m) levels. In addition there are individual single-bay Cpol antennas for each station, fed with a 3-1/8 inch (79 mm) line.

The income projected from the use of the 2 way radio antenna facilities can defray the operating costs of the entire plant including the electrical power bills.

This community FM antenna project is important because it clearly demonstrates the technical feasibility of a large system with nine FM users. It demonstrates that the full intent of FCC Docket

[22]Fisk, Ronald: "Design and Application of a Multiplexed Nine Station FM Antenna, Senior Road Tower Group" Technical Monogram, Harris Corp. Quincy, IL 62305 1983.

80-90 can be met to the broadcasters satisfaction, as well as its wider range of listeners.

The technology is now available to combine multiple Fm stations efficiently and without problems. The only hindrance is the chemistry required to bring broadcasting managements together to start, talk, fund, and complete such a large undertaking.

FM ANTENNA INSTALLATION ON AM TOWERS

The current trend is to locate FM transmitters in places where the best service may be rendered to the most listeners. This usually permits the maximum possible height to be used. Sometimes however, it may be economical and convenient to install the Fm antenna on a tower used for AM broadcasting. If the steel AM tower is not base insulated but is grounded and shunt fed, the FM coaxial line may be connected to the tower, without any further problems.

However if the AM tower is insulated at the base in the conventional manner, an isolation transformer may be used. This is designed to couple the FM power across the base insulator of a transmitting tower used jointly as an AM and FM radiator without introducing objectionable mismatch into the FM antenna feed line. An isolation transformer is especially desirable for feeding high impedance AM radiators or AM radiators which are part of an AM directional antenna system which might be adversely affected by a bazooka type (quarter wave) isolation system.

These transformers have two tightly coupled RF coils which are resonant at the FM operating frequency. An adequate air gap is provided for the AM power thru the two resonant loops. The capacity is quite low resulting in a very high capacitive reactance placed across the tower base insulator.

Fig. 14 shows the internal basic construction of a typical isolation transformer. The insulation for AM under the top of the box may be high density polyethelyne, teflon, or fiberglass. The metal top provides a rain shield as well as protection from dust, mud or snow.

The use of these isolation transformers permits the AM tower to operate undisturbed by the presence of the FM antenna. It also allows the FM coaxial line to be connected in the usual manner, except for the placement of the isolation transformer. These have internal gas blocks and permit the passage of dry air pressure thru the transformer via a plastic tube.

In addition to lower cost, the isolation transformer method has another advantage in directional AM tower use. It does not cause undesired

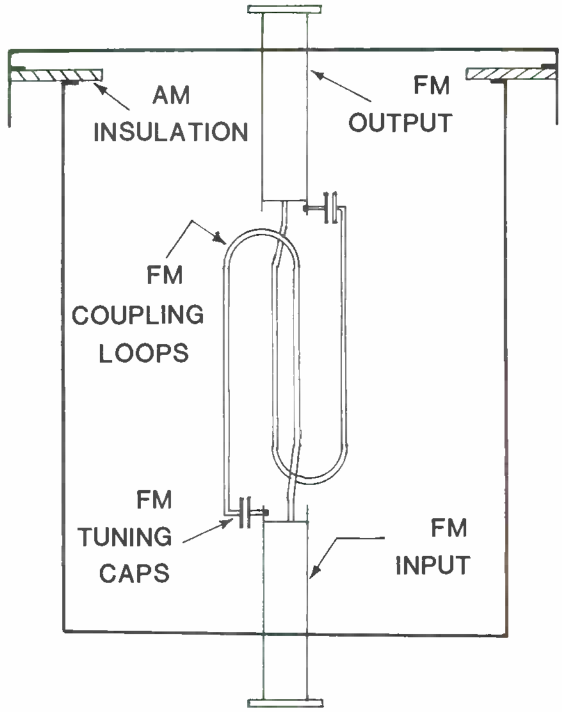

Fig. 14. Typical AM-FM tower isolation transformer, used to decouple FM transmission line on a series fed AM tower.

AM radiation which may change the protection null values.

A less popular and older method is to use the technique of quarter wavelength transmission lines. Simply stated, the opposite end of a shorted quarter wavelength line has high impedance. This high impedance is placed across the AM tower base and may be successfully used to provide the necessary isolation. It is more difficult to physically accomplish this as the tower should be at least one quarter wavelength high, and the FM antenna coax line must be insulated all the way down the tower. In practice the insulated part may be as short as 75 degrees of line, as the line hangers and distributed capacity of the line tend to electrically increase the physically shorter line.

FM TOWER GUYING

Need For Breakup

The presence of continuous steel guy cables going thru the FM antenna level on a steel supporting tower was studied by Jampro Antenna Company (now Cetec Corp.) in 1968. It was found that guy cables had an effect of less than 0.6 dB in the azimuth pattern of a Hpol antenna. On Vpol the maximum variation was 1.8 dB on the azimuth pattern. The strongest effect is on Cpol where the azimuth pattern change was as great as 3.4 dB. The elevation pattern was also affected since the first and second nulls were filled as much as 4 dB.

In addition to pattern anomolies the steel cables reradiate near the ground. This may cause RF feedback problems in some high power installations with low level audio equipment located in a building near the base of the tower.

Strong currents may be induced when the steel guys are in the immediate vicinity of the radiators, and pass very close to them. If that guy passes close to the side of the radiator, it will be acted upon by the field on that particular side of the antenna element and currents will be induced on it. The radiator currents become unbalanced and the impedance of the element is disturbed, changing its VSWR and radiation pattern.

Because of these effects, it is now common practice either to break up the guys using insulators, fiberglass rods, or plastic guy cable, within 10 feet (3m) of the antenna radiators. When a Cpol antenna is side-mounted on a guyed tower, the vertically polarized field will have an appreciable component parallel to the guy wire in its aperture and will induce currents in the wire. If the guys are continuous, a progressive wave traveling toward the ground will result, and will radiate most of its energy before reaching the ground. The energy will be radiated in cones concentric with the wire. A small amount of the Vpol power will thus be bled off.

Porcelain Insulators

If the FM antenna is side-mounted on an AM tower, which usually will have metal guys and porcelain break-up insulators, those insulators will probably be spaced several FM wavelengths. The induced currents will form standing waves on the sections between insulators and radiate multilobed patterns into space at many angles from the wire axis. If the sections between insulators happen to be of a resonant FM wavelength however, currents in the guy wires and their radiated fields will be considerable.[22]

Some broadcasters have thought they should be spaced 3/8 wavelength. It has been pointed out that a single isolated piece of guy wire with its ends insulated can only resonate in multiples of one half wavelength, and so this spacing of insulators must be avoided. In fact, with the capacitive end loading of the insulators, the resonant length of wire will be somewhat less than one half-wave, and so 3/8 wavelengths should also be avoided. A quarter wavelength is much better, but this would be quite expensive as it requires insulators every 30 inches (762 mm).

Because of this all the guys thru the FM antenna aperture on the tower should be replaced with plastic cable, which is transparent to RF energy.[23]

Plastic Guys

To keep up with the state of the art, any guy cable going thru the antenna level should be of non-conducting material. Plastic fibreglass (GRP) insulating rods as well as flexible plastic rope covered with a PVC plastic jacket are often used. The black jacket prevents deterioration due to ultra violet sunlight radiation, which may be injurious to the plastic strands of the rope. This plastic rope has been successfully used for more than 25 years.

The idea is to remove metallic RF conducting steel guy cables from within the antenna aperture. The rest of the guy may be of steel construction. The length of the steel guy from its attachment point near the antenna is simply replaced with an equal length of fibreglass rods, or plastic rope.

The plastic rope is available in continuous lengths of up to 1,000 feet (304 m) and kits are available for installing the end fittings. The cable is quite flexible as the Fig. 15 shows a 225 foot (69 m) length coiled up with its end fittings installed at the factory.

The cable may be purchased in strengths exceeding similar diameter steel guy cable. These strengths are shown in Table 9 for corresponding size of commonly used EHS (extra high strength) steel guy wire. Sizes smaller and larger than shown in the table are available.

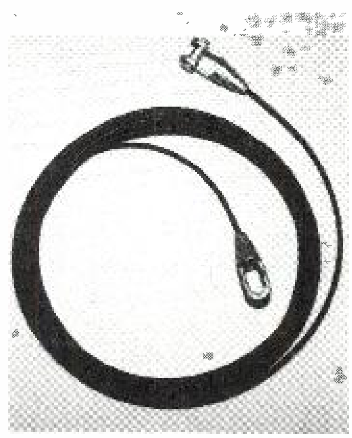

Fig. 15. A roll of plastic guy cable with eye and jaw end connectors in place. Diameter strength is equal to EHS steel stranded guying cable. (Photo courtesy Phillystand—Philadelphia Resins Corp.)

[23]Gregorac, L.: "Electrical and Mechanical Analysis of Plastic Guys of Broadcast Towers" Technical monogram. Radio-Television Ljubljana, Yugoslavia. 12 pp 1973.

TABLE 9. Phillystran type HPTG plastic guys.

Outside Diameter		Break Strength		Jacketed Weight		EHS
Inches	mm	Pounds	Kgs	1,000 Ft	300 m	Equivalent
0.20	5.1	4,000	1,815	18	8.2	3/16
0.29	7.4	6,700	3,039	31	14.1	1/4
0.42	10.7	11,200	5,080	55	24.9	5/16
0.46	11.7	15,400	6,975	69	31.3	3/8
0.53	13.5	20,800	9,435	93	42.2	7/16
0.58	14.7	27,000	12,247	115	52.2	1/2
0.63	16.0	35,000	15,876	142	64.4	9/16
0.68	17.3	42,400	19,235	167	75.8	5/8
0.73	18.5	58,300	26,445	195	88.5	3/4

PATTERN OPTIMIZATION

Single station FM antennas are usually side mounted on a pole or tower. This is economical and it frees the tower top for other possible uses. Unfortunately the pole or tower tends to distort the radiation pattern, seriously affecting station coverage in some directions.[24]

This problem arises from the fact that FM antennas have nearly always been randomly attached to a support tower. FM antenna makers do not manufacture and sell towers. A few have made supporting poles on which the FM antenna has been affixed, adjusted, and pattern tested. TV antenna makers, on the other hand, always make the antenna as a complete self-supporting structure to be mounted on top of a support. They are not usually faced with this side mounting problem.

Due to the early uneconomic days of FM broadcasting this practice of arbitrarily mounting the single channel antenna continues. The logical but more expensive solution would be to make the FM antenna a self supporting structure just like TV antennas.

Best guess and gut feelings used to pick a particular mounting or orientation on the tower leg or face have proven futile and in some cases disastrous. Measured patterns have indicated many times that the maximum radiation can be in the opposite direction from the best guess direction.[25]

Why Optimize?

Why gamble with the FM stations antenna coverage? Nulls may be toward important service areas. Nulls as low as one percent of the RMS power have been measured with towers varying in width from 18 to 120 inches (0.5 to 3 m).

Another problem is that with nulls come lobes. Lobes as great as 9.8 dB over RMS have been found. When used without pattern optimization, this lobe would produce an ERP in a given direction nearly ten times the FCC licensed value.

Translating this to a 50 kW ERP station there would be radiation in some directions of only 0.5 kW and others with 477 kW. This is a maximum to minimum ratio of 29.8 dB and clearly not acceptable to the broadcaster.

With Cpol came additional problems as the Hpol and the Vpol ratios are not always the same and vary moderately in any given azimuth. This ratio can be as great as 15 dB and must also be addressed in order to resolve the horizontal plane circularity problem. The axial ratio should be improved, as the Vpol radiation in certain directions can be much stronger than the Hpol. This violates the Commission's requirement that with Cpol, the Vpol must not be stronger than the Hpol component.

Section 73.316 of the Rules covers FM antennas but does not specifically address this problem of azimuth circularity. In fact the FCC assumes that FM non-directional broadcast antennas have perfectly circular horizontal radiation patterns.[26] In practice they do not.

In order to produce a horizontal plane pattern which even approaches a circle requires considerable work by the firm making the antenna. Since it is nearly impossible to do so with a non-symetrical side mounted antenna, the term optimum—to do the best possible—is in common usage now.

Theory of Optimization

Fig. 16 indicates how energy from the horizontal loop representing Hpol is intercepted by a pole and re-radiated. Similarly, in Fig. 17 energy from the vertical "dipole" is intercepted and re-ra-

[24]Knight, Peter: "Re-radiation From Masts at Radio Frequencies" Proceedings of IEEE, Vol. 114, pp 30–42, January, 1967

[25]Jampro Antenna Co., division of Cetec Corporation. Internal technical communication. Cetec Corp. 6939 Power Inn Road, Sacramento, CA 95828

[26]FCC Public Notice "Criteria For Licensing of FM Broadcast Antenna Systems" Notice 84-437 35004, September 14, 1984 Federal Communications Commission, 1919 M Street, N.W. Washington, D.C. 20554

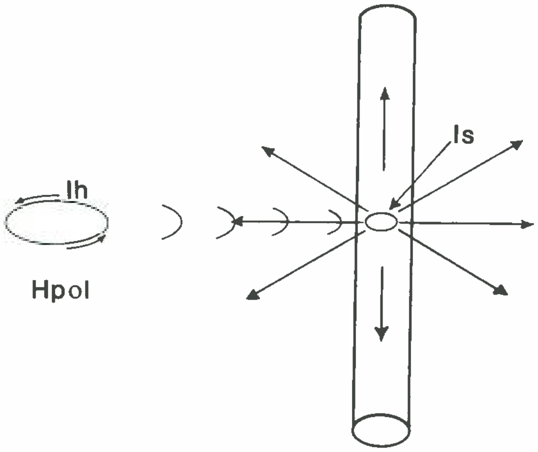

Fig. 16. The effects of supporting steel towers or poles on one side of a non-symmetrical antenna are shown as horizontally polarized currents Ih flow on supporting members as Is and re-radiate in all directions.

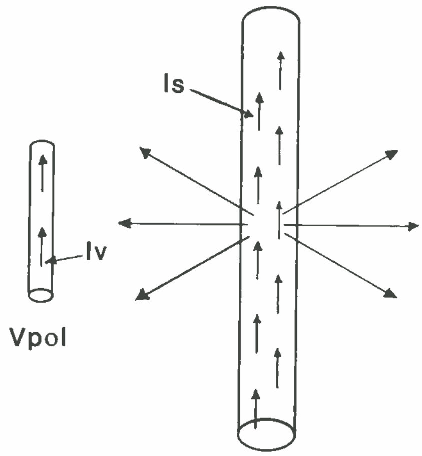

Fig. 17. Vertically polarized current Iv flow over the supporting structure members as Is and re-radiate in all directions.

diated as Vpol. In the first case, the pole diameter is small in wavelengths in the direction of the electric field, thus, scattering is minimal and not much in the Hpol radiation pattern can be expected. However when the Vpol dipole excites the pole, a large amount of energy is intercepted (Is) and re-radiated because the large dimension of the pole (length) parallels a great part of the electric field. A similar effect is produced by the vertical transmission line which is common to the antenna itself, Iv in Fig. 17. The result is appreciable distortion of the vertically polarized azimuth pattern.

Fig. 18 compares the resulting Hpol and the Vpol patterns. As seen, the pole and/or vertical

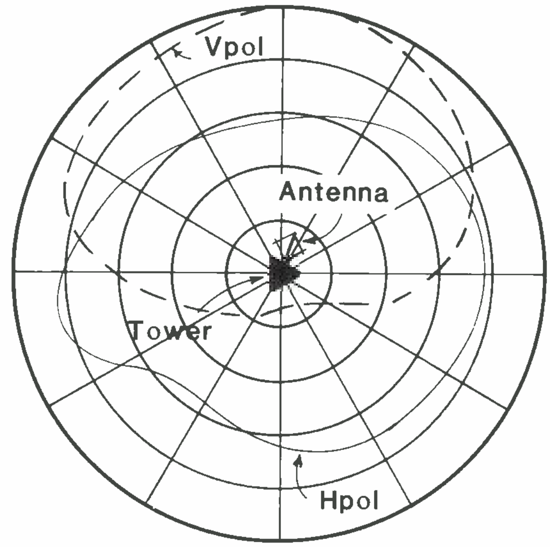

Fig. 18. Combined results of Hpol and Vpol re-radiation distort both patterns, producing more than 17 dB variation. This poor Cpol pattern should be pattern optimized to smooth out the azimuth pattern.

coaxial line have transformed the Vpol pattern from circular to a cardioid, while the Hpol pattern remains essentially omnidirectional. The null of the cardioid is generally more than 7 dB down from the RMS value. This phenomenon is well known, and as a compromise, broadcasters generally install the antenna on the side of the tower support structure facing the main service area. There are many exceptions to this, as some measured patterns on triangular towers of standard construction have shown.

In Fig. 18 the Vpol is much stronger than the Hpol in the favored direction. In the opposite direction, there is little Vpol. The power ratio of Hpol to Vpol is 16 times. This makes for a very poor Cpol antenna.

Towers and poles under about two feet (0.6m) in cross section will exhibit the same effects on the antenna patterns, as in Fig. 18. Towers greater than this size obviously will increase the complexity of scattering effects. Three or four tower legs, the horizontal and diagonal cross members, transmission lines, ladders, if any, tower lighting and deicer conduits, all will be excited by the vertical and horizontal currents from the radiators. All these surfaces will re-radiate and affect the horizontal plane patterns.

In contrast to the unique simplicity of the antenna on the side of a pole, the tower supported antenna may be mounted on the face, or on a corner, at or between horizontal cross members, or tilted at various angles compared to the tower—all multiplying the complex factors affecting the patterns.

Optimization Methods

The most popular technique to achieve the desired pattern is thru the use of Yagi antenna principles wherein parasitic elements are placed in the field of the radiator to modify its radiation pattern. As known, a shortened dipole (director) placed in close proximity to a radiator re-inforces radiation in the forward direction, and suppresses the signal in the opposite direction. If the parasitic element is longer than the radiator (reflector), the effect is reversed. The signal is suppressed on the side of the parasitic element and reinforced in the direction of the radiator.

Similarly, parasitic elements can be used with FM antennas mounted on the sides of towers or poles, to produce pattern changes. As discussed here, both directors and reflectors may be used. Both are frequency sensitive. The effects of the supporting structure are also frequency sensitive.

Therefore, an arrangement of parasitic elements for a given FM frequency will not necessarily be the same for another, nor will the pattern be the same for a given arrangement, if it is moved up or down the tower by as much as one and one half feet. (0.5m)

The resulting patterns cannot be predicted. There are many factors which affect the horizontal plane pattern. Only by actual antenna pattern range testing can the patterns be adjusted and properly measured. Therefore the cost for doing this is high, since it is time consuming, and requires qualified antenna technicians and the use of a complete range. In addition the final parasitic arrangement must be fabricated, and hot dip galvanized. However the results are well worth it.

Pattern Service

There are two basic types of pattern service furnished by several antenna manufacturers in the United States. FM antennas may be adjusted for the best omnidirectional pattern possible or they may be adjusted to provide minimum ERP values in particular azimuth directions. One California firm takes the minimum required values plotted on a polar chart by the broadcasters, with the tower orientation. Using the customers make and model tower, two or more bays of the antenna are fabricated, installed on the tower, and put on the test range. Adjustments are made such as leg chosen, distance from the leg and the orientation of the antenna with respect to that leg. After this has been optimized, parasitic elements are used to further improve and shape the pattern, so that the minimum ERP values will be achieved in the customers service area as given with the order on the polar plot.

For example, the customer of a Class A station may wish that a minimum of 3 kW be radiated in a pie from say 90° to 120° and the remainder of the azimuth be no less than 1.5 kW. This would then require the technicians to achieve a pattern without any field voltages less than 70% and that the vectors between 90 and 120 degrees to be 100%. This sort of work has been done since 1964 by Jampro/Cetec, and later by ERI, Shively and Dielectric Products/RCA. See Fig. 19 for a typical optimized pattern.

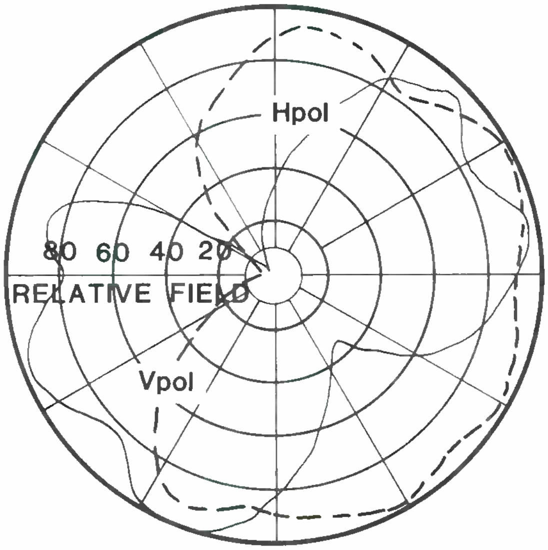

Fig. 19-A. Measured non-symmetrical Cpol pattern of tower side mounted antenna. Vpol variation is ±15 dB, while Hpol is ±12 dB. The axial ratio was 24 dB. Antenna patterns are very poor.

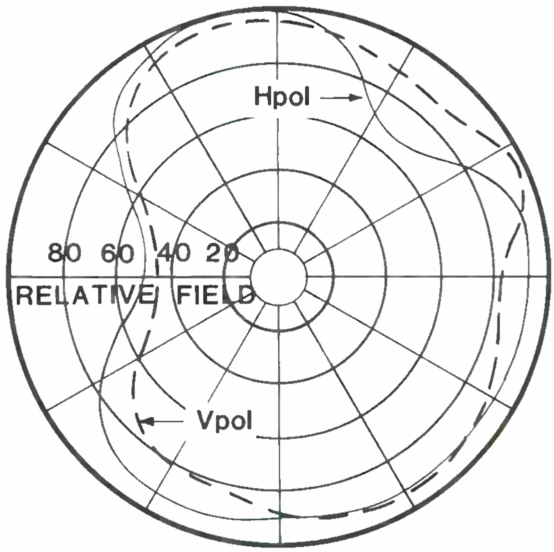

Fig. 19-B. Same antenna as 19-A but much improved after pattern optimization. Hpol variation is ±3 dB and Vpol is ±3.4 dB. Axial ratio is quite acceptable at 2.9 dB.

Various methods have been used to optimize FM antenna azimuth patterns. Some firms use models at twice the operating frequency. Others use theoretical methods, backed up by experimental proof. The best method, assuring greatest accuracy is to use the actual tower section(s) from the customer, and to build the new FM antenna right on that portion of the tower. The final optimized antenna is match marked on the tower sections so that it will be assembled exactly as it was made and tested at the fabricators plant, and tested on its antenna range.

A complete set of installation prints must be provided so that the antenna is assembled exactly as tested, with all the correct locations, and angles of all the parasitic elements.

INSTALLATION PROCEDURES

If the installation is not properly planned and carried out, there may be unwarranted delay and cost associated with putting the FM antenna on its support tower. It is suggested that the following be carried out so as to avoid unnecessary delays and expenditures.

Receiving And Unpacking

The boxes are usually numbered and the total number is indicated on each box; contact the shipper if not all boxes are delivered, or if equipment is received damaged. Do not store the material outdoors, boxed or otherwise.

As soon as the antenna is received, open and examine for shipping damages so that any necessary claims may be filed with the shipping company immediately as well as the material checked against the parts list and installation drawing.

The box with the installation drawing and instructions are usually so marked; open it first, so that the balance of the items may be easily identified and counted. Contact the factory immediately if any material appears to be missing or is damaged during transportation.

Do not call the riggers until all antenna and coaxial line is completely on hand at the site. To do otherwise will result in unnecessary delays and costs.

Planning The Installation

Because of the extremely high cost of rigging services, it is essential to carefully plan the installation, making sure that all parts are on hand.

The installation of the antenna should be planned by a technically qualified person who must supply accurate tower construction information to the antenna manufacturer. If this information contains errors, these will be carried thru the design and fabrication of mounting hardware, and finally show up in the field to plague the installing crew, wasting time and money at every stage of the process.

The station should consider hiring a tower rigging firm that is financially qualified and mechanically well equipped to do the work. A written contract should exist between the station and rigging firm, with a fixed price. The rigging contractor should be licensed as a contractor in your state, and should post a completion bond. He should also supply an insurance policy to hold the station harmless, and making the station and its personnel co-insured. Only in this manner will the broadcaster be protected in the event of death or property damage.

The tower man, should be knowledgable regarding antennas and coax line, should inspect the tower and check out the mounting design of the brackets before the full rigging crew arrives.

If any factors are discovered which appear to negate the installation design, contact the factory immediately. Particular attention should be paid to the following:

a) Fit of mounting brackets to tower members

b) Freedom from interference of the mounts with gussets, leg flanges, guys, and their attachment points, tower face members, obstruction lights, etc.

c) Compatibility of transmission line and antenna input coax terminals.

d) Location of transmission line run relative to antenna input terminal

e) Use of fiberglass guys on the tower in the region occupied by the FM antenna; refer to the paragraphs on guying in this chapter

f) Availability of proper voltage, current and tower cable size for deicers if required.

g) Adequacy of tower to carry the windload placed upon it by the antenna, particularly where radomes are used. This radome/antenna load should be checked by a competent structural engineer, as all antenna installations should be checked. This is usually required by the insurance company carrying insurance on the tower.

Installation Procedures

This information by the writer is based upon nearly 15 years of experience as a chief engineer, plus 25 years as a broadcast antenna manufacturer faced with field installation problems nearly every week. These instructions should be closely followed by the rigger. The suppliers furnish detailed installation procedures with their products. Those together with these will insure a perfect installation saving time and money.

The following items are specifically called to the attention of the broadcasters engineer, in addition to all those stated before, to permit proper installation and good performance for many years.

1. Follow manufacturer's instruction. See that the riggers also read these instructions.
2. Do not leave antenna parts where rain or moisture can enter. Store indoors or keep units capped as received.
3. Do not allow dirt or other foreign matter to enter any coaxial part.
4. Protect all antenna parts from physical damage and abuse.
5. Hoist antenna members carefully, with a tag line to prevent damage by striking against the tower.
6. Install on the tower as indicated by the manufacturer's instructions, remembering that bay number 1 is the uppermost top unit.
7. Riggers should lubricate "O" rings with a small amount of silicone grease before mating flanges.
8. The full complement of flange bolts must be used and they should be as tight as possible.
9. Tuners or individual element devices, if used, should be adjusted only after the entire antenna and tower installation has been completed.
10. Rigid transmission lines should be properly installed with two hangers per 20 feet (6m) length, and with the inner conductor retaining pin on the top of each section.
11. If semi-flexible cable such as Heliax or Wellflex is used, it should be firmly tied down at least every 5 feet (1.5m) for 3 inch (76 mm) line, and every 3 feet (1 m) for 1-5/8 inch (43 mm) coax line.
12. After physical installation has been completed in accordance with the manufacturer's recommendations, the main transmission line should be pressurized with dry air thru a dehydrator, air pump, or by using dry nitrogen gas. See elsewhere in the chapter for complete information.
13. Dry air or gas pressure should be maintained at all times. Most antenna warranties are not valid unless this is done. It is the riggers responsibility to make certain that the entire coax and antenna holds air pressure.
14. The antenna system should be checked by a qualified rigger every time the obstruction lights are replaced, or if lights are not used, at least once a year. The rigger should look for vibration and storm damage, loose or broken coax hangers, and signs of arcing across exposed insulators. A dry rag soaked in 91% isopropyl or other solvent alcohol or equal should be used to wipe clean all exposed insulators in each antenna element. (DO NOT USE CARBON TETRACHLORIDE!)

STRUCTURAL CONSIDERATIONS

Most FM antennas in the western hemisphere are installed on the sides of a steel tower, between 18 and 60 inches (45 to 152cm) wide. The antenna and its transmission line together with all mounting bracketry introduce wind loading, in addition to their dead weight. The live wind loading is a result of the amount of physical surface presented to the wind. It is sometimes called the wind catch area. This consists of either flat or round antenna members, coaxial lines and mounting brackets, hardware, all represented as surfaces which are exposed to the wind.

The dead weight of the antenna system is fixed and is always present on the tower. The live load is a variable, depending on the wind velocity, and is added to the dead load for the total amount present.

The standard wind load starts at an assumed wind velocity of 87 mph (139km), which will produce a push of 35 pounds per square foot. (170.8 kgs/sq.m) With lesser wind speeds the wind push is less and more with higher velocities. Various building codes determine the rated winds to be considered in the design of the tower system. While most of the United States has a 35 pound per square foot minimum rating, some parts of the country have higher requirements due to higher wind velocities. Some insurance companies may require even higher safe wind ratings.

ANTENNA POLE MOUNTING

Non-symetrical antennas may also be installed on a round pole, made of various diameters of steel pipe. Several antenna manufacturers supply these as a complete system and will optimize the horizontal plane pattern. The advantage of pole mounting on top of a tower or building is that the pattern may be more easily contoured. This provides more signal in the service area since the antenna orientation is not limited by a fixed triangle formed by a guyed tower.

TRANSMISSION LINE SYSTEMS

Two types of coaxial transmission lines may be used to feed FM antennas. One uses rigid coax-

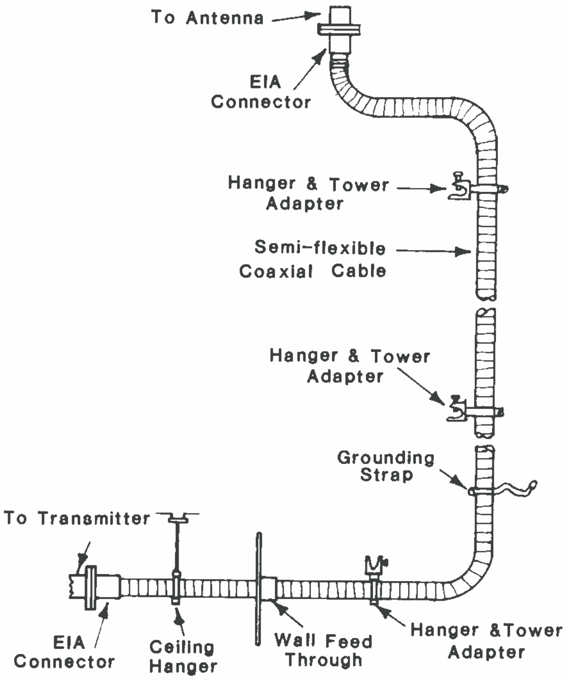

Fig. 20. Typical semi-flexiable coaxial cable installation on a tower. Number of various pieces of hardware depend on length and the diameter of the cable.

ial line sections, each 20 feet (6.09 m) long and requires elbows, flanges, spring hangers and other devices.

The other has a semi-flexible coaxial line which is available in either air or foam dielectric, with fixed hangers. Semi-flexible cable is available on a spool whose diameter depends on the line size. EIA end flanges mate to the antenna flanges as well as other RF equipment. A typical semi-flexible coaxial transmission line layout is shown in Fig. 20.

A supply of dry air should be used with all air dielectric transmission line. Its purpose is to keep out moisture, which may find its way into the line. Dry air not only keeps the mosture from covering the internal plastic insulation and thus arcing is greatly reduced. It also keeps the internal copper from corroding. Copper which has been exposed to moisture will turn dark brown and oxidize after due time. Rigid as well as semi-flexible line in the 3 and 3-1/8 EIA size which had not been pressurized have been measured with increased attenuation of nearly 4 dB per 100 feet (30.4 m) at 100 MHz. This is a power loss of 60 percent. See the section on Air Pressurization on how this may be accomplished.

Popular types and sizes of coaxial cable transmission line are shown in Table 10. The most popular are the semi-flexible air cables marketed by some manufacturers. Also made is the foam dielectric type of line. Rigid coax in 20 foot lengths (6.09 m) is available from several manufacturers.

The safe power ratings shown in Table 10 are for a perfect VSWR of 1.0:1 It is considered good engineering practice to derate this by dividing the power in kilowatts by the expected VSWR. For example three inch Heliax rated at 36.8 kW at 100 MHz and divided by 1.1 derates it to 33.45 kW. Other increases and decreases of coaxial cable ratings may be found in the catalogs of most manufacturers of transmission lines.

Ratings are for a VSWR of 1.0:1; ambient temperature of 75 °F (24 °C) with one atmosphere of dry air pressure. Rigid line at 122 °F (50 °C). LDF and HJ series are manufactured by Andrew Corp. of Chicago, IL while the rigid line is by Shively Labs., of Howell Labs. Inc. Bridgton, ME.

AIR PRESSURIZATION

If the antenna is operated without positive pressure of dry air or nitrogen, the manufacturer will not assume any responsibility for failure under power. Moisture or even the accumulation of water within the coaxial transmission line is a very serious matter. Its presence causes the VSWR to rise, and when a sufficient amount of moisture is present, arcing will take place, burning the line or antenna radiating elements. High humidity or moisture will cause the inside of the coaxial transmission line to corrode over time, thereby increasing the line loss. For this and other reasons, the entire antenna system must be dry air pressurized.

After the antenna is installed and the transmission line connected, the system is purged with dry gas or dry air to remove entrapped moisture, before RF power is applied. A manually opened or pressure actuated purge valve is installed in nearly all FM antennas made by American firms. When the gas pressure is raised to 10 psig (0.68 atmospheres), the automatic pressure relief valve (if the antenna has one) will open up letting moist air out, until the dry air from the building reaches it. The complete system purge requires a considerable volume of dry gas.

Before expending this amount, it is good practice to perform a quick check for major leaks. The system pressure is raised to a point below the relief valve setting, such as 8 psig (0.48 atmospheres) the source of supply shut off, and a pressure gauge left on the antenna side of the shut-off valve. The pressure, when corrected for temperature, should not fall to less than half its initial value in a 24 hour period.

If more than this, it should be gone over with a leak detector, or soap suds, to locate the leak. A pinched or missing O ring is the most common cause for large leaks.

TABLE 10. Coaxial transmission line.
(Characteristics At 100 MHz)

Line Type & Number	Nominal EIA Size	Attenuation In dB	100 Ft Eff. %	Safe FM Power-kW
-Foam-				
LDF5-50	7/8	.385	91.5	5.2
LDF7-50	1-5/8	.231	94.8	13.1
-Air-				
HJ5-50	7/8	.373	91.7	6.4
HJ7-50A	1-5/8	.205	95.4	14.2
HJ8-50B	3	.142	96.7	36.8
HJ11-50	4	.115	97.4	56.1
HJ9-50	5	.078	98.2	73.9
-Rigid-				
1213-1	1-5/8	.191	95.7	10.0
1313-1	3-1/8	.096	97.8	40.0
1413-1	4-3/8	.070	98.4	81.0
1613-1	6-1/8	.050	98.8	161.0

Once the system is known to hold pressure, it should be purged with dry air or gas. Either must be dry enough to have a dew-point well below the coldest temperature expected to be encountered. When using nitrogen, it should be of the "oil dried" type, to remove nearly all the moisture from the gas.

Five to eight psig (0.34 to 0.48 atmospheres) should be maintained in the system at all times to ensure that no mositure will be able to enter. Very small leaks, will pull in moisture, if the pressure is lower than suggested above, if the transmitter is turned off nightly. This is due to the pumping action due to expanded dry air/gas pressure, cooling down, and contracting below the outside air pressure, during cold ambient temperatures.

PROTECTION FROM ICING

High Q antennas are subject to increased VSWR ratios as well as pattern distortion, with light to moderate coatings of ice. Low Q antennas such as the panel type are usually not affected in this manner. Where climatic conditions cause sufficient ice or in some cases snow to affect the antenna's performance, there are two remedies. The radiating element may be covered with a plastic cover, or, it may electrically be heated to melt or prevent the formation of ice on its sensitive surfaces.

Electrical Heaters

By far the more popular method is to order electrical heaters at the time the antenna is ordered. Electrical deicing equipment is supplied as an option and is factory installed. Kits are furnished for interbay connections but the broadcaster must supply power from the building to the center of large arrays, or the bottom element on smaller antennas. Local electrical codes of course must be followed.

While a thermostat may be used with small total deicer wattages, a power relay operated by such a device is required, and furnished with most electrical deicer kits by the antenna supplier. Due to the higher power costs a sophisticated deicer control which operates when both temperature and humidity conditions produce sleet or icing is often required.

Most deicers use a resistance heating element which is inserted inside the antenna radiator arms. One maker however uses a different method, dropping the 230/240 volts to a few volts with a transformer located at each bay level. The low voltage is passed thru the ice sensitive arms of the radiator and connected to the far ends, by a heavy teflon coated wire. The current return is by the stainless steel antenna element, whose ohmic resistance is sufficient to produce enough power heat loss to melt or keep the ice off. This method is becoming obsolete as the transformers are expensive and heating costs are rising, as hourly electrical rates go up. The voltage dropping transformers as not as efficient as direct heaters.

A word of caution when selecting a FM antenna with electrical heaters. Some deicers use 1 kW of power for each bay as described above and increase the wind loading by 225%. Others have a switchable power option feature using 125/500 watts per element, with only a 15% increase in windloading, when compared to an antenna without electrical deicers. The continuing cost of electrical deicers is a consideration of the operational cost of the station and should not be overlooked.

Fig. 21. Rigger finishing electrical tie in box for deicers. Looped stainless steel heaters were factory installed in the four arms, plus one in the feed support boom. (Photo courtesy Cetec Antennas)

In the most basic system the heaters are switched on and off by means of a thermostat which will turn the heater on when the temperature gets below a pre-set level. Recommended automatic deicers are those with a thermostat for mounting near the antenna for accurate temperature sensing of the actual ambient temperature. The temperature zone of +20° F to +35° F (−7° C to +2° C) is generally the most likely icing range, depending on humidity conditions. Deicers should be turned on at +35 °F, prior to ice formation, because it is better to prevent icing than to remove it once it is formed. Power should be turned off when the temperature goes below +20° F since ice does not usually form below this temperature. Fig. 21 shows electrical deicers being wired.

Radomes

The primary purpose of using radomes on FM antennas is to prevent the VSWR from rising with the formation of ice, if the site and height causes icing to occur during the winter months. Ice formation detunes high Q radiators, increases the VSWR, and causes vertical plane pattern changes. See Fig. 22 for a typical radome enclosing a radiator.

Ice may form on the radome but does not particularly affect the operation of the radiator if that ice is kept at least 0.05 wavelengths from the sensitive portions of the antenna element.

Radomes are particularly desirable in heavy icing environments where deicers are not adequate even with very high heat density. They are also useful in protecting antenna elements from falling ice when they are so exposed.

They are cost effective with single channel high Q antennas where electrical deicer heating power costs are expensive. The deicer power cost is a continuing one, while radomes are a one time capital investment, which may be depreciated over time.

A radome is a protective dielectric housing for an antenna radiating element. Its function is to protect the antenna not only from ice, but snow and physical damage due to ice dropping from above. Radomes also protect the radiating element from environmental corrosive atmospheres.

Radomes are generally composed of low loss dielectrics with low values of dielectric constants and loss tangents. Laminated fiberglass, using glass cloth re-inforcements, has a constant of about 4.1 and a loss tangent of about 0.15. Water absorption by the radome increases its dielectric constant and loss tangent. Materials which do not easily absorb water or those treated with a protective gel coat are often used to shed water and prevent the adhesion of ice.

Good radome designs take into consideration operating temperature, a relative humidity of 100 per cent, safe wind pressures, ice, hail, and snow loads, rain adhesion, wind and supporting tower vibration, fire retardant plastic, and the ability to safely withstand air contaminants over the useful life of the antenna. All these factors increase the cost, but are necessary for long useful life. Radome shapes are dictated by the form of the radiating element in most instances.

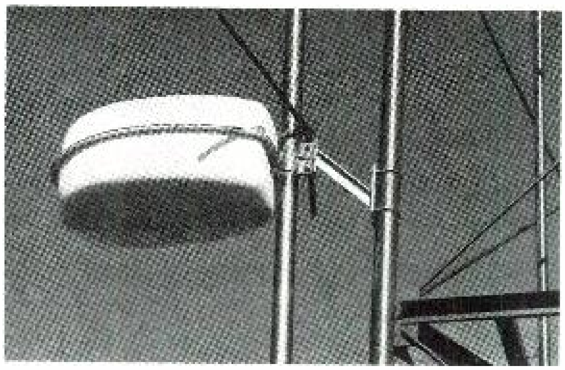

Fig. 22. Radome over radiating element. Transparent to RF, it keeps ice from detuning high Q radiator. (Photo courtesy Cetec Antennas)

In all cases radomes are supplied by the antenna manufacturer, and usually supplied in two pieces which are bolted together with stainless steel fasteners.

LIGHTNING

Lightning is a natural phenonmenon that has always fascinated man. It performs the function of maintaining a balance in the global electrical system. But apart from this, lightning is an extremely destructive force—annually killing an estimated six thousand people and inflicting a billion dollars in propery losses—including FM antennas.

Because FM towers are usually located on high ground, hilltops, or high buildings, they require lightning protection since they are likely recipients of lightning strikes. The type of damage that can be caused by lightning to a FM tower is varied. Smaller coaxial lines will usually melt; larger coax (1-5/8, 3-1/8) will also melt in some cases, and others will conduct the heavy current into the transmitter building to do damage there.

The FM antenna itself may heat, arc, melt, and otherwise be damaged. Holes in the outer conductor, burns and melting at flanges are common. Teflon or polyethlene insulation will burn, depositing a film of carbon, causing further damage if RF from the transmitter continues after the strike.

Protection of the FM antenna system may be provided to some degree, by taking several pre-cautions. The top of the tower should have a lightning rod, about one foot (0.3m) higher than the uppermost obstruction light part. The FM antenna itself should be firmly grounded to the tower. If the coaxial cable is buried between the tower and the transmitter building, it must be at least six feet away from any tower base grounding system copper wire or strip.[27]

A ground system should be located immediately around the base of the tower. This should have a direct current loss of less than 10 ohms to earth ground. This low resistance may be obtained by using ground wires buried in the soil. Six radials spaced 60° degrees if possible, buried as deep in the soil as possible and running out up to 150 feet (46 m) each, should provide a suitable ground of less than 10 ohms, even if the soil is shallow or rocky.[27]

Guyed tower anchors should also be grounded. This is covered in the chapter Design, Erection and Maintenance of Antenna Structures. It is important to install the proper number of ground rods and/or copper wire radials in order to obtain a connection to earth ground of less than ten ohms. In any event these ground rods or radial wires must be tied together with number AWG 4 or larger copper wire, or copper strap two inches (5cm) minimum width. This is to provide for thousands of amperes of current flow for less than one second in the event of a direct lightning hit.

If the FM antenna is located on an AM insulated base tower, then the spark gap should be set at the lowest point providing protection for the highest AM modulation peak voltage.

Another way to protect the FM transmission line isolator (if one is used), as well as the tower and FM antenna, is to use a RF choke across the insulated tower base. This tends to reduce the static build up voltages due to passing thunderstorm clouds, snow, hail, or dust storms. Arc-overs due to these sources usually do not cause damage, but may trip the FM transmitter reflectometer since they will create a current flow through the reflectometer circuitry.

If the base insulated tower supporting the FM antenna is located in an area of regular thunderstorms, another way to protect both antennas from lightning is to ground the AM tower at the base, and shunt feed it. Several excellent methods exist. The folded unipole method not only grounds the tower for lightning purposes, but improves the VSWR bandwidth, so necessary for AM stereo. See the chapter for AM Antennas for several suggested methods.

FM SCA MULTIPLEXING

With a 92 kHz sub-carrier, 110% modulation could result in a peak deviation of 110 kHz. Intermodulation products may be created due to mixing of the various sub-carriers with their own harmonics within non-linear devices. One such non-linear device can be the antenna system.

Antenna linearity is determined by its VSWR response curve versus frequency. Phase delay in the antenna system is also important. In the past with 67 kHz being the highest SCA frequency, the ±100 kHz bandwidth was considered sufficient. Now with a 92 kHz sub-carrier and 110% deviation (82.5 kHz) the minimum bandwidth is ±130 kHz under 1.1:1 VSWR.[28] See VSWR BANDWIDTH in this chapter for more specific requirements and recommendations.

Tests have shown that 92 kHz is the frequency of choice for a new aural SCA service after 67

[27]Marshall, J.L.: "Lightning Protection" Canadian Broadcasting System, John Wiley & Son, New York, NY pp 53-54 1973.

[28]Kean, John: "Distortion of FM Signals Caused by Mismatched and limited Bandwidth Transmitting Antennas" National Public Radio, Washington, DC 20036 pp 37-42 1984.

kHz.[29] This produces lower intermodulation product levels and less interference to the main channel stereo service than 67 kHz.[30] It may be successfully operated in addition to stereo and existing SCA services.

Other non-linearities in the exciter, transmitter, plus multi-path reception, receiver mis-alignment and user mis-tuning are contributions to the received intermodulation distortion of the baseband signals. In addition these products can cause small levels of audible swishing beat notes in some types of FM receivers.

SPURIOUS FREQUENCIES

Interferences to other stations within the FM broadcast band as well as to other services outside the band can be caused by RF intermodulation product energy developed between two or more FM broadcast transmitters. It may be due to coupling thru a diplexer or coupling between two antennas. This phenomenon has been well documented.[13]

Detailed information on the susceptibility of various types of transmitters to interference from other collocated transmitters has not been thoroughly investigated. A method has been devised by which the mixing loss between two transmitters can be accurately characterized.

When two or more transmitters are coupled to each other, new spectral components are produced by mixing the fundamental and the 2nd harmonic of each of them. The dominant intermod product generated by each transmitter is at twice the transmitter's frequency minus the interfering transmitter frequency. For example, 101.1 and 102.7 transmitters would produce two intermod signals appearing on 99.5 and 104.3 MHz.

Second harmonic traps or low pass harmonic filters in the transmission line of either transmitter prior to the diplexer have little effect on the generation of intermod products. This is because the harmonic content of the interfering signal entering the transmitter output circuit has much less effect on intermod generation than the harmonic content within the non-linear device itself. The resulting intermod falls within the passband of the low pass filters and outside the reject band of the second harmonic traps, so these devices offer no attenuation to intermod products.

Even the perfect diplexer by its very nature will reflect some of the undesired energy back to each transmitter, generating intermod products. The key to this problem is to keep that undesired power level as low as possible using proper transmitter output circuitry and tight diplexer specifications.

HARMONIC FILTERS

The FCC specifications Sec. 73.317(a)(10) calls for the harmonics of FM transmitters to be up to 80 dB or more below the transmitter output. This requirement is usually met by using a low pass filter which passes the station carrier frequency power but attenuates its harmonics.

The transmitter provides some harmonic attenuation of course, and is usually 25 to 38 dB for single ended amplifiers. The worst case harmonic is the third. Harmonic filters by several firms provide a minimum of 50 dB for harmonics from the second through the tenth. Adding the transmitter attenuation to that of the filter normally provides more than the required level.

The high level of rejection is made possible by using high impedance (inductance) and low impedance (capacity) coaxial sections for m-derived three to five section filters, with half-pi end sections. Harmonic filters are commonly made in three production schedules while one firm actually adjusts them to the customers operating frequency, so that there are no attenuation gaps in the higher harmonics. They are not tunable outside the factory as the insertion loss and attenuation along with pass band VSWR are closely related. It requires sophisticated knowledge and equipment to properly adjust.

The insertion loss in the pass band varies from .05 to .08 dB while the rejection from the second through the tenth harmonic is from 50 to 60 dB, depending on the number of internal filter mid-sections. The VSWR in the pass band varies from 1.05 to 1.1:1 Harmonic rejection is due to the very high VSWR on the harmonic frequencies which may be as high as 15 to 1. This rejected power is passed back to the transmitter amplifier.

Harmonic filters are available in straight rigid coaxial line sections and may sometimes be pressurized. Power capacity varies from 10 kW for 1-5/8 EIA line size to 50 kW for the 6-1/8.

ACCESSORY ANTENNA SYSTEM EQUIPMENT

Several other devices are associated with the antenna system. The dry air pressurization of coaxial transmission line was discussed under that heading in this chapter.

[29] McMartin, Ray B.: "Super Eight" Preceedings of the 38th Annual Broadcast Engineering Conference, NAB, Washington, D.C. 20036 pp 160-166 1984.

[30] Denny, Robert: "Report on SCA Operation" Preceedings of the 37th Annual Broadcast Engineering Conference, NAB, Washington, D.C. 20036, pp 187-196 1983.

Reflectometers

The reflectometer is a device for detecting the ratio of power flow from the transmitter to the antenna (forward) and the rejected power back from the antenna (reverse). A short coaxial line section about 12 inches (305 mm) contains diode detectors, coupling loops and terminations to produce D.C. current, which drives a suitable. VSWR meter.

Reflectometers are wide band devices and therefore must be placed AFTER the harmonic filter. Putting them between the transmitter and the filter causes them to read the rejected harmonic power along with the reflected, thus giving an erroneous reading.

Dummy Loads

A very useful test device in an antenna system is the terminating load. This is extremely useful when two amplifiers are combined and fed to the antenna, or when a number of diplexers are used in a community antenna arrangement. Dummy loads are available in several power levels up to 50 kW and are cooled by air. Water cooling types are also available.

RF Switches

Sometimes used with a dummy load, coaxial line switches are available to provide electrical or manual switching of transmitter power to diplexers, antennas, standby transmitters, etc. They are not pressurized.

2.6

Antennas For Television Broadcast

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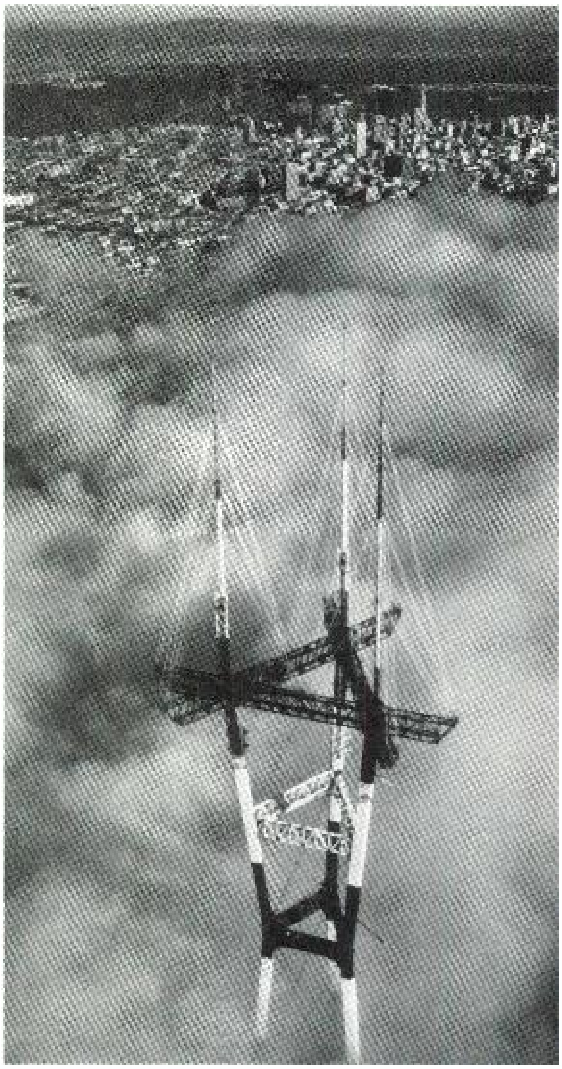
This chapter begins with a review of the demands placed on broadcast radiating systems, including radiating patterns, power handling capacities, and gain. This is followed by a review of antenna theory as it relates to these demands, as well as a review of specific applications. The chapter concludes with a summary of tests, installation and maintenance procedures.

To facilitate using the material here, a brief chapter outline is provided.

—INDEX—

NOTE: This chapter incorporates some material from Chapter 14 of the previous, 6th, edition of the *Handbook* prepared by H.E. Gihring, RCA Corporation.



The Mt. Sutro installation serves the San Francisco area with eight active and 5 standby broadcast television antennas. (Photo courtesy of RCA)

REQUIREMENTS

Television broadcast antennas currently operate at the following frequencies:

Channels 2 to 6—54 to 88 MHz
Channels 7 to 13—174 to 216 MHz
Channels 14 to 69—470 to 806 MHz

Definition

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.

The antenna terminal is defined as an accessible point where the entire antenna including the distribution system terminates into one feed line at the design characteristic impedance.

The azimuth pattern shall be circular or omnidirectional unless a directional pattern is authorized. A directional pattern can be used to improve the service area, but the null shall be less than 10 db (CH 2-13), 15 db (CH 14-69). The radiation pattern in the vertical plane can be shaped by electrical means so the maximum radiation occurs at an angle below the horizontal plane.

The gain is the increased in signal relative to the same power fed to the standard dipole.

Antenna power gain is the square of the ratio of the root-mean-square free space field intensity produced at one mile in the horizontal plane, in millivolts per meter for one kilowatt antenna input power to 137.6 mV/m. This ratio should be expressed in decibels (dB). (If specified for a particular direction, antenna power gain is based on the field strength in that direction only.)

The product at the antenna input power and the antenna power gain is the Effective Radiated Power (ERP).

The polarization (the orientation of the electric field) can be linear horizontal, or circular. If circular is used, the term ERP applies to horizontal and vertical components separately.

SPECIFICATIONS: GENERAL

Azimuth Pattern (Horizontal Plane)

Definition. An azimuthal pattern is a plot of the free-space radiated field intensity versus azimuth angle 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 taken at various frequencies in the channel.

An omni-directional antenna is defined as one that is designed to radiate the same signal in all directions. Antennas with variations up to ±3 dB have rendered satisfactory service and are considered to be omni-directional.

A directional antenna is one which is designed to radiate more signal in one direction.

Vertical Pattern (Elevation Plane)

Definition. A vertical pattern is a plot of free space radiated field intensity measured in the Fraunhofer region versus vertical angle in any specified azimuth plane which contains the center of the antenna and the center of the earth.

The Fraunhofer region, or "far field," as usually defined extends beyond a point where the distance between the transmitting and receiving point is a $2a^2/\lambda$, where a 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 is the ratio of the maximum power flow per unit solid angle from the subject antenna to the maximum power flow from a thin, lossless, half-wave, horizontally polarized dipole[1] 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[2] or by integrating the total power flow through a sphere, which is done by taking a sufficient number of vertical patterns and an azimuthal pattern. 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. The measurement of gain used in the calculation of ERP for a circular polarized antenna must be made relative to a horizontal dipole. The gain of a circular polarized transmitting antenna relative to a "like" circular polarized receiving antenna will be 3 db higher than that of the horizontal dipole.

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 by FCC are:

Channels 2 to 6—100 kW
Channels 7 to 13—316 kW
Channels 14 to 69—5,000 kW

For the most popular transmitter sizes in each range, the following gains are needed allowing 75 per cent transmission-line efficiency:

Channels 2 to 6—4 to 6
Channels 7 to 13—12 to 18
Channels 14 to 69—25 to 60

Economics. Economics is a factor in antenna choice. As a general rule for a required ERP the combined costs of transmitters and antennas are less 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.

Input Impedance

Input impedane 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.

Non-Ionized Radiation

A recent concern is the biological effect due to non-ionized radiation (the TV signal) and its influence in the selection of a TV broadcast antenna.

Lacking a federal standard, many states and localities have established their own. The levels of exposure vary.

	ANSI 95.1	**Massachusetts and Oregon**
LoV	1 mW/cm^2	0.2 mW/cm^2
HiV	1 mW/cm^2	0.2 mW/cm^2

[1] The directivity of a ½ wavelength dipole antenna over an isotopic antenna is 1.64.

[2] "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.

	ANSI 95.1	Massachusetts and Oregon
UHF-CH14	1.3 mW/cm²	0.26 mW/cm²
CH 70	2.6 mW/cm²	0.53 mW/cm²
Exposed Time	0.1 hr.	0.5 hr.

SPECIFICATIONS—TECHNICAL

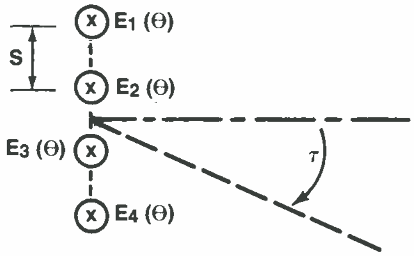
Radiating Characteristics (Element Theory—Array Theory)

The TV antenna should have an omni-directional pattern in the azimuth plane and a narrow beam in the elevation plane. For the omni antennas the gain is approximately one per wavelength[3] per like polarization. Most broadcast antennas are spaced one wavelength, therefore, the gain of a linear polarized antenna is approximately equal to the number of elements.

Elevation Pattern

The elevation pattern is the product of the element pattern times the array pattern.

[3] It can be shown that the maximum theoretical gain is 1.2 per wavelength. Ohmic loss side lobes, cross polarization, and aperture illumination contribute to a reduction in overall gain.



$$F(\theta) = E_n(\tau) \sum_{n=1}^{N} A_n e^{j[(2\pi n s)\sin\tau + \delta_n]}$$

Where: $E_n(\tau)$ = element elevation pattern
$\approx \cos^m(\theta)$
s = element spacing
τ = elevation angle
δ_n = phase of nth element
A_n = amplitude of nth element

The element spacing is normally one wavelength. For a $\cos^1(\theta)$ element pattern the gain vs spacing is shown below:

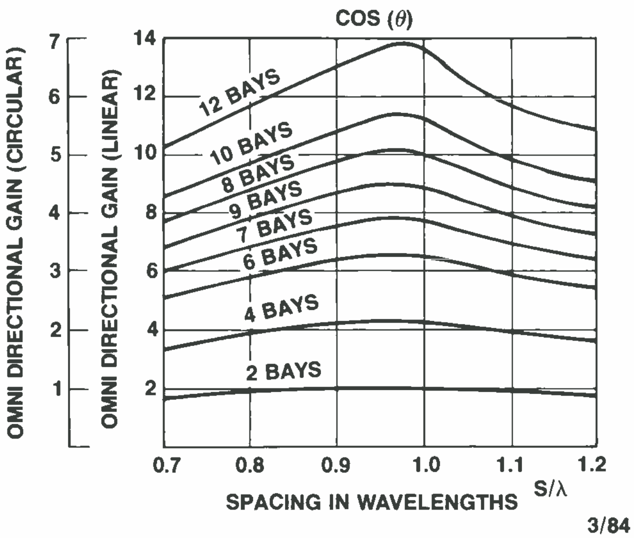


Fig. 1. Power gain vs. element spacing.

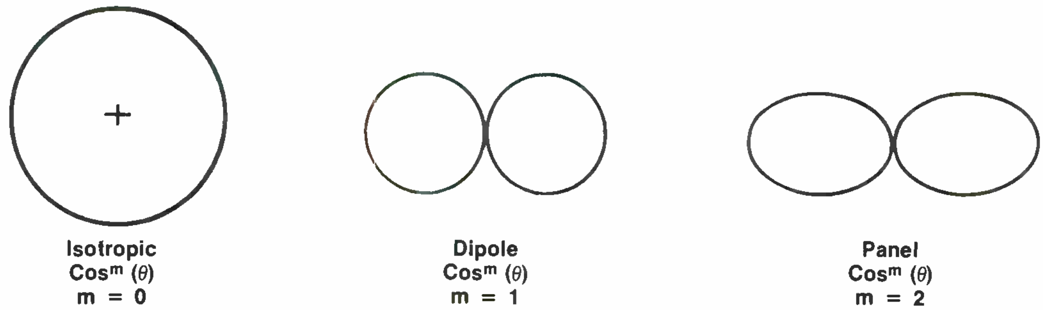


Fig. 2. Element patterns for different values of M.

The reason that most antennas are spaced approximately one wavelength is that the gain peaks at this spacing and fewer elements are needed reducing the number of feed points, wind load, and costs.

The element pattern can vary from value of m = 0 to m = 2.

The variation in gain for other than $\cos^1(\theta)$ element patterns is shown below. As can be seen there is no significant difference until one wavelength spacing is approached. The reason the gain falls off rapidly as one wavelength is approached for the isotropic pattern is that the element pattern does not drive the array pattern downward lobe to zero at ±90°.

Azimuth Patterns

The ripple content of the azimuth pattern is dependent on the element pattern and ρ the distance to the phase center.

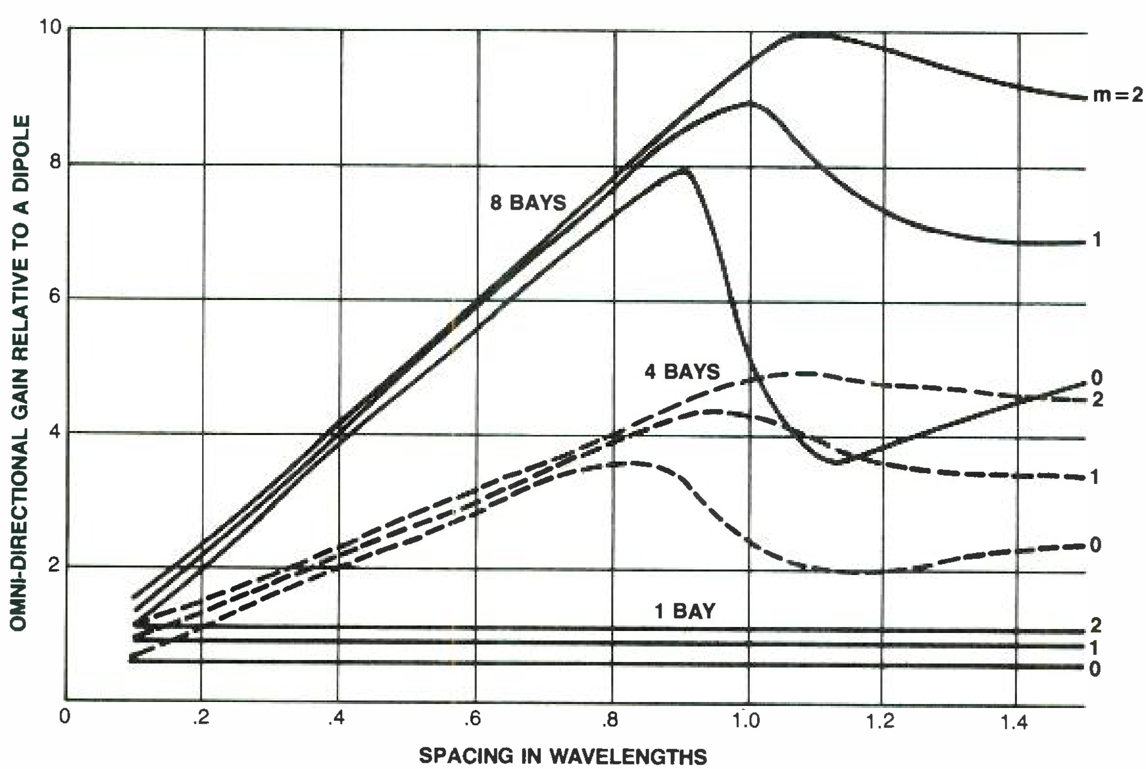


Fig. 3. Power gain vs. element spacing for 1, 4, 8 bay array and m=0, 1, 2.

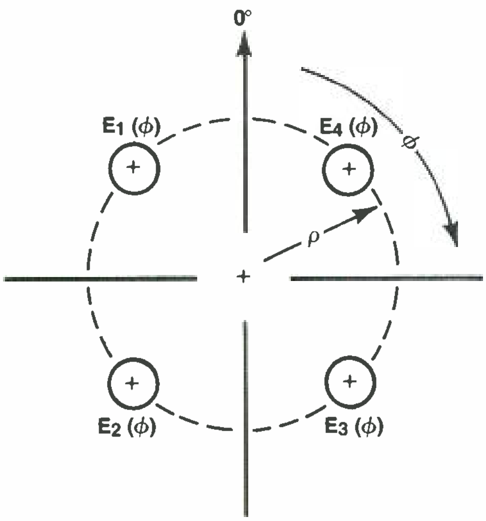
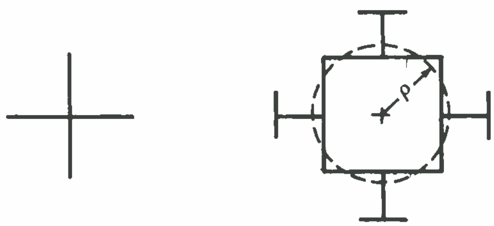


Fig. 4. Azimuth pattern calculation.

$$F(\phi) = \sum_{n=1}^{N} E_n(\phi) A_n e^{j[(2\pi)\cos(\phi-\phi_n)+\delta_n]}$$

Where:
$E(\theta)$ = element pattern
ϕ = azimuth angle
δ_n = phase of nth element
A_n = amplitude of nth element
ρ = distance to phase center (in wavelengths)

Some antennas such as cross dipoles (turnstile/batwing) have $\rho = 0$. Others such as panels have value of $\rho = .25$ to 1.0.



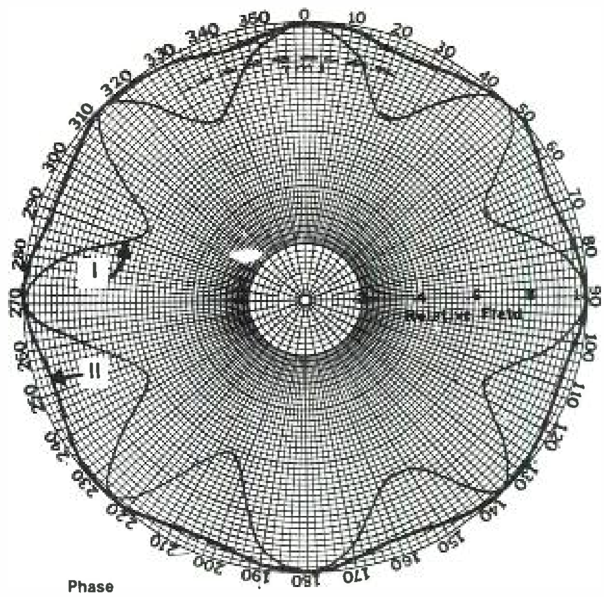
BATWING **PANELS**

Fig. 5. Arrangements of cross dipoles for turnstile and batwing antennas.

The ripple content in the azimuth plane is dependent on ρ and the element pattern. The ideal element pattern for a three-sided tower is $\cos(\phi)$, four-sided $\cos^2(\phi)$. Below is the ripple of four panels having $\cos^2(\phi)$ with $\rho = 0.5\lambda$, 1.5λ.

ERP

In achieving the given effective radiated power (ERP) required to serve the area under consideration, there is a choice between using a low power transmitter and a high gain antenna or vice versa.



	Phase Center Diameter	Gain	Ripple
I	1.49λ	.762P	±1.5dB
II	.485λ	.949P	±0.3dB

Fig. 6. Ripple content for four panels having COS².

For VHF antennas, the transmitter power to antenna gain ratios are fairly well established. For Channels 2-6, antennas usually use gain values from about 4 to 6 depending upon the length of the transmission line run. For the Channels 7-13 band gain values vary from 12 to 18, depending upon the transmitter power and the length of the transmission line run. For UHF antennas, it is economically not feasible to use low gain antennas such as are used for VHF, for several reasons:

1. The ERP values permitted are higher in order to compete with VHF performance.
2. Transmitters must generate higher powers and are therefore more costly.[4]
3. The antenna gain must also be increased since otherwise the cost of the transmitter would be excessive. Hence, vertical gains of the order of 25 to 60 are used. It is feasible to do this since the mechanical structures are of a reasonable height because of the shorter wavelength.

However, the higher gain requires some special considerations since the higher gain results from narrowing the main beam. For a given transmitter input, the high gain antenna may

[4] At 0.07¢ per kW/hr. it costs $1500/yr. to generate 1 kW of RF.

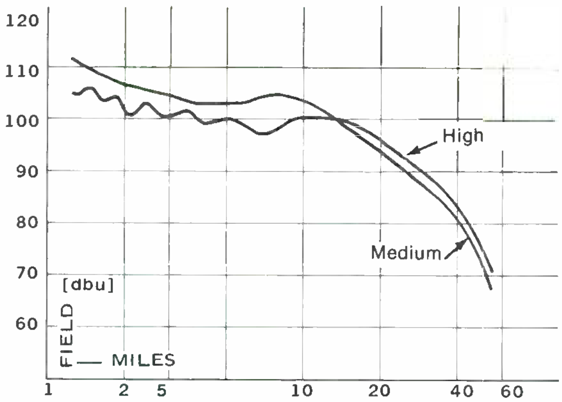


Fig. 7. Comparison of high and medium gain antenna performance with the same power input. Note the reduction in local coverage with an increase in gain.

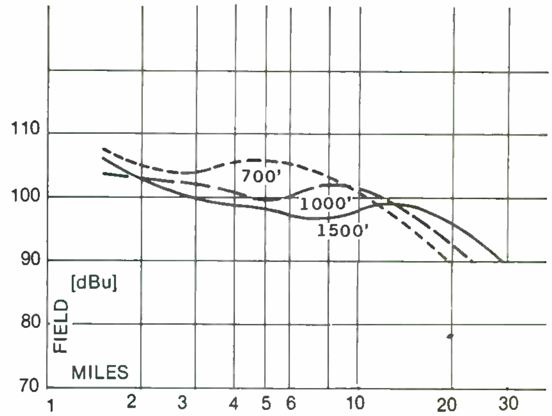


Fig. 8. Comparison of the same antenna, and the same ERP at a height of 700, 1000, and 1500 feet. Note the reduction of local coverage with an increase in height.

sacrifice local coverage for more distant coverage, see Fig. 7.

Hence, if a higher gain antenna is contemplated, local field strengths should be calculated, using the FCC (50,50) propagation curves. It is generally advisable to maintain a 100-dBu level over the important local area to be covered. Most UHF vertical patterns are designed to accomplish this with an ERP of the order of 1 megawatt at 1,000 ft. In hilly terrain it may be desirable to increase this figure by 10 dB or more and in heavily populated cities with large structures by 6 dB or more.

If fields of this order cannot be achieved with a high gain antenna, the transmitter power should be increased.

An increase in height over terrain has the same general effect as increasing the gain of an antenna. For distant areas within line of sight covered by the main beam of the antenna the field strength is millivolts per meter for a given ERP increases approximately as the height over smooth terrain. However, the nearby areas generally receive less field strength since the vertical angle looking up towards the antenna is steeper to a point where the vertical pattern usually radiates less energy (See Fig. 8 comparing a 46 gain antenna at three heights). Hence, an increase in height should be studied in the same manner as an increase in gain.

Circular Polarization

FCC regulations covering FM circular polarization (CP) broadcasting do not specify the 'sense of rotation', i.e., whether it is left-handed or right-handed, either of which characteristic may be built into a true CP signal; nor is there any limit as to how elliptical the signal may be. In fact, slant linear polarization of 45 degrees is permitted (Fig. 9.)

In the case of television, however, since several of the anticipated advantages of CP broadcasting rely on the use of rotation-sensitive CP-receiving antennas, the sense of rotation is specified as right-handed.

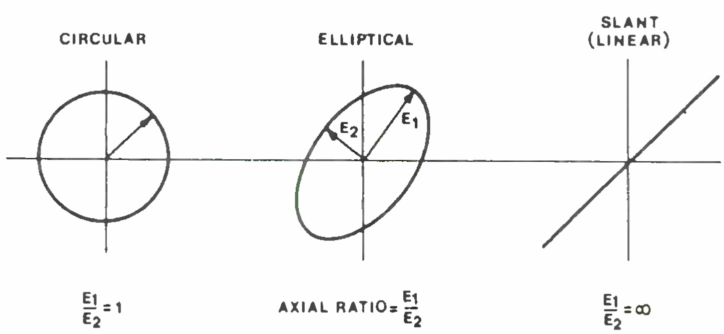


Fig. 9. The ideal circular pattern (left) of a CP signal produces an axial ratio of 1, and in practice is never achieved. The lowest quality CP signal is the slant linear field (right).

The advantages that may accrue from the use of circular polarization are:*

1. Less critical antenna azimuth orientation, permitting good reception on all types of indoor antennas including rabbit ears, whips and rings.
2. Improvement in service and penetration because of the two orthogonal fields—one horizontal, the other vertical—each with the same power as the original horizontal signal.

When circularly polarized receiving antennas are used, these further advantages are foreseen:

1. Reduction of reflection problems due to ghosting. This important benefit is realized because reflected CP signals tend to undergo a change in the sense of rotation, and are rejected by the right-hand CP receiving antenna (Fig. 3).
2. Improvement in coverage at the fringe area due to twice the power. Through use of CP receiving antennas, improvement on the order of 3 dB, amounting to 5 to 8 kilometers in calculated coverage, can be expected.

Many of the stations that have gone to CP have at the same time moved their complete transmitting plants and changed the heights of their antennas, making a direct measured signal comparison between HP and CP impossible. Experiences reported by stations using CP indicate:

1. Receiving antenna orientation is less critical, specifically for rabbit ear and whip antennas.
2. People in close proximity to portable receiving antennas have less effect on reception.
3. Signal penetration has improved.
4. Fringe area coverage has improved.
5. No ill effects have taken place.
6. In some areas where CP receiving antennas have been used, reductions of approximately 14 dB have been observed.
7. No change in adjacent or co-channel interference has been reported.

*Matti Siukola, "Evaluation of Circular Polarized TV Antenna Systems." IEEE, BC-24, March 1978.

Beam Tilt

Beam tilt should be used to bring the main vertical beam tangential to the earth (radio horizon), which is curving away from it. The distance to the radio horizon can be determined from Fig. 11.

It should be noted that height over the service area may not necessarily be the height over average terrain especially in a mountainous area. Also, if a body of water limits the service area, as in the case of Los Angeles, with the transmitter on Mt. Wilson, it may be desirable to aim the main beam to a point somewhat below the radio horizon.

In some cases, a little higher beam tilt may be desirable to improve local coverage. Beam tilt does reduce the vertical power gain in the horizontal direction, especially for a higher gain antenna. However, the loss in local coverage is generally a more important consideration than vertical power gain in the horizontal direction.

Power Capability

Power in TV systems is usually in terms of "Peak TV Power," which is the instantaneous power developed in the peak of the synchronizing pulse of the visual transmitter. Since the black level signal is 0.75% of the total voltage value of the pulse, the black level power (for a totally black picture) is 0.75^2 or 0.5625. The duty cycle of the synchronizing pulses, both horizontal and vertical, adds about 4 percent to this power so that black level power is 60% of the peak TV power. Since the aural FM transmitter is usually 10% of the peak TV power, the total heating or

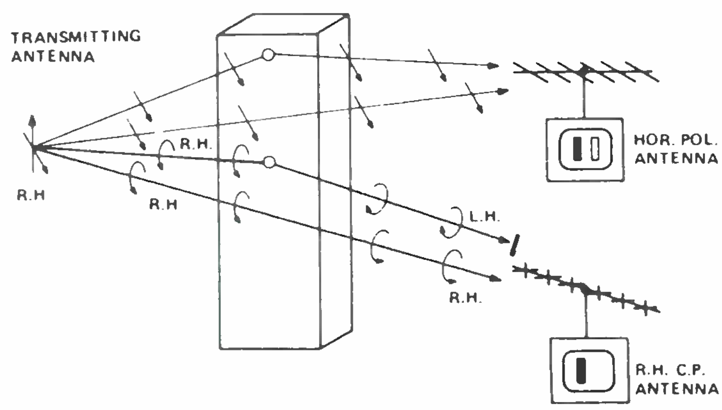


Fig. 10. Right-hand CP signals after striking an object are converted to left-hand signals which are rejected by the right-hand CP antenna, eliminating them as ghosts.

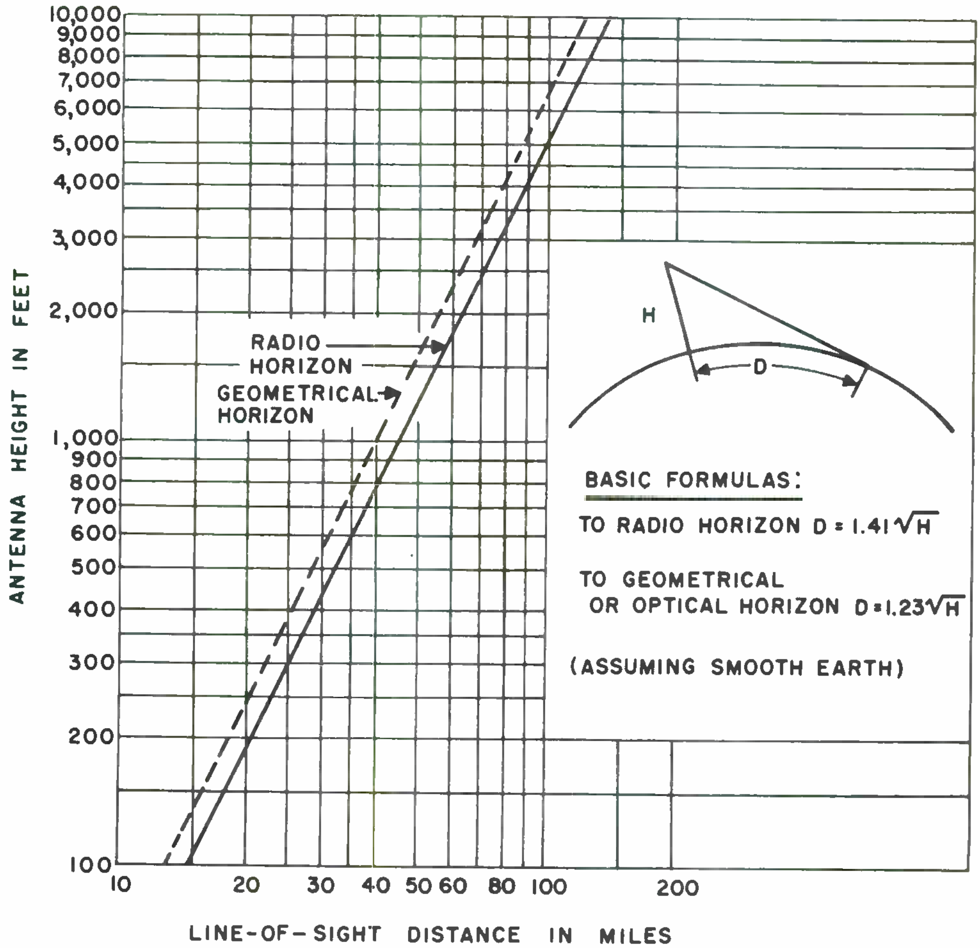


Fig. 11. Distance to radio horizon vs height of transmitting antenna.

CW power of the TV signal is 70% of the peak TV power.

The average power level (APL) of the video signal with typical program has recently measured* over a long period of time and shown to be 4.32dB (37%) below the peak TV power. The total CW power during programming would be 47% of the peak TV power.

The design of all TV antennas should allow for a sufficient safety margin to handle the peak to peak sync level, imperfections in the transmission line, VSWR, changes in pressure, and the aural power. Long transmission lines feeding the antenna will usually attenuate this figure by 10% to 20%.

Non-Ionizing Radiation—Design Consideration

As mentioned in the above Section 11 the antenna pattern is the product of the array pattern times the element pattern. The array pattern for one wavelength spacing has a downward and upward lobe as large as the desired side lobe. If the element pattern is not a $\cos^1(\theta)$ the element pattern will not drive the array downward lobe to zero, hence we could have a very large signal in the vicinity of the tower. See below.

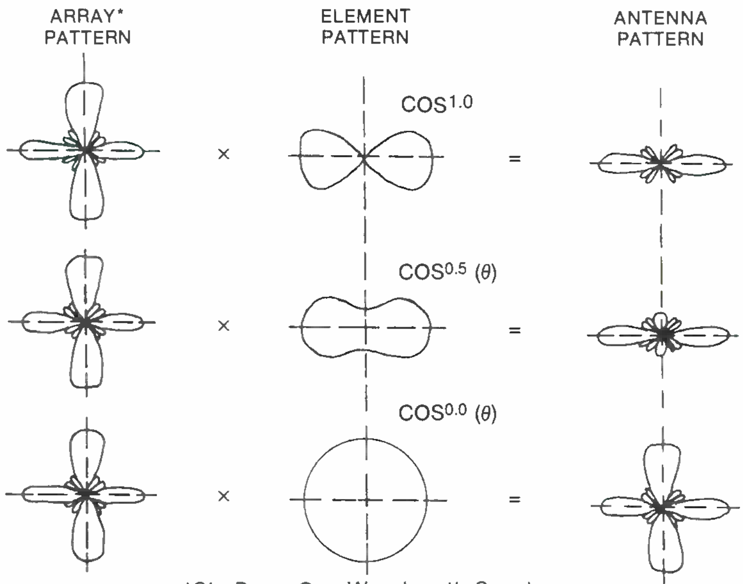
Care should be exercised in making sure the element pattern has a distribution in the elevation plane of $\cos(\theta)$ or $\cos^2(\theta)$.

A well designed antenna system should not create a non-ionizing radiation problem. The tower for maximum signal coverage should be high enough and therefore free from directional radiation into habitable areas.

Some older antenna installations may be economically locked into existing sites, and because of Co- and adjacent channel considerations, moving may not be possible.

The distance along the main beam to the 10,1,0.2 mW/cm^2 contour for maximum power installations is listed in the enclosed table.

*J. Giardina, T. Vaughan, J. Neuhaus, "True APC Levels" Broadcast Symposium, 1984.



*Six Bays, One Wavelength Spacing

Distance in Feet Along the Main Beam to Different Power Density Levels

	LoV	HiV	UHF
ERP	**100kW**	**316kW**	**5,000kW**
EIRP	**164kW**	**518kW**	**8,200kW**
Power Density			
10 mW/cm²	80 Ft.	142 Ft.	568 Ft.
1 mW/cm²	251 Ft.	443 Ft.	1,764 Ft.
0.2 mW/cm²	565 Ft.	3,146 Ft.	12,471 Ft.

These calculations are very conservative in that they assume a far field condition and allow for a 2:1 reflection. A more exact "Near Field"* analysis would show the following:

Distance to 1 mW/cm²

	Exact	Approximate
LoV	89 Ft.	251 Ft.
HiV	163 Ft.	443 Ft.
UHF	629 Ft.	1,764 Ft.

The minimum height the antenna should be above ground assuming typical patterns, side lobes, etc., would be as follows:

Distance in Feet Between Array Center Line and 6 Feet Above Ground

	LoV	HiV	UHF
ERP	**100kW**	**316kW**	**5,000kW**
EIRP	**164kW**	**518kW**	**8,200kW**
Power Density			
10 mW/cm²	35 Ft.	64 Ft.	269 Ft.
1 mW/cm²	120 Ft.	203 Ft.	851 Ft.
0.2 mW/cm²	268 Ft.	453 Ft.	1,898 Ft.

Near Field Analysis of Broadcast Antennas, by J. Pezgar, T. Vaughan.

Here again a more exact "Near Field" analysis would show the following:

Minimum Height to 1 mW/cm²

	Exact	Approximate
LoV	43.0 Ft.	120 Ft.
HiV	72.6 Ft.	203 Ft.
UHF	304.0 Ft.	851 Ft.

Pattern

Vertical Patterns

The vertical pattern is usually shown as a plot on rectangular coordinate paper of relative voltage versus depression angle below the horizontal.

The angular width of the main beam of the antenna is directly related to the gain although this may vary somewhat with the method of pattern synthesis.

The half power beam width (0.707 voltage point) for an array with a uniform field distribution is

$$\text{B.W.} = \frac{58.3}{L} \approx \frac{58.3}{\text{Gain}}$$

since the gain for a omnidirectional linear polarized antenna is approximately equal to the length in wavelengths.

Hence, the specified gain generally determines the shape of the main beam. The amount of fill at greater depression angles than the main beam can be varied within limits although this will also decrease the gain. The greater the fill, the lower the gain. These relationships can be seen from the patterns Fig. 12 and the table below where

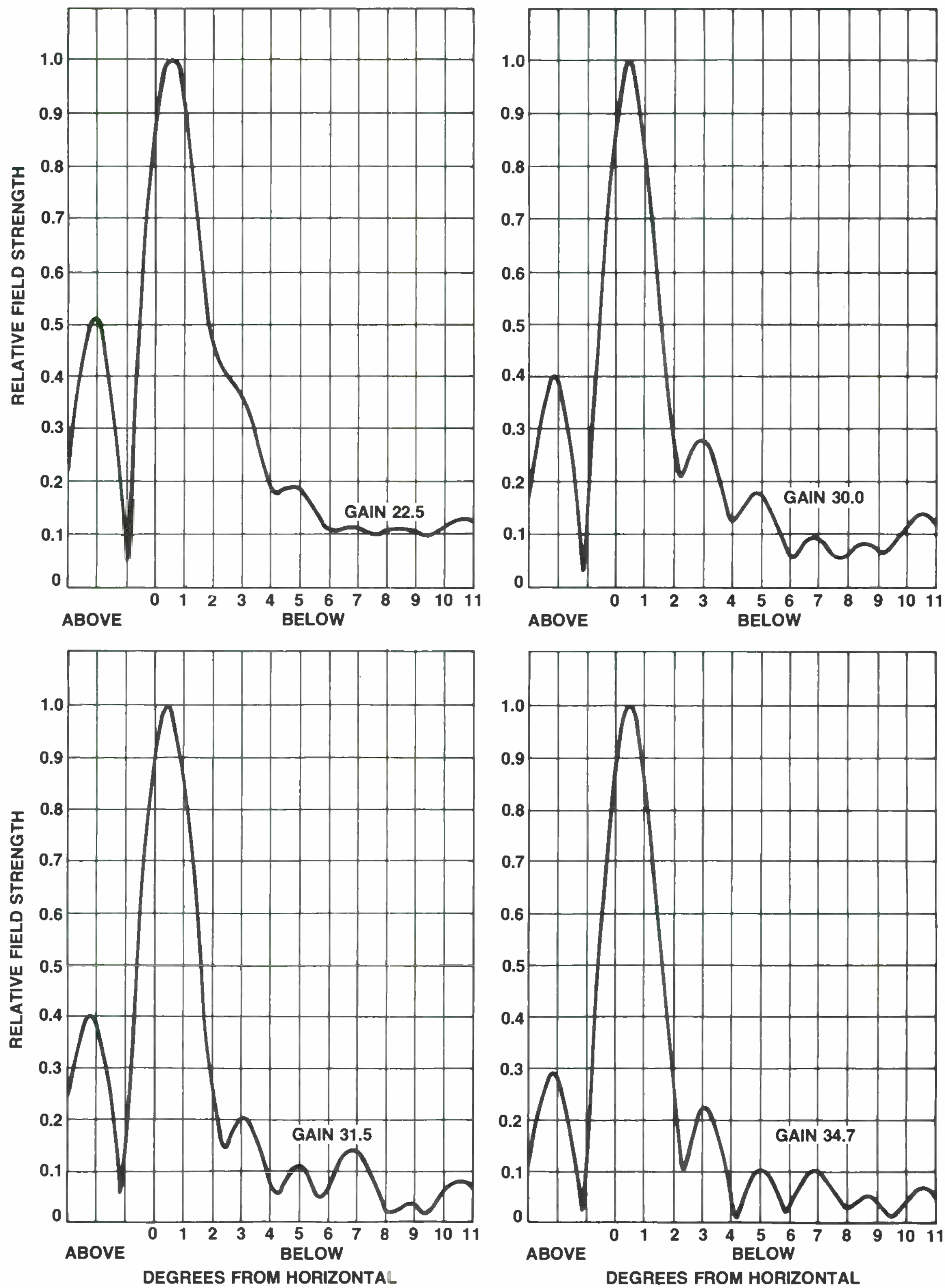


Fig. 12. Four vertical patterns of the same thirty-one layer antenna. Note the decrease in gain as the fill from 2.5° to 11° is increased.

the same number of layers for a given beam tilt will have gains and values of fill as follows:

Null Fill Value in Percentages

	Null No.		
Gain	**1**	**2**	**3**
34.7	11%	1%	2%
31.6	15	6	5
30.0	21	7.5	6
22.5	39	17	10

The amount of null fill and the number of nulls that need to be filled depends upon how close the populated area is to the transmitter site. Allowance should of course be made for population movement towards the site in the fiture. The depression angle below the horizontal, which requires null fill, can be determined from Fig. 13 for the known value of height and distance to the population center.

If the transmitter site is in the center of the population area or right on the edge of it, consideration should be given to a "shaped" pattern of the types shown in Fig. 14 which will provide fill to fairly steep angles.

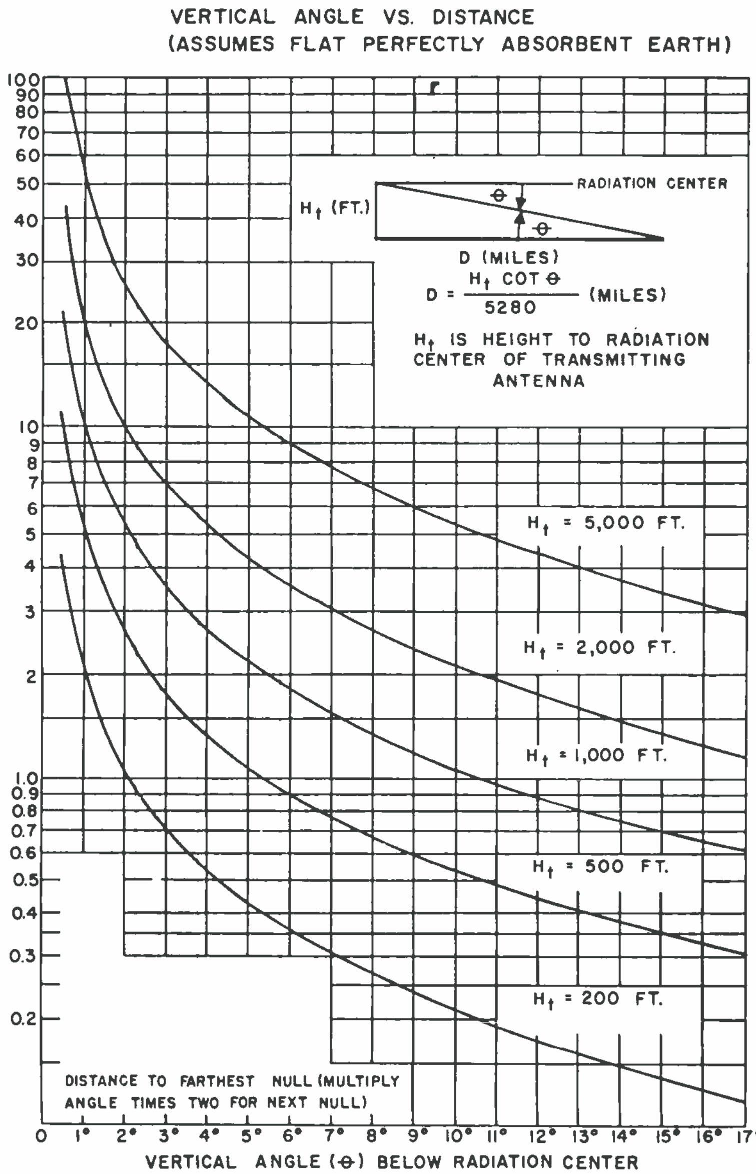


Fig.13. Distance to farthest null as a function of depression angle below horizontal (multiply angle times two for next null).

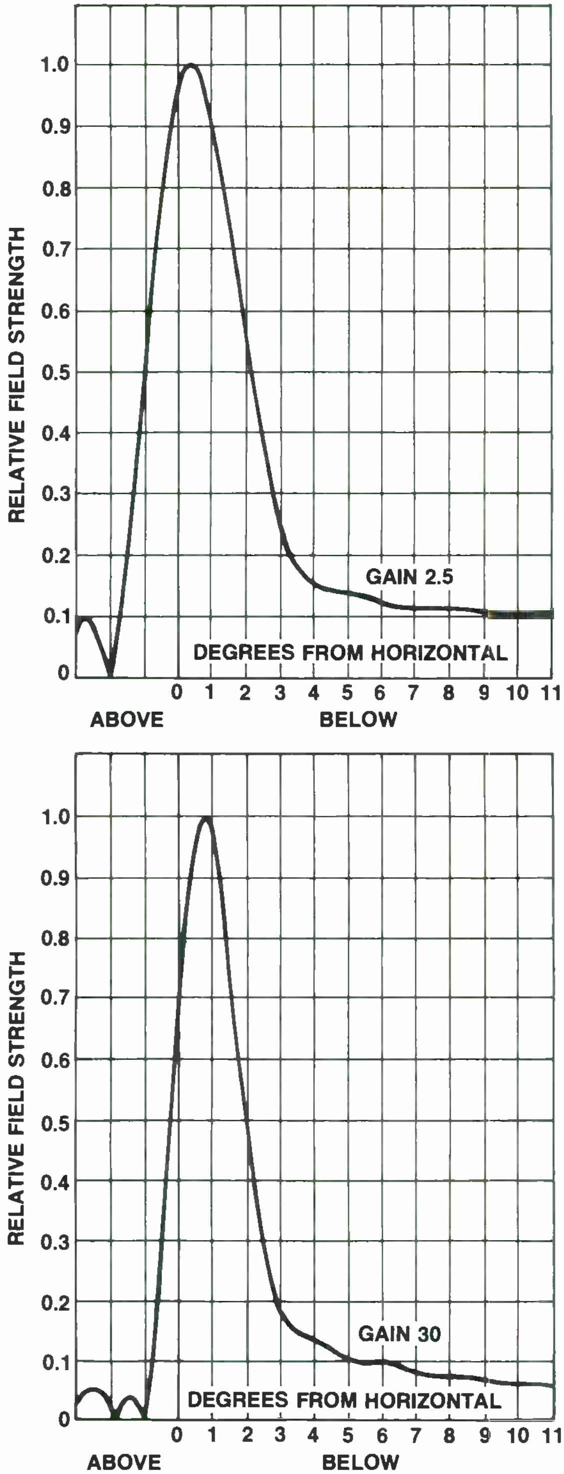


Fig. 14. The "shaped" pattern is generally used in large metropolitan centers where the service area starts very close to the antenna.

Horizontal Pattern

Most omni-directional antennas have a circular pattern with a "circularity" of the order of ± 3 dB.

A directional antenna is advisable only for special terrain situations where the antenna is located near a large body of water or where the service areas are at certain separated locations. It must be recognized that the number of square miles over which a given field strength is obtained is always less with a directional antenna. The optimum condtion in this regard is an omnidirectional antenna located in the center of the area to be served. This can be seen from the following considerations:

Some relative approximate relationships can be deduced from propagation formulas which pertain within the radio horizon over plane earth, as follows:

$$r \propto \sqrt[4]{p}$$
$$A \propto \sqrt{p}$$
$$P \propto \sqrt{h^2}$$

Where r is the distance to a given field contour; p is the "effective radiated power" in the main beam;[5] A is the area served within a given field contour; h is the height of the antenna above the service area.

In Fig. 15 the area enclosed by a given field intensity contour for a relative "effective radiated power" of "1" and a relative height of "1" is πr^2. The transmitting site can also be moved to the perimeter of the circle and a directional entenna employed which has a horizontal pattern in the shape of a quarter of a circle as shown in Fig. 15b. The horizontal gain of such an antenna is four, hence, P = 4.

From the relationship above r $\propto \sqrt[4]{p}$, r becomes the $\sqrt{2}$. The area to the same field intensity contour served is then:

$$A = \pi \frac{(\sqrt{2}r)^2}{4} = \frac{\pi r^2}{2}$$

Hence, using the same transmitter power with an optimum directional antenna with a horizontal gain of 4, only one-half of the area is covered as compared to Fig. 15a and, hence, the coverage efficiency is 50 per cent.

It can be stated generally that because of the fourth root relationship between distance and radiated power, the center of the area to be covered is the best location for maximum coverage efficiency.

However, there is another factor: height. From the relationship above, it is noted that if the height is doubled, the "effective radiated power" increases four times. Hence, in Fig. 15b, doubling

[5] The value here used is not only the product of transmitter power and antenna gain, but also the increase in "effective radiated power" due to an increase in height.

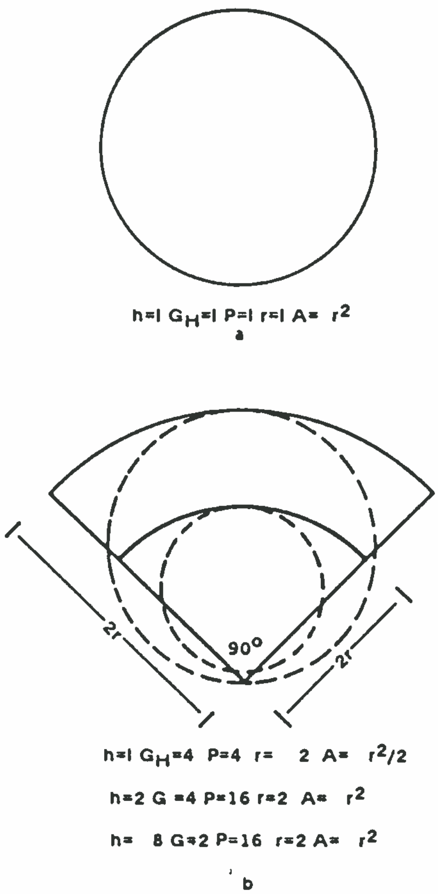


Fig. 15. The most efficient coverage is obtained when the antenna is located centrally in the service area. Only one half of the area is covered with the same input power at the same height from the perimeter using a directional antenna.

the height will provide "effective radiated power" "p" of 16 and "r" becomes 2. The area covered is then:

$$A = \frac{\pi(\sqrt{2}r)^2}{4} = \pi r^2$$

which is the same as for "a".

The antenna postulated in "b", however, is not permitted under the 15 dB rule. A practical antenna may have a horizontal gain of about 2. To obtain an "effective radiated power" of 16 will require a height increase of $\sqrt{8}$ or 2.8 times.

Another general rule is that where a sufficient natural height can be obtained, a directional antenna can be an advantage. To obtain any advantage, however, heights beyond a relative value of 2.8 must be obtained under the conditions postulated above. Hence, it can be seen that the maximum area is covered with a given ERP from the center of the area to be served. If the antenna is located on the perimeter instead of the center of the same area using a directional antenna, the area covered drops to approximately one-half or less. This results from the fact that the service radius varies approximately as the fourth root of the ERP. If a natural low cost height, such as a mountain site, is available at the perimeter which is approximately three times as high as that which would be used in the valley, the full area can be recovered. The economics of each situation should be studied. Because of the fourth root relationship between the service radius and the ERP, a voltage plot of a directional antenna can be misleading. The area to be covered should calculated using propagation formulas to obtain a true evaluation. Often the benefits may be found to be marginal and possibly detrimental.

Antenna Input Impedance

The primary purpose of an input impedance specification is to obtain a good match to the transmission line which carries the power up to the antenna. If the mismatch is too great, the reflected power may be of such magnitude that it travels back to the transmitter where it is generally re-reflected back to the antenna and appears as a secondary image on the television picture. The image is delayed by twice the length of the transmission line.

Subjective experiments have established that the reflection should be no greater than 3 percent of the incident voltage. The method of measuring this is described under "System Specifications."

However, when the antenna is being designed and tested, a complete system is not available so that VSWR (voltage standing wave ratio) across the channel is used as a design guideline.

The relationship between the percentage of reflection and the VSWR of the antenna to achieve it can be related by a computer program. Due to the concentration of energy at picture carrier and ¾ mHz above, the VSWR values should be kept fairly low in this region, say below a VSWR of 1.05 at visual carrier. The values below visual carrier are not as critical since the slope in the receiver cuts off most of the energy in this region as shown in Fig. 16. Hence, the VSWR over the balance of the picture pass band should be as shown in Fig. 17.

However, these values are really only designed guidelines and should not be used as a specification since the real criteria is the 3 percent pulse reflection value, which is the only specification that is really meaningful. It is a temptation to include as many specifications as possible in the hopes of arriving at a good system. However, specifications that are redundant and more stringent than necessary only serve to increase costs without any improvement in performance.

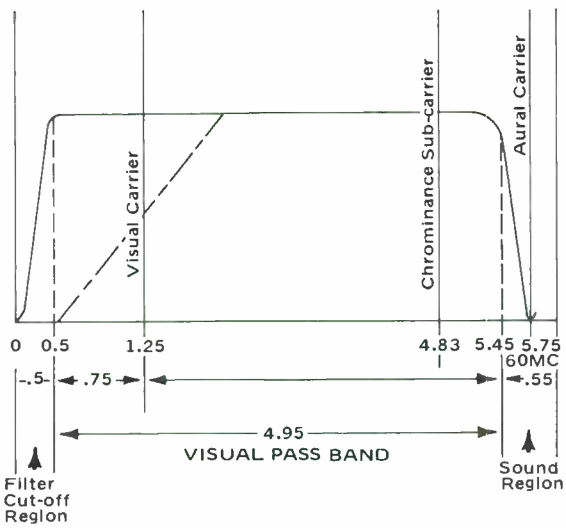


Fig. 16. Note that the visual band is located one half megacycle away from the edges of the channel. Due to the receiver characteristic the VSWR values below visual carrier have a relatively lesser effect on the RF pulse reflection value.

System Tests

The primary purpose of testing the antenna system in threefold is:

1. That the transmission line and components are properly assembled.
2. To determine that the reflection from the antenna and other components at or near the tower top are sufficiently well matched so that no visible ghost occurs.
3. That the impedance presented to the transmitter will result in the maximum transfer of energy.

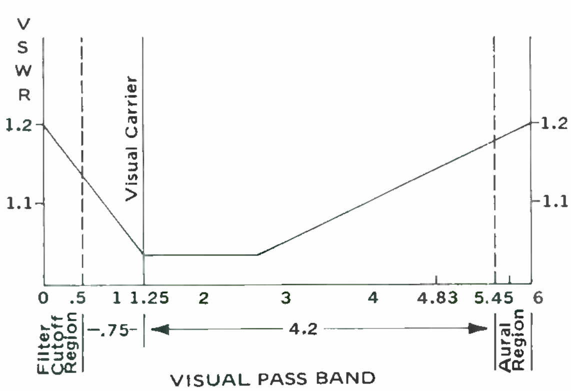


Fig. 17. Based on the visual energy distribution in the channel and the receiver response, the above VSWR versus frequency characteristic will achieve better than a 3 percent pulse reflection value.

Transmission Line and Components

For an extremely broad band device like a coax transmission line which is usually designed to cover the entire, or at least, a large portion of the TV band, the dc pulse is very effective test to determine if the line and components have been properly assembled. This is a short pulse of perhaps 20 nanoseconds at about a 15,000 cycle repetition rate. The wave front is steep enough so that each section of line can be discerned on an oscilloscope. Each joint will manifest itself as a separate vertical line. If one of the pulses is higher than the others, the joint should be investigated for an improper connection or other fault. It is sometimes good practice to assemble the line from the bottom up so that the reflection from each piece can be seen as it is inserted and an immediate correction made. It is also advisable to tap each joint with rubber mallet to locate incipient trouble due to single point contact or improper connection.

Time Domain Reflectometers (TDR) are now generally available for making dc pulse measurements. For UHF installations, a circular or rectangular waveguide is now used. Since a waveguide has no inner conductor, dc pulse measurements cannot be made. Measurement must be made with RF signals.

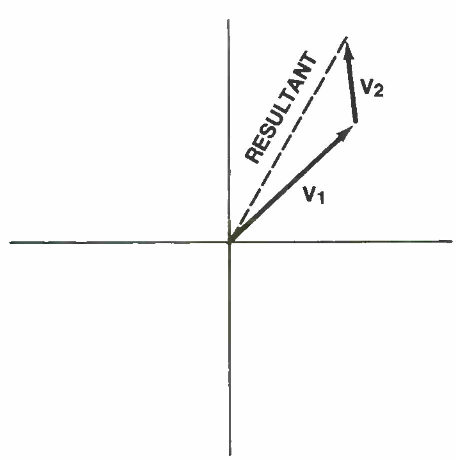
It should be understood that measurements made of the input to the transmission line measure the combined input impedance at that point only, and not the discreet reflections that can cause ghosts.

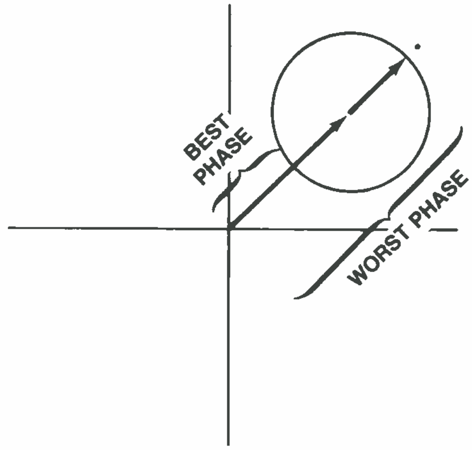
There are usually two sources of reflection assuming the line to be reflectionless:

(A) Lower elbow complex—V1
(B) Upper elbow complex and antenna—V2

When measured at the input to the system these can be thought of as two vectors.

Each vector individually will rotate about the preceeding vector at a frequency corresponding to the distance from the point of measurement.





The frequency of rotation can be calculated as follows:

$$\Delta f = \frac{496^*}{L} \quad \text{coax}$$

$$\Delta f = \frac{496^*}{L}\left(\frac{\lambda o}{\lambda g}\right) \quad \text{waveguide}$$

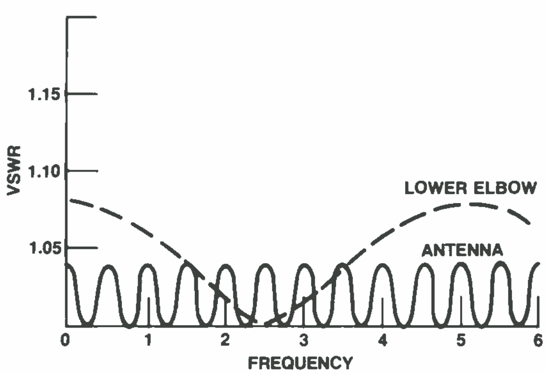
*Half (coax) the velocity of light with L in feet.

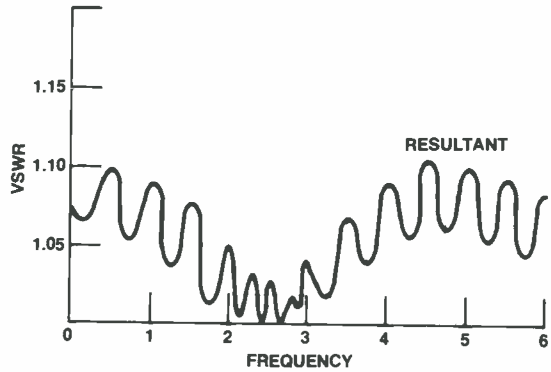
The displacement of the corresponding echo (ghost) on a TV screen would be the reciprocal of the frequency Δf (Echo = $1/\Delta f$).

If we use the following example

Reflection Location	Distance	Magnitude VSWR	Γ1	Δf MHz	Displacement Microsec on TV Receiver
Lower elbow complex	100 ft.	1.08	4%	4.96	0.2
Antenna	1000 ft.	1.04	2%	0.496	2.0

The resulting combined reflections (VSWR) would be as shown:





The worst VSWR would be when the vectors are in phase (1.08) × (1.04) = 1.12 and the best (1.08) / (1.04) = 1.038 assuming both vectors remain on the same side of the Smith chart.

The half period between 2 and 3 MHz is because the antenna vector is going to the other side of the Smith chart.

The antenna reflection would be more objectional than the lower elbow complex because of its distance and displacement rather than its magnitude. A 5% (VSWR 1.10) echo would not be as objectional at 0.2 μsec as it would be at 2.0 μsec.

The antenna reflection should be kept to less than 3% although the input reflection may read higher due to near and far end reflections.

An example of combined transmission line and antenna VSWR can be seen in Fig. 18.

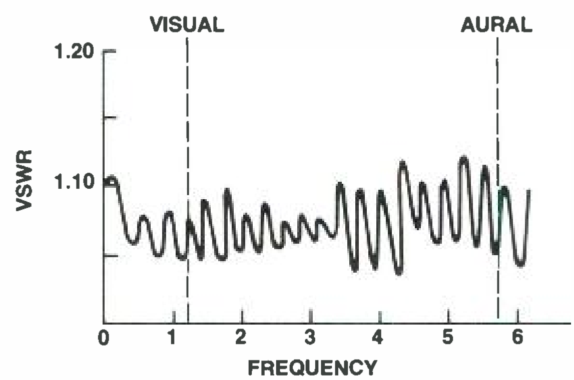


Fig. 18. Example of combined transmission line and antenna VSWR.

Careful examination will show three cycles in this UHF waveguide installation.

		DISTANCE TO REFLECTION	
SOURCE	PERIOD	COAX	WAVE-GUIDE
LOWER ELBOW	8 MHz	62 FT	44 FT
TRANSFORMERS	2 MHz	248 FT	177 FT
ANTENNA	0.27 MHz	1837 FT	1312 FT

The directional coupler used to measure system performance is located in the transmitter. Another source of near in reflections would be the components in the transmitter room.

This would include elbows, switches, combiners, diplexers—etc. The combined transmitter room reflection should be kept very low (less than VSWR 1.08) not because of its echo displacement but because the interaction of this reflection with the antenna reflection can result in varying transmitter readings when line lengths change due to thermal expansion and contraction.

AT UHF frequency where the guide wavelength is 2 or 3 feet, a 50° C temperature change on a 1,000 foot tower can result in electrical length changes of $\lambda/4$ to $\lambda/2$ wavelength.

Deflection and Wind Load

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 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 stated as the angle from the vertical of the chord that connects the base to the top of the antenna.

In order to evaluate the effects of deflection, an example for a high gain UHF antenna will be given.

Figs. 19 and 20 show the pattern variations of a UHF antenna of the slotted cylinder type with a gain of 46 when the antenna is 102.8 ft. in height. The entire antenna is constructed of 18 in. steel tube with a 1.218 wall using six peripheral slots in each layer.

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.

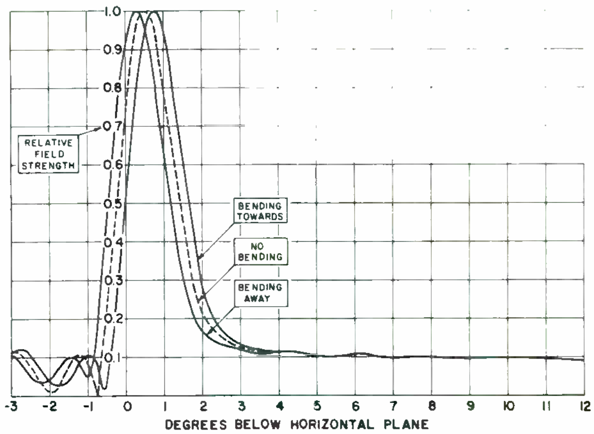


Fig. 19. Calculated vertical patterns of the TFU-46C antenna affected by static load: flat-surface wind load 10-psf, wind velocity 50 mph.

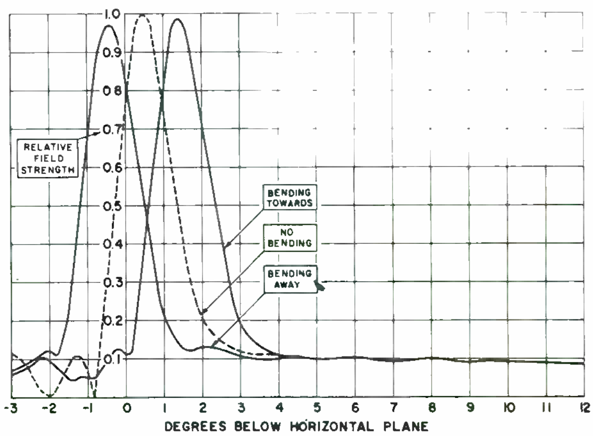


Fig. 20. Calculated vertical patterns of the TFU-46C antenna affected by static wind load: flat surface wind load 40psf, wind velocity 100 mph.

Two conditions are shown for a wind velocity of 50 to 100 mph as summarized in Fig. 21.

The 50 mph wind condition is one that may occur[6] 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.

[6] Report of TASO Committee on 1.3 on Television Antennas. Final Report of TASO Sub-Committee 1.3.2 on Towers, Sec. 3.6.

Wind Velocity mph	50		100	
Wind load psf	10		40	
Deflection of antenna at top, in.	4.9		19.6	
Deflection, degrees, of chord from bottom to top	0.227		0.914	
Tower deflection degrees	0.125		0.5	
Antenna and tower deflection degrees	0.352		1.414	
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*	−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

*Values are not the same, since in this antenna, radiation above the horizon has been suppressed and the pattern is not symmetrical.

Fig. 21. Signal strength variation as a result of transmitting antenna deflection in high winds.

Most television receivers are designed to have a flat AGC response down to 100 microvolts 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 area 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 microvolt level at the receiver terminals.

Analyzed on this basis even the 100 mph wind condition is not too serious except 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.

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 charactristics 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.

Half-wave Dipole

If the ends of the open-wire transmission line are turned outward, as shown in Fig. 22A, 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. 22B. 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."

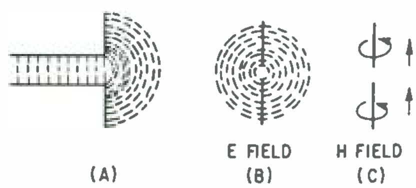


Fig. 22. Electric (E) field, and magnetic (H) field of a dipole.

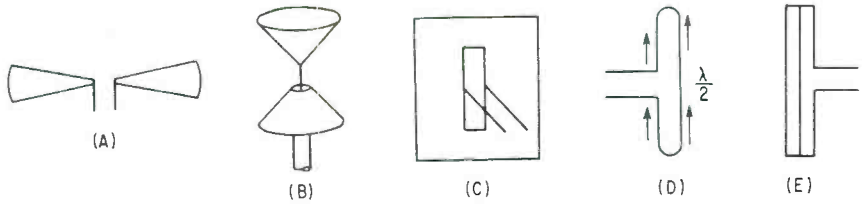


Fig. 23. Examples of radiators having dipole-like charateristics: (A) and (B) biconical antennas, (C) slot-fed sheet, (D) folded dipole, (E) folded dipole with additional element.

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. 23a and 23b and to the slot-fed sheet radiator, Fig. 23c.

Another form of the dipole is the half-wave folded type shown in Fig. 23d. 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. 23e increases the input impedance by a still greater factor.

Because the folded ends act like stubs, they become capacitive at high 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.

The loop or ring radiator may be rectangular or circular, as seen in Fig. 16a 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. 24a are considered to be 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.

Figs. 25a and 25b show 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 both 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. 25c and 25d

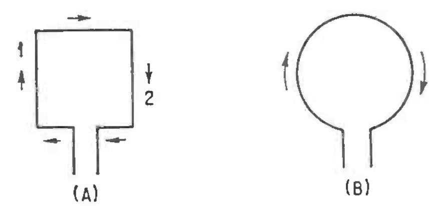


Fig. 24. (A) Square loop and (B) ring radiator.

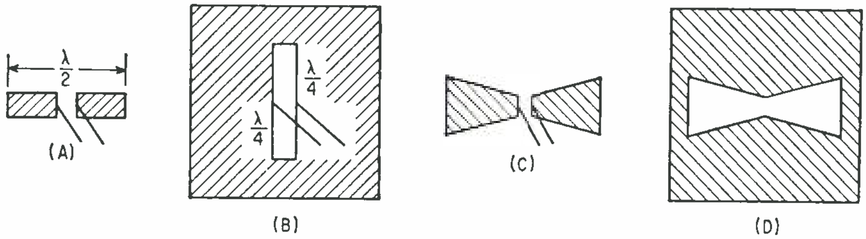


Fig. 25. Dipoles (A) and (C), with complementary slot-fed sheet radiators (B) and (D).

are the same. A very similar situation occurs in optics, where the phenomenon is known as Babnets 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.

Radiation can be limited to one side of a very large sheet by boxing in the slot on the othe side. If the depth of the box is such as to present zero susceptance at the feed point, the input impedance will be approximately double that of the same antenna without the box (see Fig. 26).

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. 27).

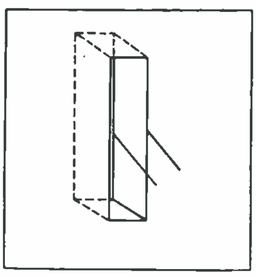
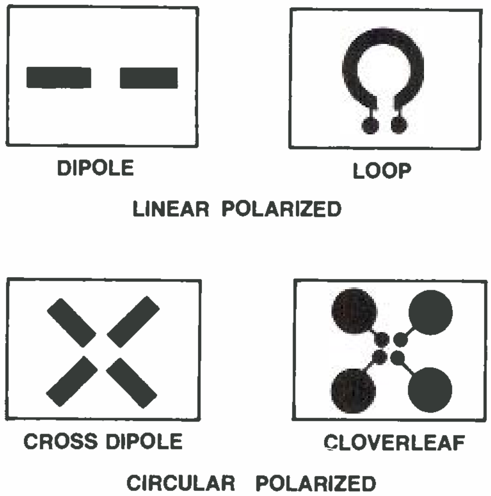


Fig. 26. Slot-fed sheet radiator with slot boxed to limit radiation to one side of sheet.

Panels

Many of the newer antennas are of the panel type that is either dipole or loops mounted $\lambda/4$ in front of a panel. These antennas will have a directional ($\cos\theta$ or $\cos^2\theta$) pattern in the azimuth and elevation planes.



The pattern is directional since the energy radiated from the element sees its image in the ground plane resulting in a $\lambda/2$ spaced end fire radiator.

The omni-directional pattern ripple of panels mounted around the tower is dependent on the physical size of the tower hence dependent on the channel. As mentioned previously, there is an optimum relationship between the phase center diameter and element pattern for square and triangular towers. A large variety of pattern

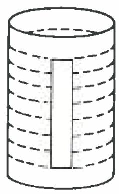


Fig. 27. Slot-fed sheet radiator bent to form a cylinder, showing resemblance to stack of ring radiators.

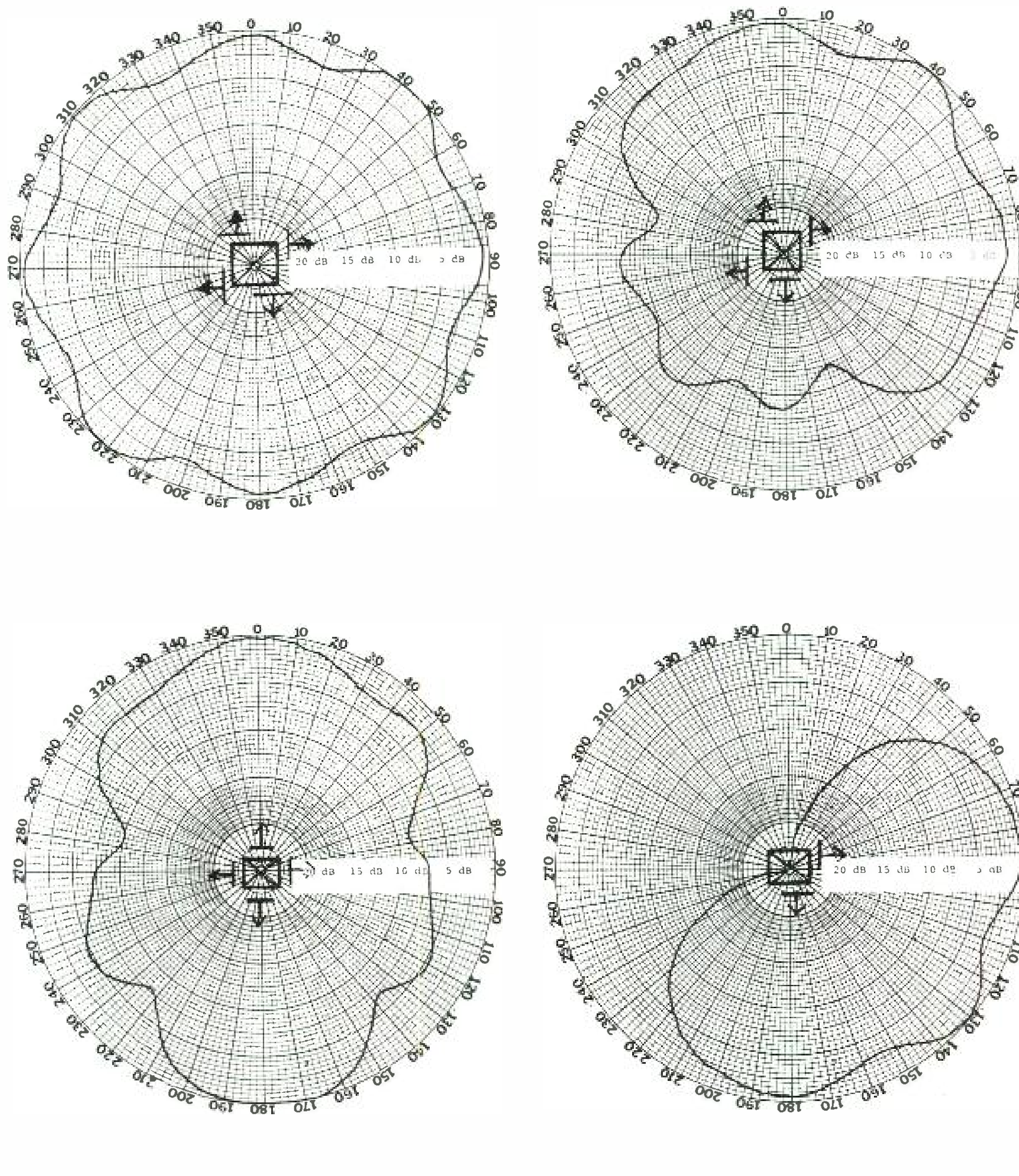
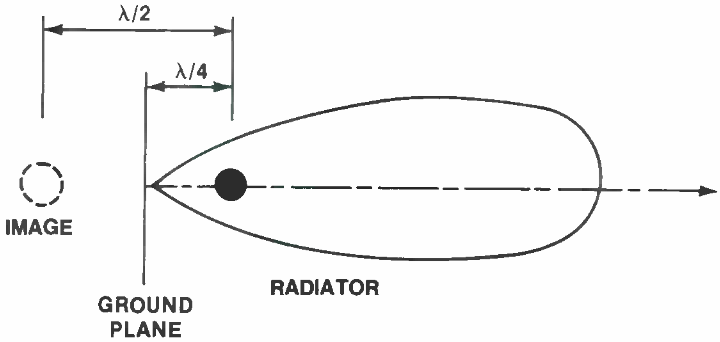


Fig. 28. Examples of azimuth patterns of an H panel low band antenna on a 3.2 meter tower.



shapes can be obtained by controlling the position and power fed to each panel.

Traveling Wave Antenna

There is a large variety of traveling wave antennas now available.

The traveling wave slot antennas are either resonant (standing wave) or non-resonant (traveling wave). All are bottom fed. When the far end is shorted, an infinite standing wave is set up in the transmission line (either coax or waveguide). When the slots are appropriately sized and spaced, energy will be coupled out. The amplitude and phase developed across the aperture can result in a high gain antenna. The band width limits this technique to narrow band or UHF high channel application.

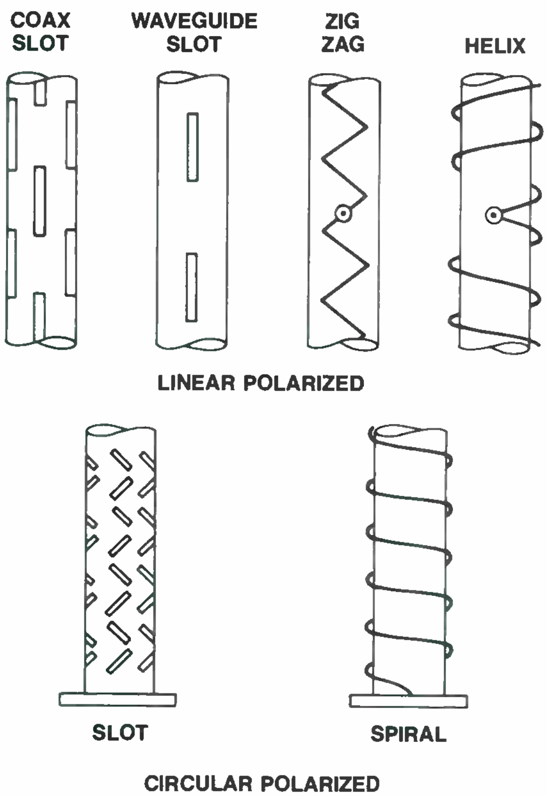


Fig. 29. Traveling wave antenna configurations.

The most common bottom fed traveling wave array is the non-resonant array. The number of half wavelength slots arranged about the periphery is dependent on the shape of the pattern desired. The circumferential slots are usually displaced by $\lambda/4$ and spaced vertically one wavelength. The coupling from the bottom to the top increases since the power radiated successfully reduces the power on the line. This method produces an amplitude taper across the aperture hence null fill. With all non-resonant arrays, there is a small amount of energy left over. This is radiated in specially designed end-loaded slots or in the opposite polarization.

The zig-zag is essentially a strip transmission line mounted over a ground plane; the spacing controls the radiation. Each element is a $\lambda/2$ radiator, and because of the orientation, the vertical components cancel. The choice of pitch angle and length on circumferential the helix will result in very good horizontally polarized broad side radiation.

Circular polarization can be obtained by orienting successive slots at 90° and exciting them in phase quadrature.

The circular polarized spiral or multi-arm helix are multiple wires mounted around a large cylinder forming a current sheet. The optimum parameters are a complex function of the number of arms, the length of one coil, and the spacing to the support pole.

Excellent circularity can be obtained since in any heading the radiation is essentially that from a current ring.

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 Com-

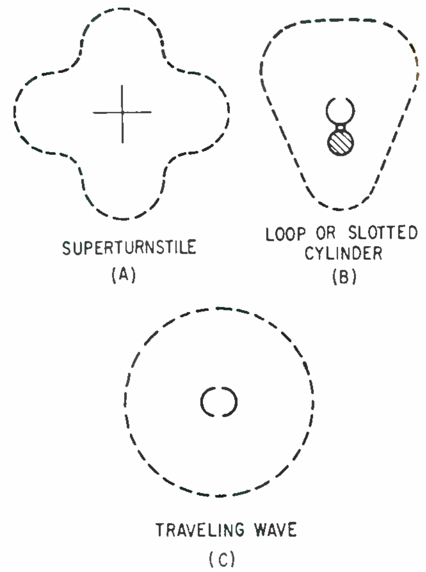


Fig. 30. Typical azimuthal patterns of well-known types of TV broadcast antennas.

mission, the large majority of requirements have been for omnidirectional 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. 30.

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. Fig. 31a 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 patterns will overlap, as shown in Fig. 31b. If both are fed in phase, addition of the radiated energies will result in a pattern such as is shown in Fig. 31c.

Other methods of obtaining omnidirectional patterns which have been used are the "clover leaf" of small loops (Fig. 32b), the triangle of folded dipoles (Fig. 32c), the small loop (Fig. 32d), the "supergain" with the dipoles backed by screens and fed in quadrature (as are the turnstiled dipoles) (Fig. 32e), and the helix wound around a tower structure with phase compensators to maintain correct phase relationship between successive turns of the helix (Fig. 32f).

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,

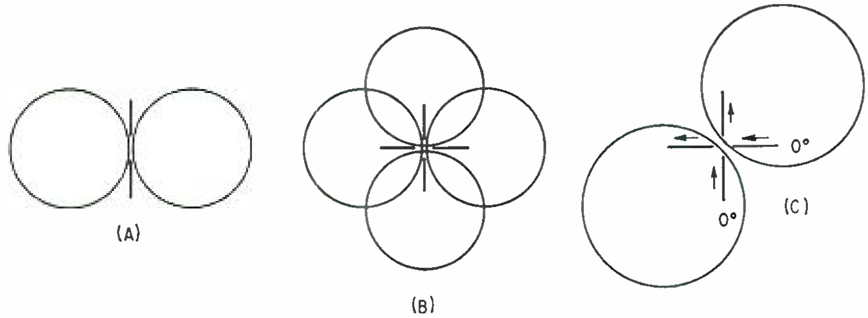


Fig. 31. Addition of fields of crossed dipoles. (A) Figure-eight pattern of a single dipole, (B) superposition of a second dipole at right angles, (C) pattern obtained when both dipoles are fed in phase.

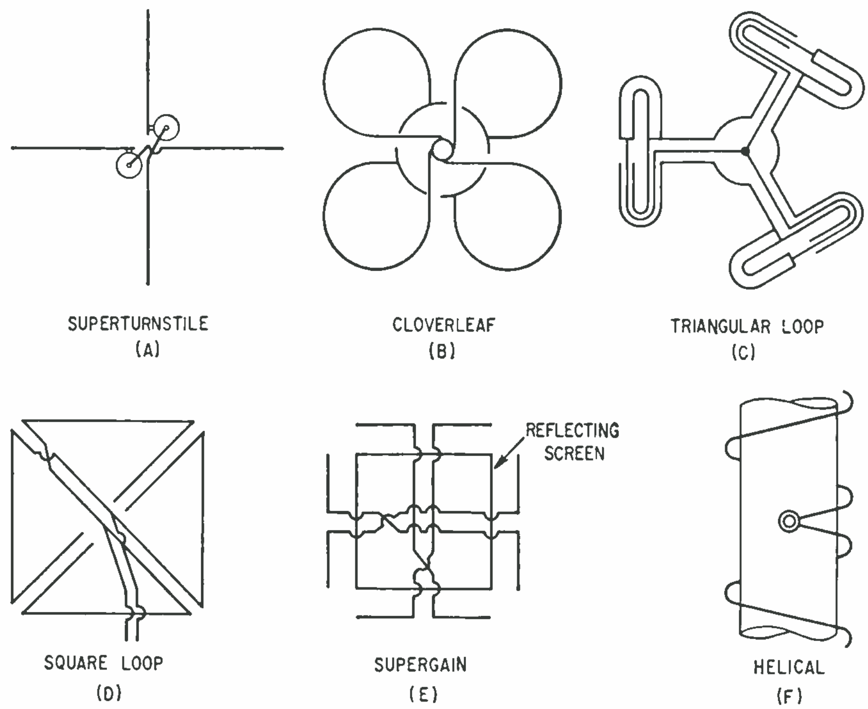


Fig. 32. Configuration of elements used to obtain omnidirectional patterns.

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. 33 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 of 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.

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.

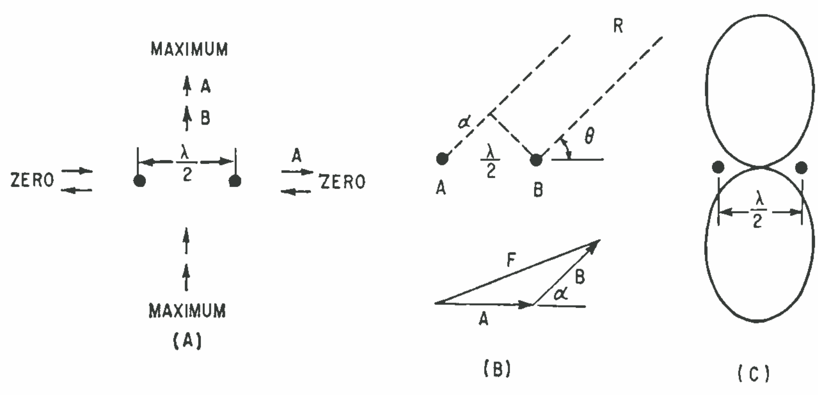


Fig. 33. Formation of field pattern from two souces placed a half wavelength apart, as shown in (a) and fed in phase. Leg of signal from source A in direction R is shown in (B) and the sum F of the signals from A and B are shown in (C).

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. Fig. 34A shows the vertical pattern of a point source or of a horizontal dipole. Fig. 34B and 34C show the effect to stacking two- and six-point sources one above another, a half wave apart, with currents of equal amplitude and phase. Fig. 30d shows the same information as Fig. 30c for the portion of the pattern between $\theta = 0°$ (horizontal) and $\theta = 270°$, 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

$$\theta = \arctan \frac{\pm K}{nd}$$

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. Single 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. 35A).

A more complex power distribution was proposed by J.S. Stone, wherein successive elements are fed with amplitudes proportional to the coefficients of a binominal 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).

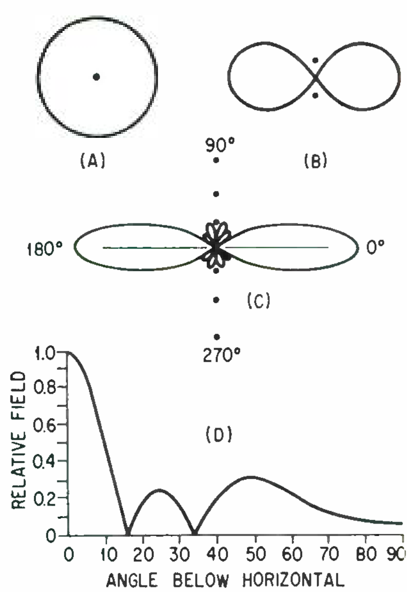


Fig. 34. Effect of stacking several point sources having equal currents and phase. (A) Vertical pattern of single source, (B) two sources, (C) six sources. Information given in (C) is shown in rectangular coordinate form in (D) for angles between horizontal (0°) and directly below the array (270°).

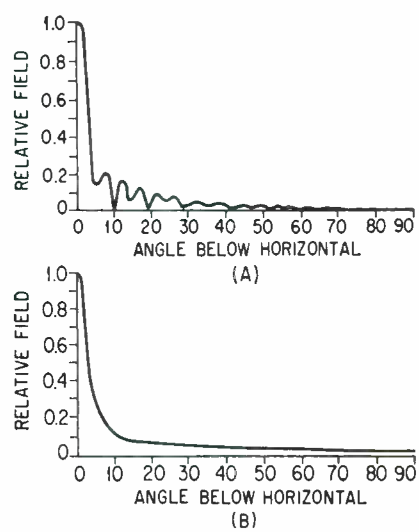


Fig. 35. (A) Vertical field pattern of antenna with a gain of 12 having twice as much power in the upper half as in the lower half. (B) Vertical field pattern of an antenna with many separate radiating elements with ideal phase and power distribution to obtain smooth pattern.

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. 35B).

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 nondirectional 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 of 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 usefully 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 raidated above this region serves little useful purpose, and it is desirable to reduce it as much as possible.

To indicate the effectiveness of this directional 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.

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 using an isotropic source as a base of comparison by use of a multiplying factor of 1.64.

An illustration of this in one plane only is given in Fig. 36. The circle contained the same area as the pattern being considered and represents the field pattern of an isotropic course with the same power input. The gain in the main lobe, ignoring losses, will be

$$G = \frac{E_A}{E_i}$$

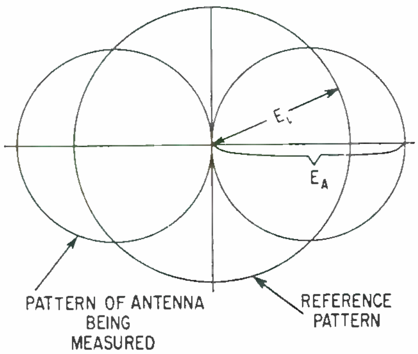


Fig. 36. Comparison of pattern of a measured antenna with circle of equal area to determine gain.

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 antenna therefore must transform 377 to that of the feed line.

The input impedance of a superturnstile antenna is about 150 ohms (both batwings together), of a helical antenna 100 ohms, of a resonant full wave slotted cylinder about 40 ohms, dipole is 73Ω.

A simple and effective method of matching for a narrow band of frequencies can be 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.

Feed Systems

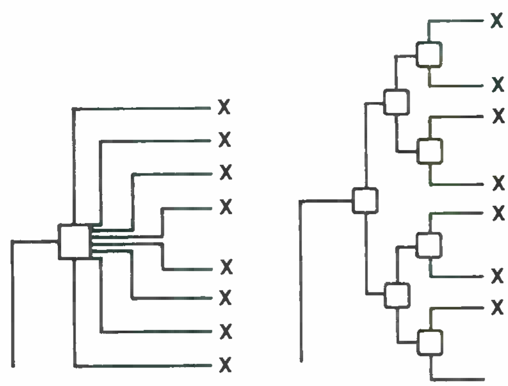
The feed system of a television broadcast antenna is commonly considered that portion of the transmission system having its input at the antenna terminal which is at the top of the vertical run of coaxial transmission line in the tower and its output at the radiating elements.

Most antenna gains in the manufacturers' literature take the losses of the feed system into account. Therefore, when system losses are calculated, the feed-system loss can be excluded.

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. Frequencies vary from 54 to 806 MHz, power-handling-capacity requirements vary from 500 to 220,000 watts, gains vary from 0.5 to 60, and where pattern shapes vary between extreme limits, good economics dictates various types of feed system.

BRANCHING: This feed system progressive divides the power as shown in Fig. 37.



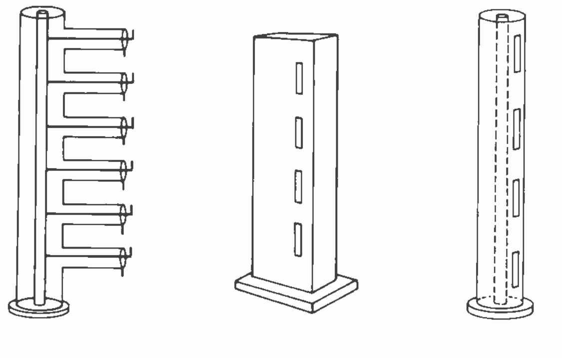
(A) (B)

Fig. 37. Branching feed systems.

This feed system would be used when the radiators are individual elements each with their own terminal such a dipoles or panels. The system shown in Fig. 37A would have a narrower impedance bandwidth than Fig. 37B since for economy one 8-way power divider is used. The junction impedance is $Z_m/8$. If the element impedance is 50Ω, the power divider must transform 6.25Ω to 50Ω. The system shown in Fig. 37B uses only two way splitters. Although it has a broader bandwidth there are 7 power dividers with additional interconnect cable. Null fill and beam tilt in both of the above are accomplished by changing the length of the feed cable or in some applications by unequal power dividers.

A problem with either of the above is the presence of the feed line in the aperture of the lower elements. The feed lines will cause reradiation and distort the azimuth pattern. The branching feed system can be effectively used with these antennas that require a center support tower or mast.

STANDING WAVE FEED SYSTEMS: A transmission line either coax or waveguide can be shorted at the far end resulting in standing wave along the length of the line. If slots or coupling probes are appropriately sized and positioned energy can be coupled and a desired ampli-



tude and phase distribution across the aperture can be obtained. This resonant array structure has a desirable feature: all coupling parameters are the same and equally spaced. Its disadvantage is a narrow bandwidth and can only be used at UHF frequencies.

TRAVELING WAVE: The traveling-wave feed system operates on the principle of a gradual attenuation (radiation) of the input signal as it progresses from the input along the aperture of the antenna. An application of this principle is the spiral antenna or slot antenna known as the traveling-wave antenna.

Fig. 38A 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-phrase 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 omni-directional pattern the radiators, instead of being in line, can be moved around the periphery to form a "spiral" as shown in Fig. 38B. 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 omni-directional pattern.

A disadvantage with the traveling wave antenna or non-resonant array is the energy not radiated at the end of the array must be absorbed. This is accomplished with a special absorbing section at the top which will radiate the energy in the same or cross polarization.

The traveling wave (non-resonant) antenna is more broadband than the standing (resonant) wave antenna. Many antennas use a combination of branching and either of the above.

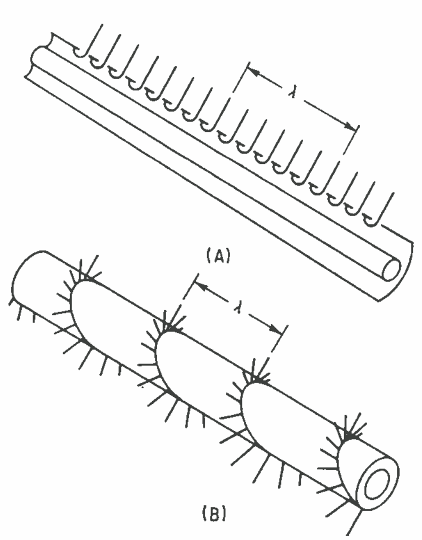


Fig. 38. Basic principles employed in the traveling-wave antenna feed system.

Bridge Diplexing

Antennas that use a single feed line must diplex the visual and aural signal together. Some antennas such as the turnstile/batwing can use either one or two lines. If separate antennas are used for visual and aural, two lines would be required.

The bridge hybrid by virtue of its 3dB coupling properties will split the visual and aural signal between the N/S and E/W antennas.

With dual lines beam tilt can be affected by differential changes in the line length or propagation velocity. See Fig. 39.

Constant Impedance Notch Diplexers

Most antennas use a single feed line because of cost. Dual lines increase wind load on the tower. The cost of single large size lines for a tall tower can cost up to $250,000.

The most common diplexer used is the Constant Impedance Notch (CIN) Diplexer.

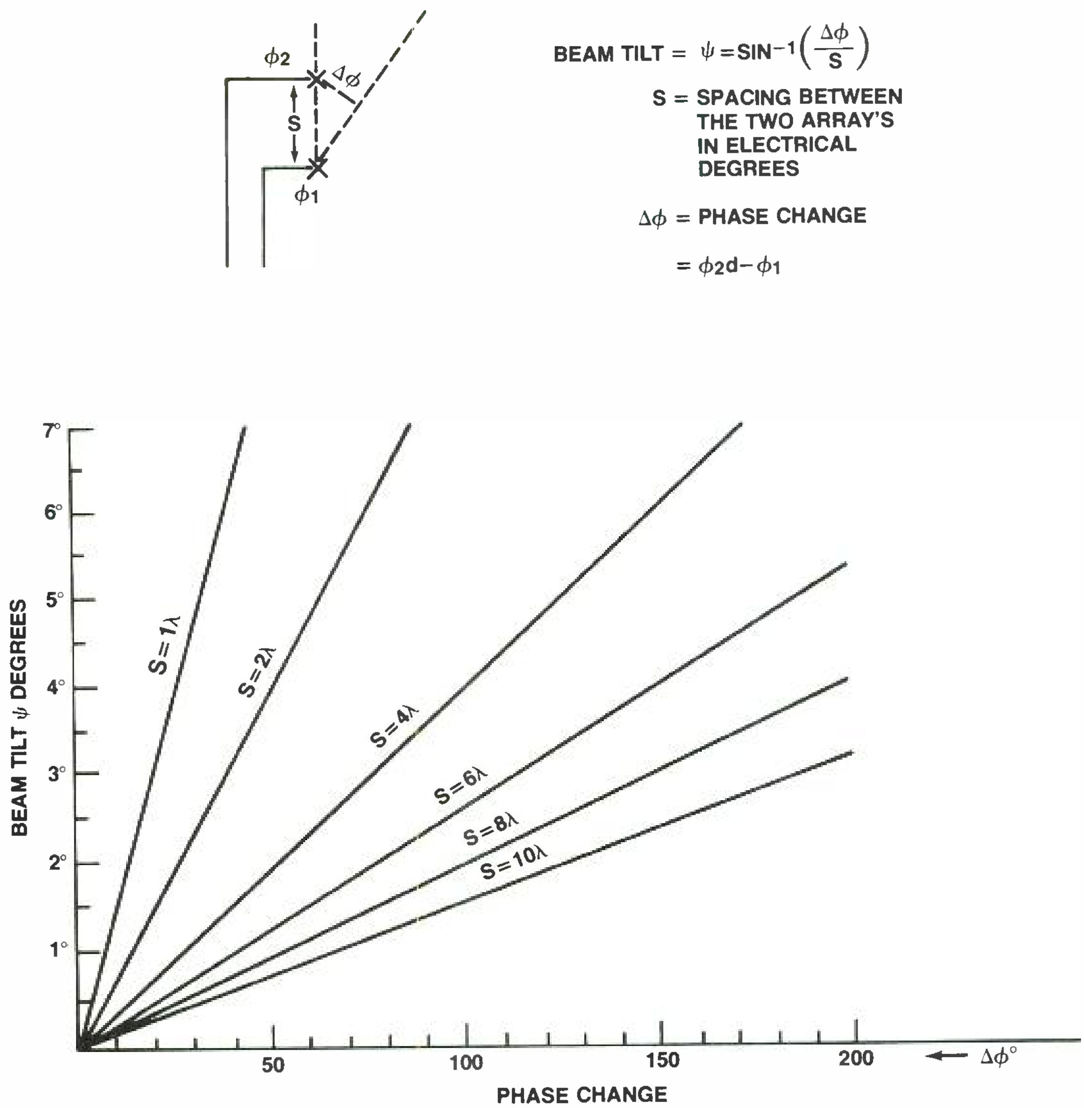
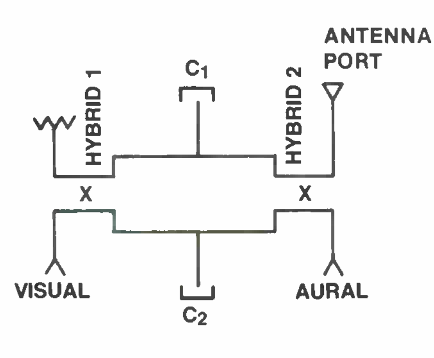


Fig. 39. Effect on beam tilt of differential phase change between elements of an array.

In the CIN type, the visual signal splits equally in the hybrid 1. The signal passes the cavity since they are tuned to resonate at the aural frequency. The signals are recombined in the second hybrid, and all the energy goes out the antenna port. The aural signal is split in hybrid 2, resonated in cavities C_1 and C_2, and reflected back toward hybrid 2. Because of the phase reversal, all the energy is coupled out the antenna port.



ATTENUATION @ +4.18 MHz	UHF (CH 5) 3 dB BW kHz	α dB	Q_L	UHF (CH 64) 3 dB BW kHz	α dB	Q_L
1 dB	400	.25	212	—	—	—
2 dB	500	.2	170	420	.9	1900
3 dB	600	.1	140	670	.4	1200
6 dB	—	—	—	1200	.2	650

Fig. 40. Diplexer cavity characteristics.

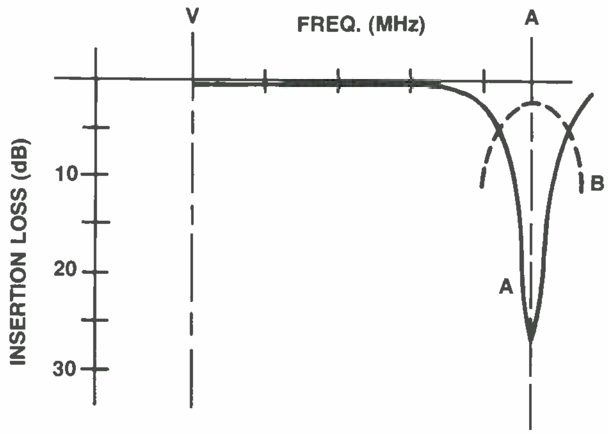


Fig. 41. System performance curve A would be the response between the visual and antenna port, and, curve B, the response between the aural and antenna port.

Since the cavities are tuned to the aural frequency (+4.5 MHz) and are very high Q resonant devices, the signal in the visual pass band (0 to 4.18 MHz) does not see the cavity reactance until the frequency approaches the resonant frequency of the cavity at 4.18 MHz. With non-MTS diplexers the cavity Q is adjusted so there is minimum loss at +4.5 MHz (aural carrier). The loss at +4.5 MHz is dependent on the ratio of Q loaded to Q unloaded.

Very high Q unloaded cavities are used. For VHF the cavities are usually re-entrant type. For UHF waveguide the cavities are either cylindrical or square operating in the TE_{11} mode.

The 3 dB bandwidth, insertion loss at resonance, and the cavity loaded Q are dependent on transmission loss at +4.18 MHz.

Typical performance would be as shown in Fig. 41. Curve A would be the response between the visual and antenna ports. Curve B would be the response between the aural and antenna port.

Insertion loss and group delay response characteristics of typical VHF diplexers are shown in Fig. 42.

MTS Diplexer

The diplexer used for mono-sound bandwidth is ±25 KHz. The bandwidth requirements for MTS (Multi Channel-Stereo Sound) should be ±200 KHz.

The bandwidth requirement for the MTS signal is shown below.

Signal	Base Band Freq.	Deviation	β	RF BW
Main	15 kHz	25 kHz	1.6	± 40 kHz
Stereo	48 kHz	50 kHz	1.04	± 90 kHz
SAP	90 kHz	15 kHz	0.16	±105 kHz
PRO	105 kHz	5 kHz	0.05	±112 kHz

The above assumes individual carriers—when multiple carriers are present a more complex situation exists and wider bandwidth may be required.

Ideally we would like the aural path to be transparent and not contribute any distortion. To accomplish this the bandwidth should be twice the RF band required.

The specifications for MTS diplexers due to the aforementioned restrictions would be, as follows:

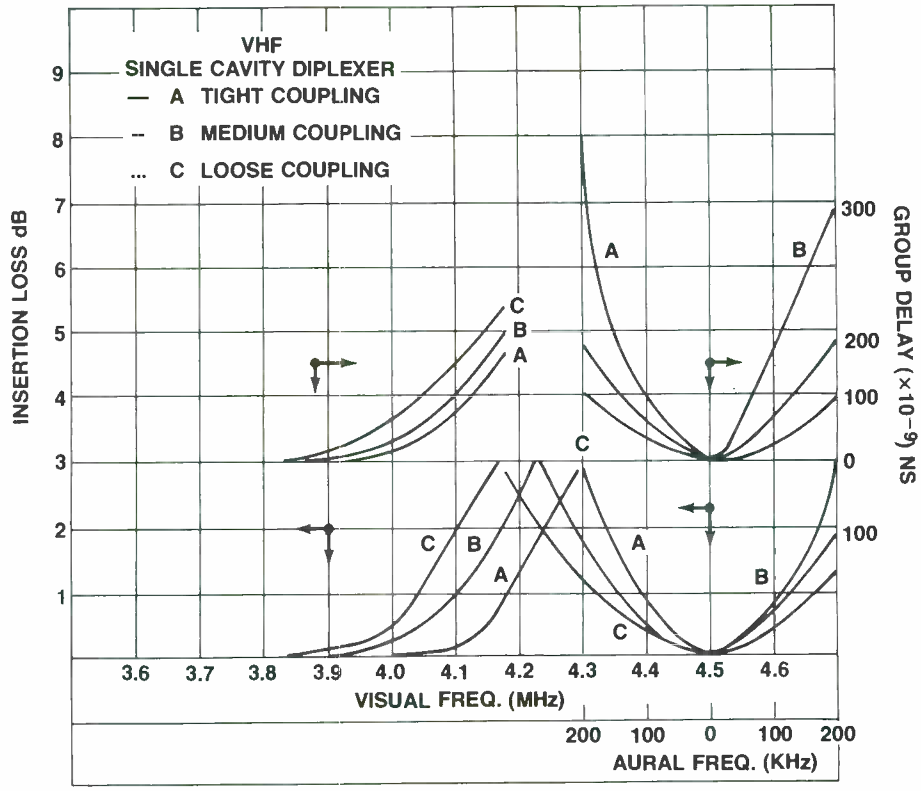


Fig. 42. Measured insertion loss and group delay response for some typical VHF diplexers.

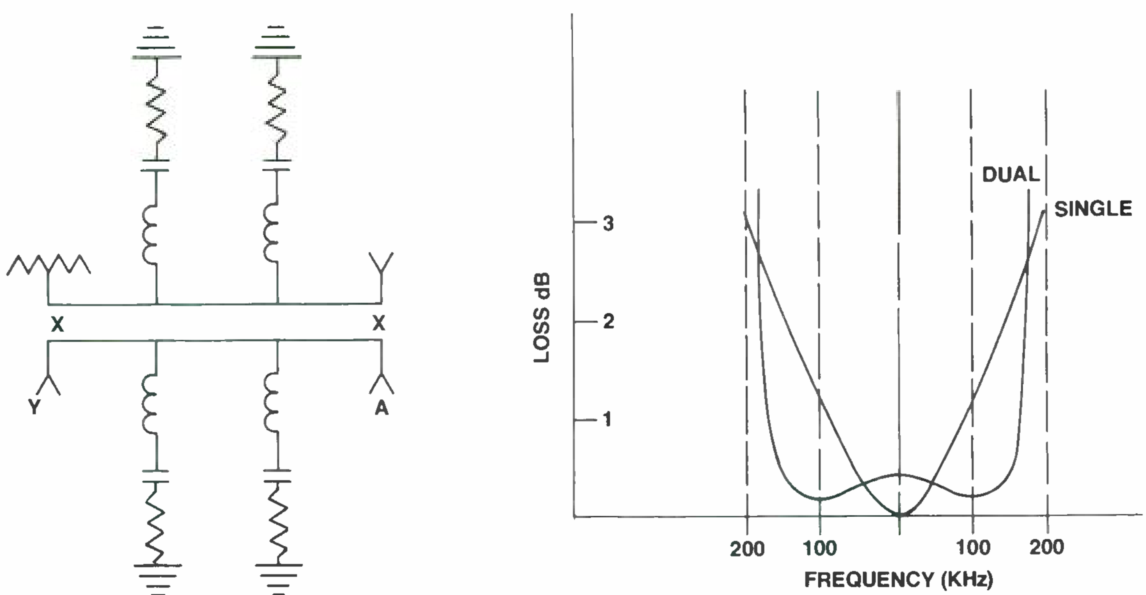


Fig. 43. Characteristics of cavity diplexers.

Bandwidth	±200 kHz
Insertion Loss	
Visual to Antenna @+4.18 MHz	3 to 6 dB
Aural to Antenna	
@Aural Carrier	<0.4 dB
Over Aural Band	<3 dB
Amplitude Asymmetry	
Over Aural Band on	±0.2 dB
Group Delay Asymmetry	
Over Aural Band	<50 ns

MULTIPLE CAVITIES

To satisfy the wider bandwidth requirements some transmitter manufacturer's use lower Q cavities and pre-distort at the front end to lower the transmission loss and group delay.

It is also possible to increase the bandwidth without pre-distortion by using multiple cavities.

The advantages of using dual cavities are:

(1) Wider aural bandwidth with lower Q cavities.

(2) Lower insertion loss at the aural carrier.

(3) Lower Q will result in less sensitivity to detuning and less asymmetry.

(4) Steeper skirts in the vicinity of the +4.18 MHz will result in lower transmission loss in the visual pass band.

(5) Less group delay.

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. 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.

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
   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.

Antenna Mounting Methods

Most antennas are flange mounted and manufacturers—either in their catalogues or upon request—will furnish mechanical and mounting data for their antennas. Standard mounting bolts are usually furnished with the antenna. If a special double plate design or other design is used in the tower top, the antenna manufacturer should be advised so that the proper bolts can be furnished. If a new antenna is substituted for an old one, an adaptor plate may have to be designed and furnished by the tower manufacturer.

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 from two to four elbows at the top 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 layout 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 specially optimized to a VSWR value of 1.015 or lower.

Main tower run. Normally, in tower-transmission-line runs composed of 20 ft. sections or 12 foot waveguide 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 water. 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—The length of the vertical run—which determines the amount of differential expansion between the copper transmission line and the steel tower and the length and size of the horizontal run—which determines the amount the line can bend without damage—must be taken into account. Transmission line manufacturers usually furnish curves or nomographs which provide this information. If the horizontal run is too short, it may be necessary to anchor the line near the transmitter rather than at the station wall which introduced complications. The length of the horizontal run required is an important item in the overall planning.

The horizontal run should have a protective shield from falling ice where such a condition exists.

RF Filter Networks and Load Location

The diplexer, 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 imbalance. 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.

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 ANTENNA

The types of antennas available can be grouped into the following categories:

(A) LoV, HiV, UHF
(B) Top or side mounted
(C) Horizontal Linear, or Circular Polarization

All of the above parameters affect the basic design concept.

The prime purpose of the tower is to support the antenna that has the required radiation characteristics in order to deliver a satisfactory signal to the viewer. Since it is desired to cover as large a viewing area as possible, tall towers are used. It is not uncommon for antennas to be mounted on 1,000 ft., 1500 ft., or 2000 ft. towers. These tall towers are guyed triangular towers with face dimensions 5, 7, 10 ft. The design and cost of the tower is dependent on the wind load (overturning moment) of the antenna.

The physical dimensions of the antenna are related to the channel (wavelength) and the gain requirements.

	λ	Length for maximum gain	Maximum gain
LoV	16 ft.	100 ft.	6
HiV	5 ft.	90 ft.	18
UHF	2 ft.	120 ft.	60

The ideal omni-directional antenna would be a smaller diameter*, infinitely stiff pole. The smallest cross section that can resonate would have to be $\lambda/2$.

At LoV frequencies the resonant element of 8 ft. is sufficiently large so that a support pole can be used in the center with the antenna mounted outside (batwing). On the other hand at UHF frequencies the resonant length of 1 ft. is so small that the resonant elements must be outside the support pole or the support pole itself must radiate like a slotted coax or waveguide array.

Ideally, omni-directional antennas should be fed from the bottom so there are no feed lines in the aperture of the antenna to distort the pattern. If feed lines are required for the upper elements, they should be on the inside. A conflicting requirement is that the diameter of the feed line be large enough to satisfy the power handling requirements, yet small enough not to create pattern distortion.

Omni-directional antennas are difficult to make directional, whereas directional antenna such as panels are difficult to make omni-directional. Some antennas require a large enough support structure so they can be side mounted. Only one antenna can be top mounted unless candelabras are used. This permits the use of multiple antenna installations. Some circular polarized antennas such as cross or basket dipoles require a large enough support structure so that they can be side mounted directly to the tower.

VHF—Horizontal Polarized

Superturnstile/Batwing

The first antenna developed for commercial service was the Superturnstile.[7] It consists of a central sectionalized steel pole upon which are mounted the individual radiators, or "batwing." 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. Fig. 45 illustrates this construction.

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 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 transmission line which carries the power from the base of the antenna. 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.[8] They can also be obtained for various types of null fill[9] (see under Vertical Patterns) and wind loading. They have also been used in stack and candelabra

*Round shapes have less wind load and present a constant drag coefficient to the wind.

[7] R.W. Masters, The Superturnstile Antenna, *Broadcast News,* January, 1946.

[8] H.H. Westcott, New 50 KW VHF Superturnstiles, *Broadcast News,* May-June, 1953.

[9] Irl T. Newton, Jr., and H.H. Westcott, The New 12BH High Gain Antenna, *Broadcast News,* March-April, 1954.

	HORIZONTAL POLARIZATION		CIRCULAR POLARIZATION	
	MOUNTING			
	TOP	SIDE	TOP	SIDE
VHF-LOW BAND	BATWING	BUTTERFLY DIPOLE PANEL	SPIRAL CROSS DIPOLE	BASKET DIPOLE RING PANEL
VHF-HIGH BAND	HELIX TRAVELING WAVE	DIPOLE PANEL ZIG-ZAG	CROSS DIPOLE	RING PANEL
UHF	COAX SLOT	DIPOLE PANEL	SPIRAL	
	WAVEGUIDE SLOT	ZIG-ZAG	H/V SLOTS	
	LONG SLOT WITH RELECTORS		45° SLOTS	

Fig. 44. Commonly used types of televison transmitting antennas.

installations.[10] 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. This antenna can also be used for two channels. A number of them are operating at Channels 4 and 5 and also in various combinations in the Channel 7-13 range. Copper feed lines

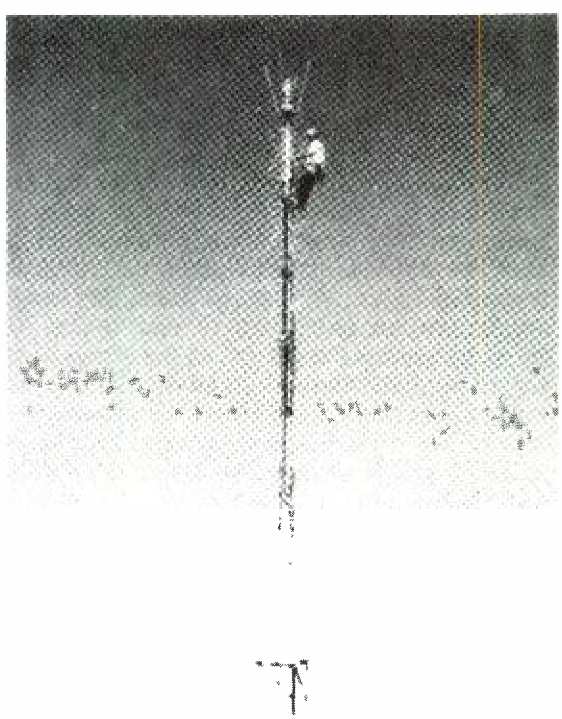


Fig. 45. Six Bay Channel 9 Superturnstile Antenna (Cetec Photograph).

instead of aluminum are available in areas where salt incrustation occurs but where there is insufficient rain to wash it off. Feed lines in both $\frac{3}{4}$-in. and $\frac{7}{8}$-in. sizes are available depending upon the power rating required. Special antennas can be built for higher power ratings.

Delta-Dipole Antenna

The delta-dipole antenna (see Fig. 47) consists of specially shaped, broadband dipoles mounted on reflecting panels. This special shape, which gives the dipole a delta-wing appearance, increases the effective area of the dipole arms, thereby increasing the bandwidth of the dipole without substantially increasing its resistance to wind pressure. Groups of dipoles and panels are arranged as required, both horizontally and vertically, so as to produce the desired horizontal and vertical radiation patterns.

This antenna lends itself to situations where it is necessary to mount an antenna around a tower or to stack several antennas one above the other. Because of its bandwidth, the delta-dipole also lends itself to situations where it is desirable to combine more than one channel in a single antenna. Both omni-directional and directional horizontal radiation patterns may be achieved by the proper choice of power division and element phasing between dipoles in any given layer.

Because the distance between the radiating element of the dipole and the reflecting panel is large (of the order of one-quarter wavelength), ice on

[10] 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.

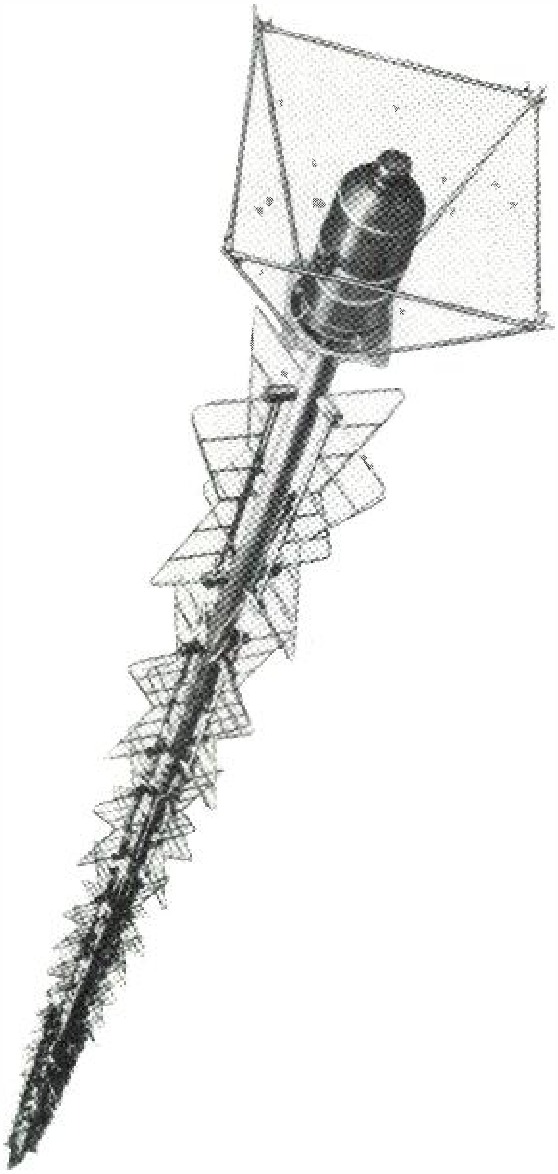


Fig. 46. RCA Superturnstile.

the reflecting panel has no significant effect on the operation of the antenna, and only parts of the dipole itself require deicing.

Traveling-wave Antenna

The traveling-wave antenna* embodies principles found in the operation of the superturnstile, the slot antenna, and the helix employs these principles in a manner which results in its being different from any of them.

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 majority of antennas in service are traveling-wave antennas.

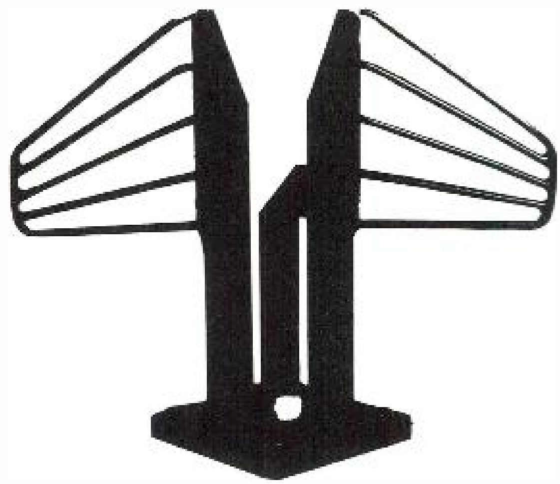


Fig. 47. Delta Dipole Antenna (Alford Photograph).

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.

Fig. 48 shows the physical shape of the antenna. The signal, entering through 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.

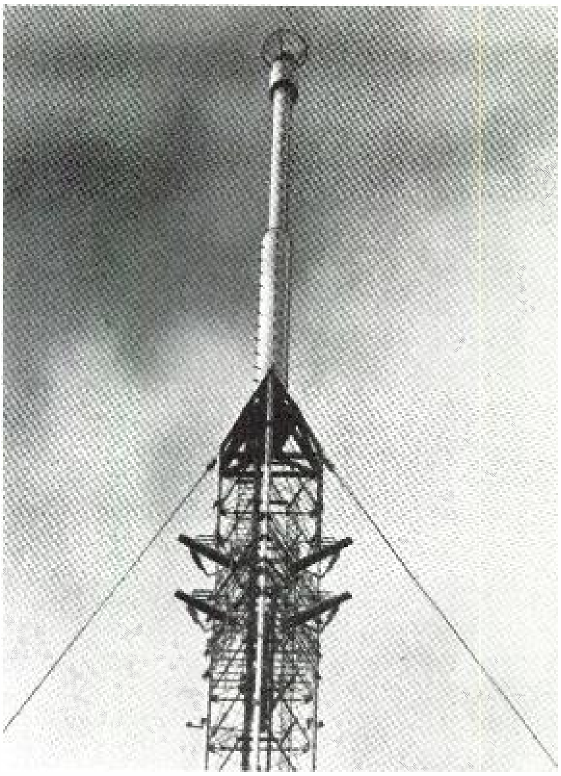
Fig. 49 shows cross sections of the antenna in the three main portions. It will be noted that the entire inner connector is supported by the base plate of the antenna and can be removed through this base.

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. Fig. 50 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. 51.

Each plane of dipoles radiates essentially a figure-eight pattern. Since the planes are fed in



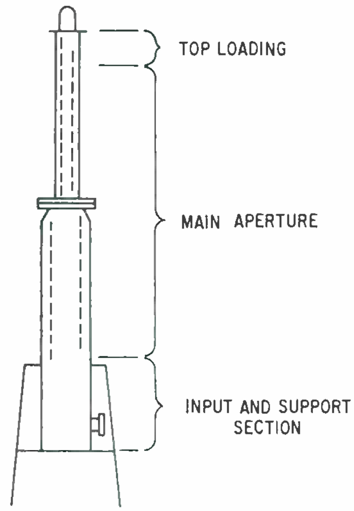


Fig. 48. The traveling-wave antenna-external appearance. (RCA Photograph)

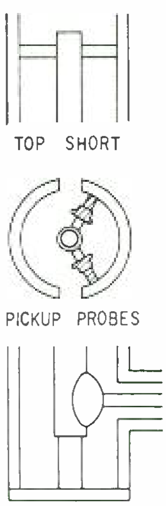


Fig. 49. Cross section of traveling-wave antenna at input, aperture, and top.

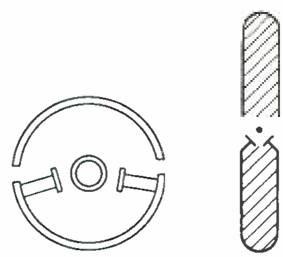


Fig. 50. Cross section of traveling-wave antenna at a slot pair level, showing resemblance to a dipole.

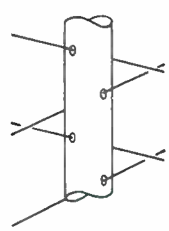


Fig. 51. Stack of half-wave dipoles which traveling-wave antenna resembles in operation.

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

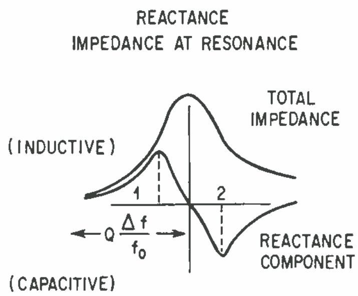


Fig. 52. Universal curve (high-Q parallel-resonant circuit).

spacing becomes 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. 52). The resistive portion is the radiation resistance.

In the region between 1 and 2 (Fig. 52), 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 slot at high frequencies and to lag it at lower frequencies within the frequency range 1 to 2 (Fig. 52).

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 for 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

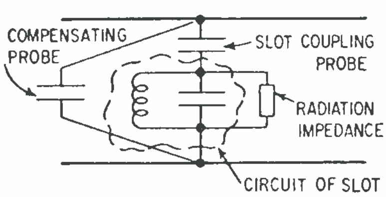


Fig. 53. Equivalent circuit of one slot pair section of traveling-wave antenna.

to bottom, bringing about a downward tilt of the main beam if desired.

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. 53.

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. Fig. 54 shows a typical vertical pattern of a traveling-wave antenna with a gain of 12.

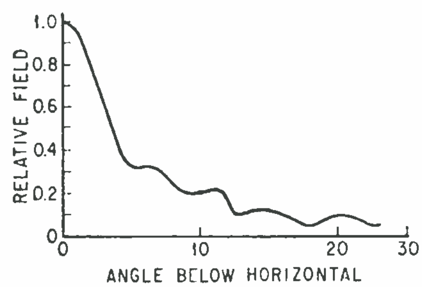


Fig. 54. Vertical field pattern of traveling-wave antenna with gain of 12.

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

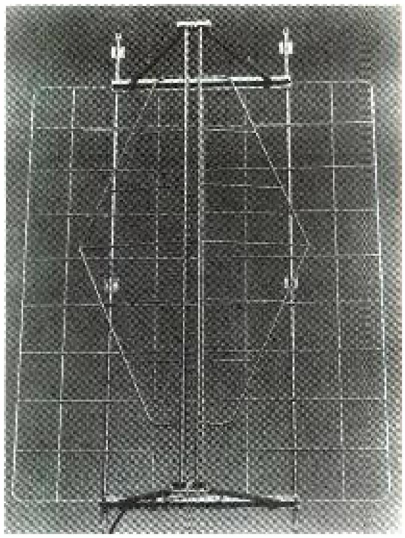


Fig. 55. RCA THP Panel Antenna, single panel.

probes, which are of aluminum treated to resist atmospheric corrosion. The slots are covered with polyethylene covers to keep out rain, snow and ice.

Fig 55. 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.

Rhombic/Butterfly Panels

The rhombic/butterfly panels are broad band dipoles mounted in front of a ground plane.

The individual panel tends to radiate $\cos^2(\theta)$ element pattern in both the azimuth and elevation plane. For omnidirectional pattern a four-sided tower would be required. The panel dimension would be $0.8\lambda \times 0.9\lambda$. For low VHF they are physically large enough to wrap around a relatively large tower.

The elements are mounted $\lambda/4$ in front of the panel and are fed via a balun. The wide band impedance can be further improved by feeding the panels in rotational phase. This will permit multiplexing several channels into one antenna. Directional azimuth pattern can be obtained by changing the power feed to the four panels.

VHF Antenna Circular Polarized

Fan-Vee Antenna

The Fan Vee is a top mounted circular polarized antenna. The antenna consists of horizontal and vertical radiating elements interleaved, spaced one wavelength and fed in phase quadrature. The horizontal polarized element is the standard batwing fed in rotational phase. The vertical polarized element is four back-to-back tilted dipoles in a V configuration. A branching type feed system is used for each radiator and the full array.

CPV Antenna

The CPV antenna is a circular polarized top mounted antenna consisting of three cross vee dipoles mounted at 120° intervals around a vertical mast. The dipoles are segmented by three vertical grids like a corner reflector used both for isolation and to shape the element for good circularity. The cross dipoles are fed in phase quad-

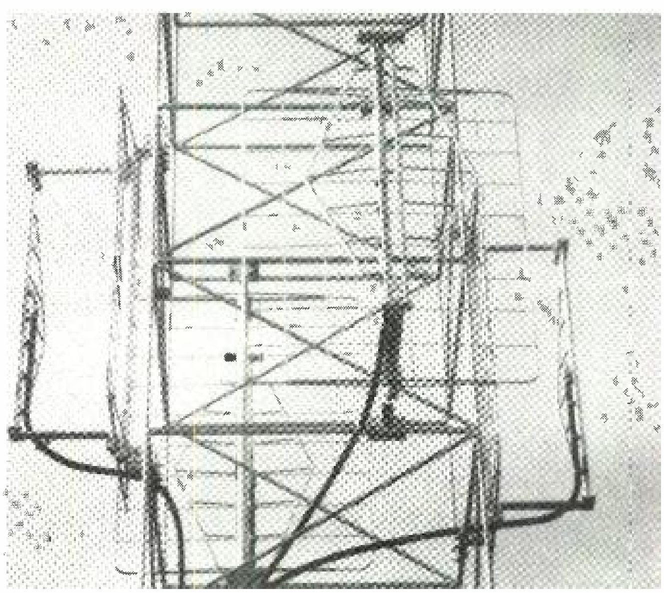


Fig. 56. RCA THP Panel Antenna, single layer on tower.

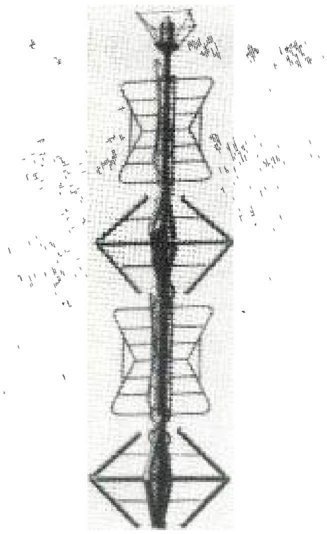


Fig. 57. The RCA Fan Vee top mounted circular polarized antenna.

rature radiate circular polarization from each element.

A branching feed system is used with the lines fed up the mast. Null fill and beam tilt is accomplished by changing the electrical length of the feed cables.

TDM Antenna

The TDM is a top mounted circular polarized antenna. The antenna consists of three slanted

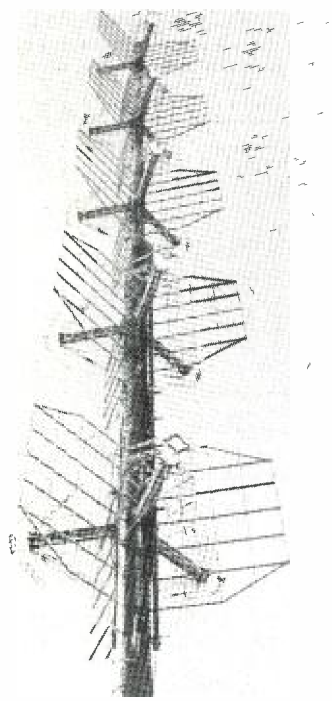


Fig. 58. The Harris CPV antenna with three cross vee dipoles mounted at 120° intervals around a vertical mast.

dipole (45°) mounted on a common phase center (support pole). Short studs are used to compensate for the distortion caused by the support pole. A branching feed system with a single feed point is used. Null fill and beam tilt is accomplished by adjusting the length (phase) of the feed cable.

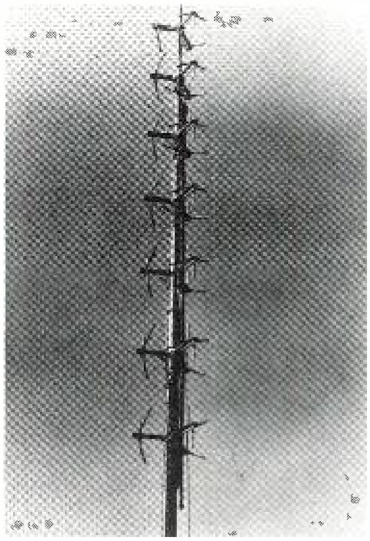


Fig. 59. RCA TDM antenna, top mounted.

Spiral Antenna

The spiral antenna is a top mounted antenna consisting of four spirals (coils) wound around a mast. The coils are fed in such a manner that in any vertical plane the combination of fields from the four coils radiate a circular polarized wave. The multiple coils are essentially a circular current sheet and have excellent omni-directional characteristics. Each section is fed from the bot-

Fig. 60. Three section spiral antenna, top mounted. (Cetec photograph)

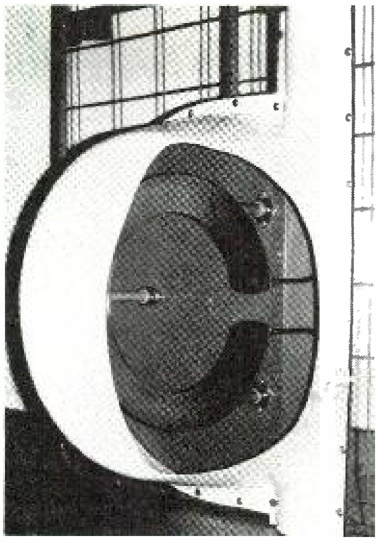


Fig. 61. Cetec ring panel.

tom as a traveling wave non-resonant antenna. Radiating coils are used as end loads at the top of each section to attenuate the remaining energy.

Ring Panel

The ring panel is designed for either top or side mounting tower. Each panel radiates a circular polarized wave. Four panels are wrapped around the tower to produce the desired azimuth radiation pattern. The panel is a traveling wave antenna of several panels with each ring spaced one wavelength.

Cloverleaf Panel

The TCP is a basket type panel radiating a circular polarized wave. It is designed to mount around the tower four panels per day. The radiating elements are fat cross dipoles in a cloverleaf configuration fed in phase quadrature for circular polarization. The panels are fed after power division in a branching line feed system.

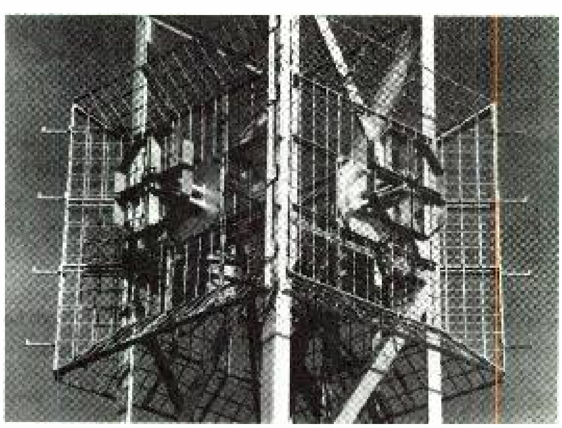


Fig. 62. Cloverleaf panel. (RCA photograph)

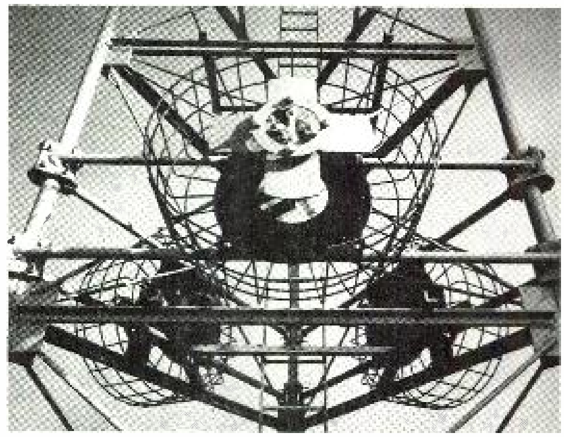


Fig. 63. Harris TPC antenna.

The cavity backed radiator is a similar antenna and is generally built for 3-sided towers.

UHF Antenna Linear Polarized

Pylon-UHF

The UHF Pylon Antenna is a coaxial transmission line with radiating slots in the outer conductor. The number of slots (per layer) around the circumference is determined by the horizontal pattern such as one slot for a skull-shaped pattern, two for a peanut-shaped pattern, three for a "trilobe" pattern and four or more slots, depending on outer cylinder diameter, for an omnidirectional pattern. The layers are located at one-wavelength spacings along the antenna with the number of layers determined by the vertical gain and pattern. The radiation parameters of phase and amplitude are determined basically by a combination of slot length and coupler bar diameter.

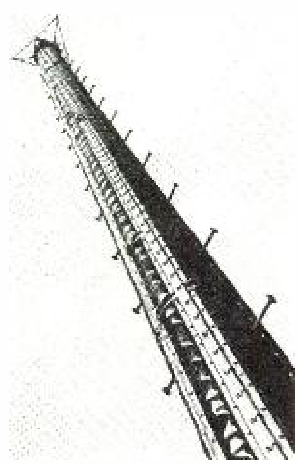


Fig. 64. RCA pylon antenna.

This feature allows discreet control of the illumination along the antenna aperture at every wavelength resulting in vertical pattern control and shaping. It also allows for maximum aperture efficiency and, in conjunction with the extremely low cross-polarized radiation component of a slot, produces the highest vertical gain for a given antenna length.

The antenna is a bottom fed travelling wave resonant antenna. Some antenna launch the energy into the coax line at the bottom. Others feed the coax radiating section at the center. The bottom coax feed is located inside the radiating coax feed.

The pylon uses radome covering the radiating slots only.

The Trasar antenna is similar except it is bottom-fed and is a non-resonant structure with a cylindrical pressurized radome covering the complete antenna.

Wave Star (Omni)

The wave star omni antenna is a bottom fed traveling wave waveguide slot antenna for top mounting. Since it is waveguide, no inner conductor is required. The signal propagates in the TM_{01} mode. The resultant current rings on the inside wall are interrupted by six rows of slots cut in the wall. The slots have radiome covers.

The wave star cardioid designed to radiate a cardioid pattern has a single row of slots. This is also a bottom fed traveling wave waveguide array only operating in the TE_{01} mode. This is built by exciting the fields in a rectangular waveguide and rolling the wave guide into a cylinder.

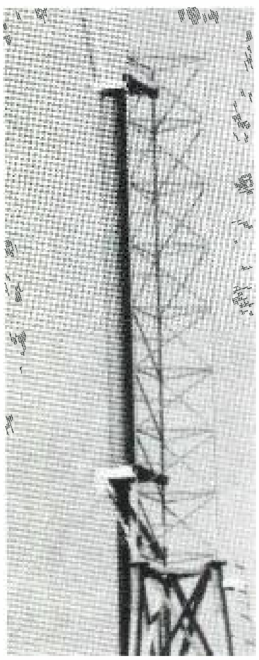


Fig. 65. Andrew Trasar antenna.

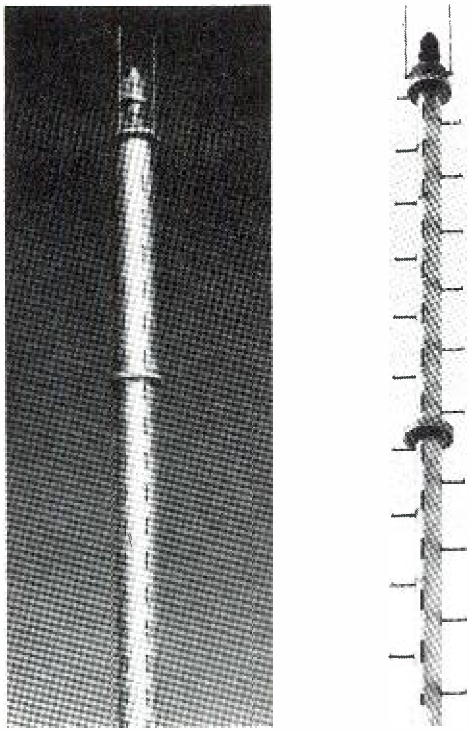


Fig. 66. Harris WaveStar antennas: left is omnidirectional; right is cardioid.

Zig-Zag

The zig-zag is a four-sided, linear polarized panel type antenna. The panels are mounted on a square mast with the complete antenna randome-covered. Each panel is traveling wave structure center fed. The panel length is approximately 8λ so the panels have to be stacked to provide the desired gain. The panels are fed in a branching manner.

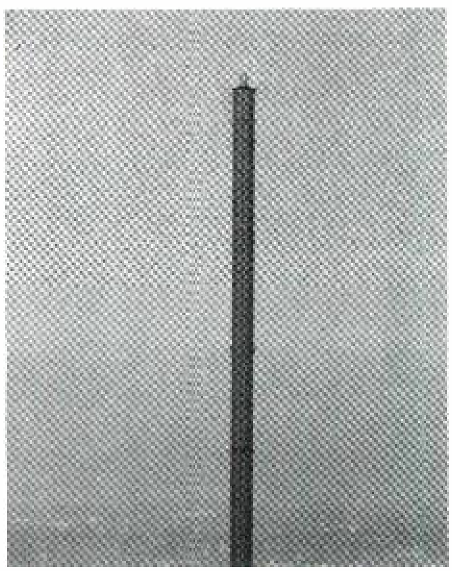


Fig. 67. Zigzag antenna. (Harris photograph)

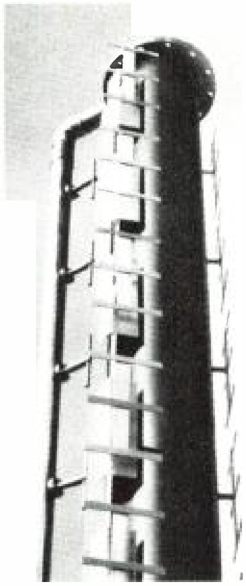


Fig. 68. Bogner slot-director antenna.

Slot-Director Antenna

The slot-director antenna is a linear polarized single row of slots with directors to fill in the low signal on the opposite side of the slots.

The slots are one wavelength long on one wavelength center line. Each is fed directly at the slot from a high power strip line feed. Each section is up to 8λ's and four sections are usually stacked for the desired gain.

Each section is branch fed while the slots in each section are fed in a traveling wave manner.

Pylon Circular Polarized

The traveling wave pylon is bottom fed for top mounting. Circular polarization is obtained by slots slanted left and right at approximately 45°. Successive slots are excited 90° in phase quadrature.

Trasar-Circular Polarized

The circular polarized Trasar antenna uses the same horizontally polarized slots as in the linear

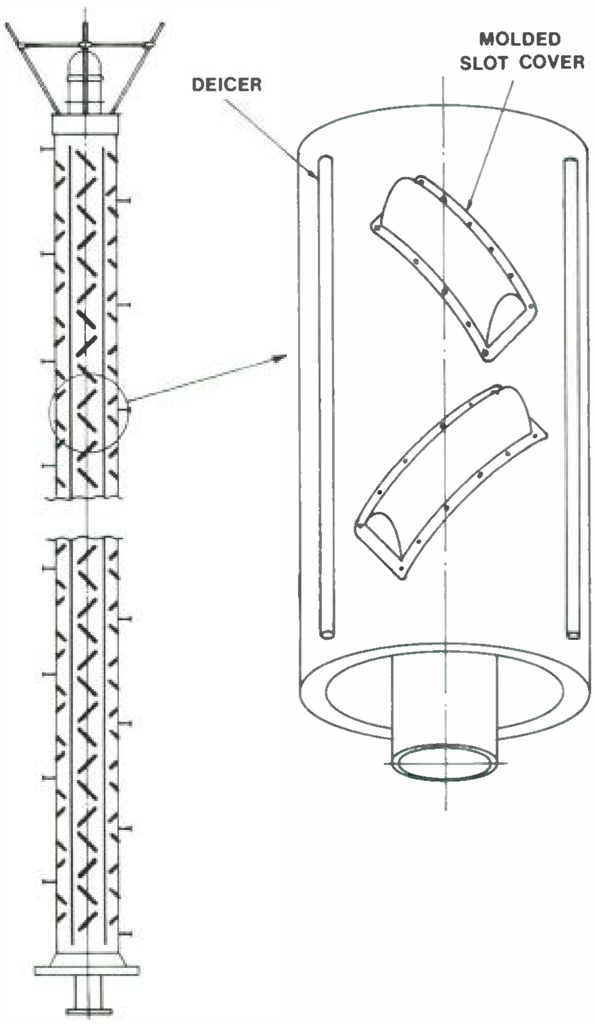


Fig. 69. RCA circular polarized pylon.

polarized antenna. The difference is that the end elements are vertically polarized slots radiating in phase quadrature.

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. As noted above under Antenna Specifications, the impedance is adjusted by the manufacturer to assure himself that the antenna will meet the 3 percent RF Pulse System Specification. These measurements are made under ideal conditions at the manufacturers plant to be certain that they are not influenced by other objects or the earth. From a Smith Chart Plot a judgment can be made by an experienced engineer to determine the percentage of reflection. It can also be determined by using a computer program as discussed under System Specifications.

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 a wooden turntable which has a speed-controlled motor drive. 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 is placed in the far field which is 2 a^2/λ in feet where "a" is aperture of the antenna in feet and "λ" is the wavelength in feet. Since the antenna is in a horizontal position on the turntable, the transmitting dipole must be placed in a vertical plane. The received signal is amplified and the patterns drawn out on the recorder. To determine gain all of the energy going through an imaginary sphere with the antenna at its center must be accounted for. Usually the area of interest in a pattern lies from about 3° above the horizontal (+3°) to about 11° below the horizontal (−11°). However, for gain determination, all energy from +90° to −90° must be taken into account. Also since some types of antennas have a degree of unwanted vertically polarized energy in addition to the desired horizontally polarized energy, this factor must also be considered. Ohmic losses in the feed system must also be considered in determining the gain.

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 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.

Depending upon the antenna type, it is generally good practice to make some electrical measurements on the ground before erection. The primary purpose is to determine if anything has happened to the antenna during the shipping and reassembly process. Hence, it is basically a qualitative test rather than a quantitative one since the ideal conditions at the vendors site may not be duplicated.

The test normally used is an impedance, or VSWR, measurement made every megacycle over the television channel. Closer measurements are not necessary since for a broad-band antenna the impedance varies quite slowly with frequency.

The practice would vary with VHF antennas and UHF antennas. It is usually necessary to be above the ground by about three wavelengths to obtain meaningful measurements. Hence at UHF, a height of 6 ft. is readily achievable. Often the antenna can be tested on the shipping trestles if they are close to this height and made of wood.

For VHF, the heights required above ground are about 15 feet from Channels 7-13, and 35 ft or so for Channels 2-6. It is manifestly impractical to provide trestles of this height for field tests. Since these antennas often have branching type feed systems, other means can be used. In the case of a Superturnstile Antenna, the E-W system and the N-S system can be separately measured for impedance at a low height by placing the plane of the radiators under measurement in a vertical plane so that the maximum field is parallel to the ground rather than into it. Since the radiators are still quite close to the ground, ideal measuremnets cannot be obtained and a judgement factor is required. Final touch-up of the impedance after erection can usually be made by using a variable transformer.

It should be noted, however, that the further the variable transformer is from the point in the antenna where the best match across the band exists, the more difficult it is to lower the reflected pulse value. This point is at or near the radiators for a Superturnstile antenna or after the last transformer when broadbanding techniques are used.

The action of the variable transformer is to insert a negative bump to counteract the positive bump due to the remaining mismatch at the antenna. If the negative bump is displaced in time, by too long an intervening transmission line, it can only partially reduce the positive bump. If it is displaced more than a 100 ft. or about 0.1 microsecond it serves no purpose and only introduces a second unwanted bump.

The use of a variable transformer could in the case of a factory assembled antenna eliminate the ground test if a good mechanical inspection is made. For antennas of the Traveling Wave type for Channels 7-13, the construction is extremely rugged and a mechanical inspection only is required. This antenna has a built-in variable transformer.

When impedance measurements are made on antennas at the customer's site, there may be site factors involved such as fences, building materials, towers and other objects in the field. If the readings are of the same order, or if the Smith chart plot is about the same but displaced, the antenna can be considered to be in good condition. To make any corrections in such a situation could correct the antenna for the site conditions which would not be present at the tower top and hence worsen the impedance. As noted above the check is qualitative to discover possible damage during shipment and not a quantitative compliance test.

The remarks above are also applicable to panel type antennas. Where possible, it is always desirable to ship antennas in one piece even though special permits and shipping arrangements are necessary.

After Erection

Overall Test

See antenna specification considerations under "System Specification Performance after Erection."

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 should 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 sometimes 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 right 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 flange mounting triangularly shaped stainless steel shims should be used fitted between the mounting bolts. Vertical alignment is best checked with transits from several directions. Allowance must be made for wind deflection and sun benching. 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.

*A pressure-tight system is defined as less than a 20% change in 24 hours.

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 standingwave ratio.

The appearance of an echo is a symptom of some change in the system which sould be investigated. New pulse techniques will make the location of faults much simpler.

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.

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.

As a general guideline, no work should be performed on an antenna while power is on. In the case of a multiple antenna system where antennas are at the same level, the power should be off for all antennas on the platform.

RF fields from UHF antennas are particularly dangerous for two reasons: due to the shorter wavelength, local heating in the body is more likely to occur without an awareness that it is happening and could have serious results. Also, since a maximum power of five megawatts can be radiated, UHF stations are now approaching this value which is 16 times as high as for the Channel 7-13 range, and 50 times as high as for the Channel 2-6 range.

2.7

The Measurement of FM and TV Field Strengths (54 MHz-806 MHz)

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MEASUREMENT OBJECTIVES

Television and FM broadcast field strengths may be measured to accomplish several objectives. These include: (1) Determination of measured coverage contours instead of relying only on predictions of coverage; (2) Evaluation of the performance of transmitting systems; (3) Measurement of spurious emission; (4) Special studies including propagation studies to evaluate the effect of factors such as terrain and vegetation on field strength. Special studies that require field strength measurements are also used for purposes such as interference and allocations.

Before the start of measurements, a plan should be designed considering the objectives of the field strength survey. For example, the constraints imposed by a survey to determine coverage of a station are different and generally less restrictive than those imposed by propagation studies. Design of a program to evaluate the performance of transmitting systems is likely to be the most difficult and require even more careful planning than programs for other purposes. Suggestions for designing measurement programs for each of the above objectives are presented in the following sections, as well as a discussion of the techniques of actual field strength measurement.

NOTE: Superscript numbers refer to Footnotes and References at end of the chapter.

There are several basic considerations, affecting all types of measurement programs, that should be addressed. These include the choice of antenna height for the measurements and allowance for factors such as weather that are beyond the control of the engineer.

The FCC Rules require measurements using a 9 meter (30 foot) receiving antenna height. This height should be used unless there are very good reasons for using another height. The bulk of reliable data were taken at 30 feet and the broadcast coverage contours are based upon the 9 meter (30 foot) height. Thus, a 9 meter (30 foot) receiving antenna height must be used for filing with the FCC, for direct coverage measurement or for direct comparison with other data. Use of a 9 meter (30 foot) high antenna raises several practical problems including safety. These are discussed in a later section.

Field strength varies with time and location. The variations are caused by factors such as terrain, man made structures, vegetation and weather. The effect of each of these on the measurements should be considered when designing the program. Except for the unusual case of measurements designed to evaluate time variation factors, the effect of weather or climate on measurements should be minimized. Variations of field strength with time are generally greatest near or just beyond the radio horizon. A more detailed discussion of this problem is included in a later section.

Measurement of Coverage

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 section describes measurement programs for measuring field strengths to determine coverage of FM and television broadcasting stations.

The quality of service is related to 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. Table I lists the frequencies employed by television and FM broadcast stations. Interfering signals from other transmitters on the same or adjacent channels may limit service to higher values of field strength.

TABLE I

Frequencies Employed for FM and Television Broadcasting

Service	Frequencies, MHz	Channel Nos.	Channel Bandwidth
TV	54-72	2-4	6 MHz
TV	76-88	5-6	6 MHz
FM	87.9-108	200-300	200 kHz
TV	174-216	7-13	6 MHz
TV	470-806	14-69	6 MHz

TABLE II

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[a]
Principal City	3,160	70
Urban	1,000	60

Television Broadcasting (FCC Technical Standards)

Gr. 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	650	56	1,600	64

(Based on TASO Data)

Gr. of Service	Ch. 2-6		Ch. 7-13		Ch. 14-83	
	μv/m	dBu	μv/m	dBu	μv/m	dBu
Primary	250	48	1,400	63	7,500	75
Secondary	50	34	200	46	630	56
Fringe	20	26	55	35	180	45

[a]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.

Table II 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 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 (Sept. 1, 1984) been officially adopted by the Commission. A number of changes in the definition of television coverage grades based upon the TASO studies and other data have been proposed from time to time since the adoption of the present definitions. None of these proposed changes have been adopted. A review of the rationale for the VHF contour definitions and some potential revisions is presented in the FCC Report FCC/OCE RS 77-01.[3]

Service is defined in Table II in terms of the median field with respect to both location and time, at a receiving antenna at a height of 9 meter (30 feet) above ground. Thus, field strength measurements to be filed with the FCC must be taken using a 9 meter (30 foot) receiving antenna height. In these frequency bands, field strength 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.

It may not be necessary or even desirable to employ a 9 meter (30 foot) antenna height for measurements that will not be filed with the FCC. For example, if comparative coverage of several stations is desired and receiving antenna heights in the area are less than 30 feet, it may be appropriate to use a lower height. Measurements taken at a lower height may be, if necessary, adjusted to reflect the standard 9 meter (30 foot) height. Because of the uncertainty of the magnitude of the adjustment, the adjusted results are ordinarily less precise than measurements taken at 9 meters (30 feet). Adjustment factors are discussed in subsequent sections.

The presence of trees, buildings, and terrain irregularities[4-9] often results in considerable variation in field strength from one location to another, even within relatively small areas. The variation in field strength with location must be taken into account in measuring field strength as well as in specifying service. Service is usually defined in

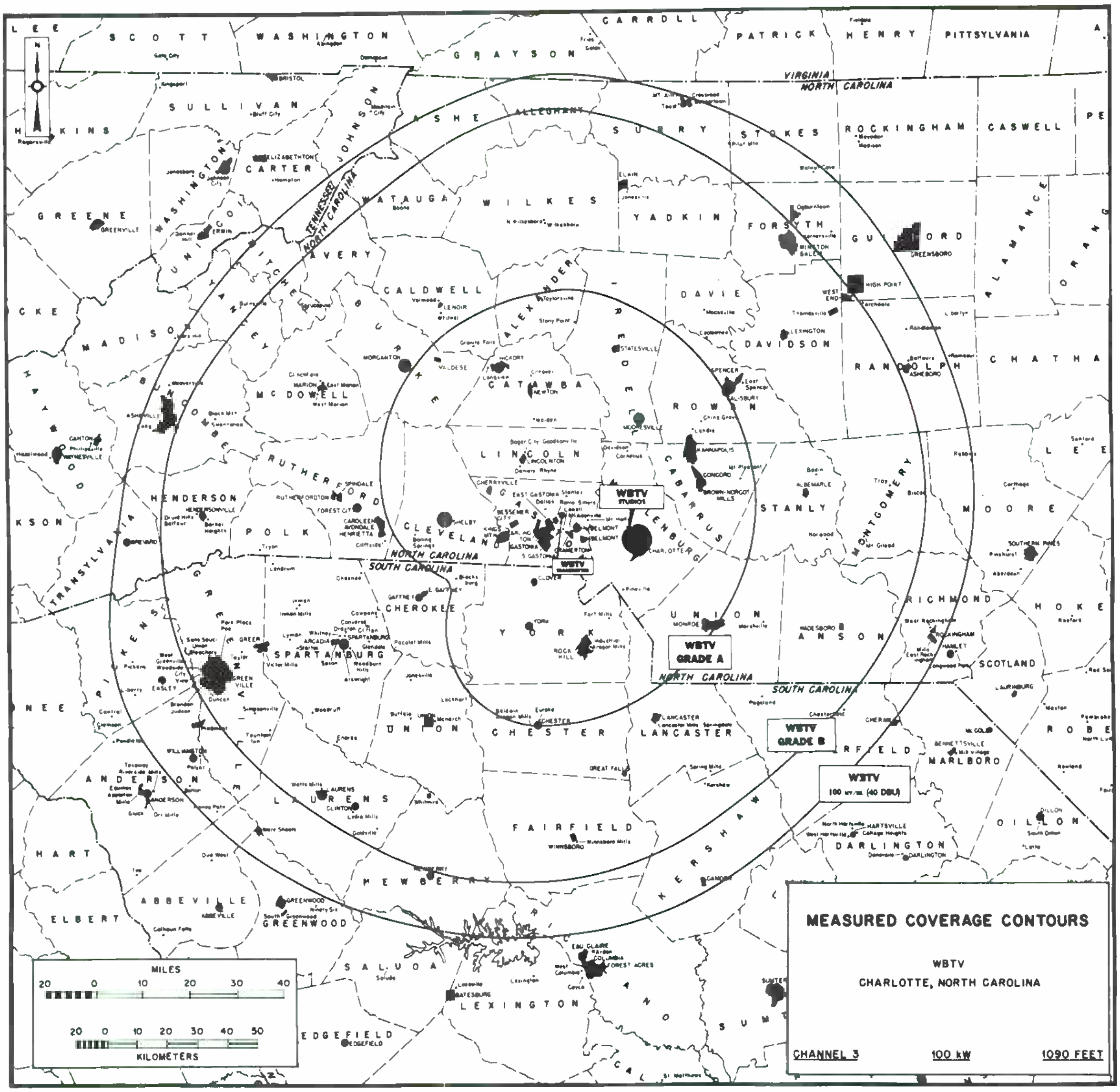

Fig. 1. Map showing measured service contours for an operating television station. (Courtesy of Jefferson-Pilot Broadcasting Company)

terms of the median value of field strength, which is the value exceeded for at least 50 percent of the time at the best 50 percent 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. 1. Methods of preparing contour maps are described in detail under the heading "Analysis of Measurements to Depict Coverage".

Much of the present knowledge of wave propagation in these frequency bands has been derived from field-strength-coverage surveys on operational 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 special techniques are often needed to supply data for special problems. Examples of such special techniques are discussed under other headings in this article.

The measurement program to determine coverage may be laid out according to the radial route method of the FCC Rules as described for propagation studies. Unless the results will be filed with the FCC, there is no need to maintain the precision required by the FCC. The precision required by the FCC Rules is primarily intended to insure statistical randomness for propagation studies and to assure that the propagation path is a true radial. For "in house" coverage studies there is generally no need for the measurement location to be "exactly" on a true radial route at random 2 mile increments as required by the FCC Rules. Since many FM and TV transmitting sites are located near the center of cities it is often convenient to take measurements along more or less radial roads. Selection of measurement location need not be random but may be influenced by population density or the desire to obtain data in particular areas.

Sections 73.314(c) and 73.686(c) of the FCC Rules describe the procedures for the measurement of service to specific communities for FM and TV stations, respectively. These rules outline a measurement pattern that is in the form of a rectangular geographic grid overlying a map of the community. The grid must encompass the boundaries of the community. Measurements are made at the intersecting points on the grid.

The number of measurement points must be at least 15 or 0.1 $\sqrt{P}$ (whichever is greater) where P is the population of the community in thousands. Additional requirements describing documentation and calibration are contained in the rules.

The rules also contain a statistical procedure to analyze field strength. This method fits the measurement data to a normal distribution and yields the median or average field strength in a community. This result is not completely compatible with other FCC Rules. The principal city coverage rule for example, is based upon the determination of the location of coverage contours. This difficulty can be eliminated by using a grid that is not truly rectangular but consists of radials and perpendicular arcs. This plan permits both radial and grid analysis. Since the resulting grid is not perfectly rectangular, use of this plan should be cleared with appropriate FCC personnel before undertaking measurements when the results will be filed with the Commission.

Transmitting System Evaluation

Field strength measurements are occasionaly used to assess the performance of a station's transmitting system, particularly the operation of the transmitting antenna. The difficulty in this case is that of separating the effect of propagation factors from the effect of the transmission system. Comparisons of measured data with standard propagation curves such as the FCC Rules curves or smooth earth curves must be used with caution. The standard deviation of measured data used to draw the FCC curves compared with the curves is 7.7 dB at low VHF, 6.8 dB at high VHF, and 9.3 dB at UHF after adjustment for terrain[10]. Even in smooth terrain field strength is affected by other factors such as trees, buildings and atmospheric variations.

In hilly terrain, the effect of clutter, terrain and atmospheric variations can be minimized by selecting sites near the transmitting antenna to minimize atmospheric effects and where ray path clearance over all obstacles obtains. This clearance should be at least 0.6 Fresnel zone. The radius of a full Fresnel zone is given by:

$$H_O = 2280 \sqrt{\frac{d_1 \, d_2}{f(d_1 + d_2)}} \qquad [1]$$

Where: H_O = Fresnel zone radius in feet
d_1 = distance from transmitting antenna to obstacle in miles
d_2 = distance from receiving antenna to obstacle in miles
f = transmitting frequency in MHz

Application of this criterion is illustrated by Fig. 2.

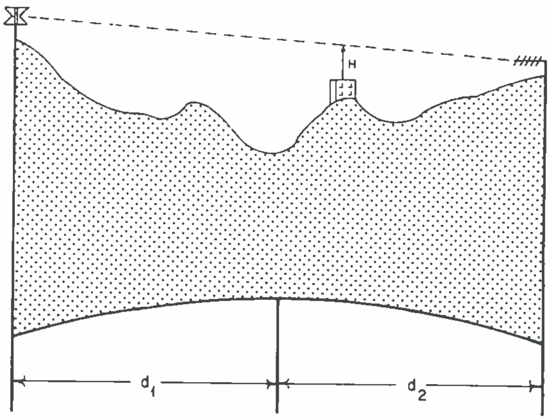

Fig. 2. Illustration of required ray clearance to avoid obstacle loss.

Even if such ray clearance over all obstacles can be obtained, reflections from terrain may often modify field strength. Allowance for reflections can only be achieved by taking measurements at a large number of locations to "average out" reflection effects.

Field strength measurements intended to evaluate system performance are sometimes taken in a helicopter in an attempt to reduce terrain effects. However, there are several problems associated with helicopter measurements, including: 1) Determination of the actual location of the helicopter relative to the transmitting system under test, 2) constraints on the design imposed by the helicopter's performance, 3) mounting of the receiving antenna on the helicopter to minimize the effect of the helicopter on receiving antenna pattern without creating a hazard, 4) uncertainties, such as actual path loss, that limit the accuracy of the measurement of absolute gain of the transmitting system under test.

PROPAGATION AND OTHER SPECIAL STUDIES

Sections 73.314 and 73.686 of the FCC Rules of the FCC describes the procedures to be employed for field strength measurements for propagation studies. This procedure is basically the technique developed by TASO. The actual field strength measurement procedure is discussed later in this article. The FCC procedure is intended primarily to yield data that may be analyzed to study the effect of terrain and other local influences on field strength. Measurement programs intended for other purposes may require substantially different plans. For example, measurements primarily intended to determine the effects of "clutter" such as trees and buildings should be taken if possible, in smooth terrain to eliminate the effect of terrain.

Measured field strength for propagation studies may be compared to calculated field strength for a number of propagation models.[10-13].

Measurement programs have been conducted to evaluate field strength time variation factors. In this case field strength measurements are recorded at fixed locations and over a period of time.

Field strength measurements may be an integral part of special field tests particularly with regard to interference allocations and changes in FM or TV operation. Examples of such field tests include those on VHF/TV Land Mobile channel sharing, tests relating to the problem of educational FM interference to Channel 6 and on circular polarization for television. Detailed discussion of special projects is beyond the scope of this article; however, the basic techniques of field strength measurement discussed herein are valid for special programs. In addition, many of the topics discussed in planning coverage, transmission equipment evaluation and pure propagation tests are appropriate for use in special tests.

Measurement of Spurious Emission

It is occasionally necessary to measure spurious radiated field strength from FM and TV broadcast facilities to show compliance with FCC cabinet radiation rules after installation. Requirements of the level of spurious signals relative to carrier level is specified in Sections 73.317 and 73.687 of the FCC Rules for FM and TV transmitting systems respectively. Such field strength measurements are nominally regulated by Section 2.993 of the Commission's Rules.

This section is quite vague and it is recommended that the person intending to take measurements determine acceptable procedures from FCC Laboratory personnel before undertaking the measurements.

BASIC EQUIPMENT PRINCIPLES

Field strengths in the VHF and UHF bands (30 to 3,000 MHz) 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

$$\frac{P_r}{P_t} = \frac{1.64\lambda^2}{4\pi d} \qquad [2]$$

Where: P_r = receiver 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

$$P_r = (0.0186E\lambda)^2 \text{ watts} \qquad [3a]$$

where λ is expressed in meters.

Or alternately in dB relative to one Watt (dBW)

$$P_r = F - 20\log f - 105.1 \qquad [3b]$$

where f is the frequency in MHz and the field strength F is in dBu.

For a resistive load of R ohms, the voltage V developed across a matched load by a dipole in a field E is

$$V = \frac{E\lambda\sqrt{R}}{53.7} \qquad [4]$$

The fundamental problem presented, therefore, is that of measuring the developed RF voltage by a practical instrument of acceptable accuracy.

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.

The following paragraphs describe the basic components used for field strength measurement using the standard FCC methods. The system described is the conventional system using chart recorders and manual analysis of recorded data. Digital sampling, recording and analysis techniques may be used to replace, at least in part, manual techniques. At this time an engineer conducting field strength measurements is most likely to use conventional equipment. Therefore, the

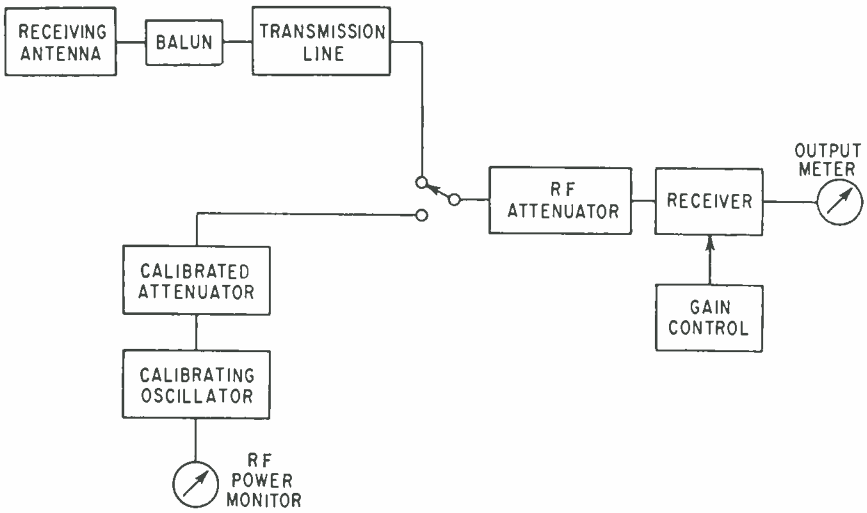

Fig. 3. Block diagram of practical field-strength meter.

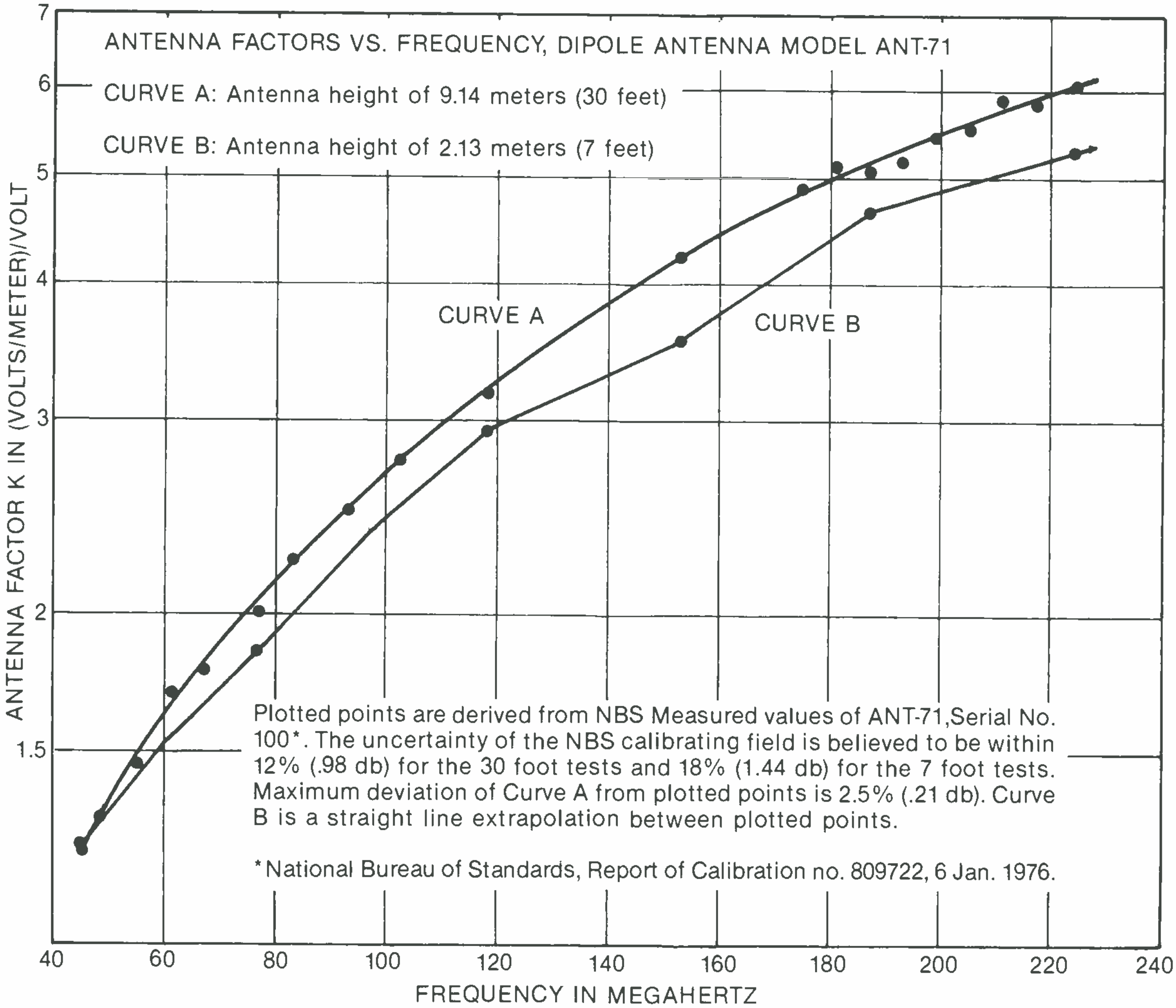

Fig. 4. Graph of K for a Typical VHF field strength meter.
(Courtesy of Potomac Instruments, Inc.)

following paragraphs will only discuss conventional equipment. However, the principles of the measurement procedure also apply to digital equipment and a discussion of conventional equipment will illustrate these principles more clearly.

Practical Field Strength Meters

Field strength meters are calibrated receivers that fall into three basic categories: (1) Receivers that contain a precision oscillator and attenuator and use direct comparison between meter readings produced by the received power and the output of the oscillator. (2) Receivers that use a precision oscillator to adjust receiver gain to produce a direct reading meter. (3) Receivers that are direct reading but do not contain a calibrating oscillator. Field strength meters of Type 3 are not considered suitable for precision field strength measurements.

Fig. 3 is a block diagram of a practical Type 1 field-strength meter. Type 2 meters are more often used presently; however, the purpose of the following discussion is to illustrate measurement principles. The Type 1 meter is more suitable for this purpose. 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. 4 above, the field at the antenna required 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. Fig. 4 is a typical graph showing values of K for a VHF field-strength meter.

A typical commercial field-strength meter of professional quality is shown in Fig. 5. The instrument shown is a Potomac Instruments type FIM-71 covering the VHF, FM and television band from 54 to 216 MHz. A companion instrument, similar in appearance, covers the UHF television band from 470 to 806 MHz.

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. 5). The calibration of the oscillator and the overall 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 both UHF and VHF[14-15] and are sometimes used in primary calibration of field strength meters. Most commercial laboratory calibrations, 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. 4.

The calibration of the internal reference oscillator section includes the calibration of both the

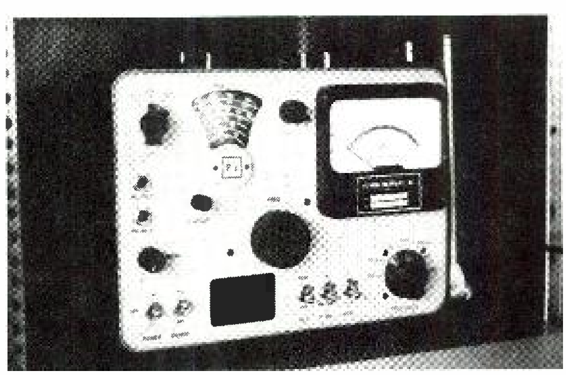

Fig. 5. A VHF meter of professional quality.

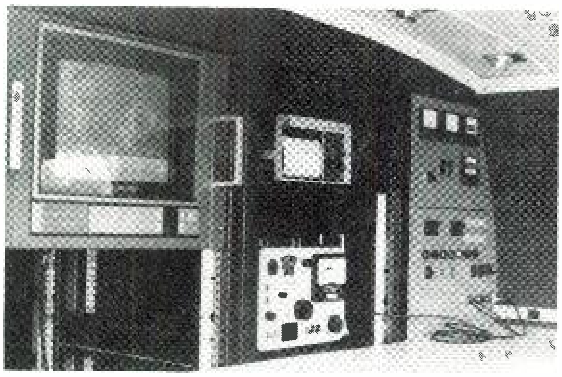

Fig. 6. Equipment set up for field strength measurement.

oscillator proper and the variable-output attenuator, if employed. The attenuator is usually of the inductively coupled piston type,[16] 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.[17] This calibration is normally but not necessarily performed 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 professional commercial field-strength meters such as the one illustrated in Fig. 5.

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. Fig. 6 shows the field strength meter, chart recorder and some additional equipment for a survey. The size and weight of the equipment usually dictate that it be mounted in an automobile or light truck. As discussed in Appendix A, all of this equipment including the field strength meter should be grounded to the vehicle frame. Fig. 7 shows a van with elevated mast supporting a UHF antenna and containing the mounted equipment of Fig. 6.

In addition to taking field strength measurements, it is often desired to use other equipment such as the television monitor shown in Fig. 6. A vehicle devoted to general field test programs should have sufficient space available for special equipment including monitors, waveform scopes and magnetic recorders.

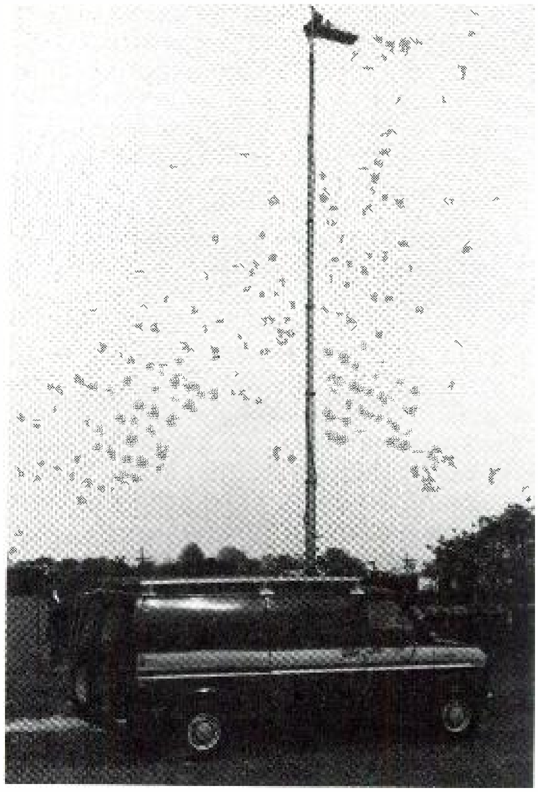

Fig. 7. Van equipped for making field strength measurements with 30 foot antenna height.

Receiving Antennas

Horizontally polarized receiving antennas are normally used for field strength measurements. At the present time, the FCC Rules require that FM and TV stations operate with horizontal only, or dual, circular polarization. If measurements on the vertically polarized components of a dual polarized field are desired, precautions must be taken to reduce the effect of coupling between the vertically polarized antenna and the supporting mast and vertical run of transmission line. If the standard antenna furnished with the field strength meter is used for measurement or calibration of another antenna, the standard antenna should be mounted at least one wavelength from all metallic vertical components. This requirement presents a mechanical problem at the lower VHF frequencies.

The measurement survey can be made by employing the standard dipole antenna furnished with the field-strength meter, or other antennas can be utilized. It is often desirable to use an antenna other than the standard antenna for actual measurements. Standard antennas are usually not mechanically sturdy. If measurements are to be taken at a large number of locations, especially with extensive driving between locations, it is desirable to use a rugged or readilly replaceable antenna and thus minimize the probability of damaging the standard antenna.

An antenna which is essentially omnidirectional in the horizontal plane does not require orientation as the vehicle is moved; however, it is generally desirable to use a receiving antenna with directivity. Directional receiving antennas possess gain which is useful principally for UHF measurements, and their directivity is useful to eliminate unwanted signals from sources other than the transmitter being measured.

The antenna employed for the measurements must be calibrated on the measurement vehicle because of ground and vehicle proximity effects.[18] The difference in the calibration curves of Fig. 4 is caused by ground proximity effects and by differences in transmission line losses. The received field is first measured using the standard dipole antenna mounted on the vehicle at the measurement height. 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. The antenna pattern is best established by rotating the vehicle with the antenna mounted as for measurements, and recording field strength and measuring antenna gain as above. If the vehicle cannot be rotated an alternate, comparable procedure must be followed.

The gain of a directional 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. In either case a location essentially free of standing waves should be used. 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 measurement system cables and baluns.

Antenna Supporting Mast

The receiving antenna is ordinarily supported at a height of 3 to 9 meters (10 to 30 feet) above ground, depending on the measuring technique employed. For the short heights, a simple mast of metal tubing can be used. For the standard 9 meter (30-foot) 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. 7 employs a telescoping mast constructed of aluminum tubing elevated by compressed air or nitrogen; 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.

Operation with an elevated antenna involves a number of safety hazards including the avoidance of overhead obstructions and potential traffic hazards posed by the measurement vehicle. Power lines are the principal overhead obstruction of concern. The avoidance of these hazards, equipment grounding and operation after encountering a hazard are discussed in Appendix A. These safety procedures were taken from the TASO Report[2] with minor modifications that update the procedures and descriptions.

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 clock drive motor. Excitation of the recorder is provided by a dc amplifier, which usually is 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 dc recorder 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-v. ac alternator may be mounted in the vehicle. The latter is employed to operate the ancillary equipment shown in Fig. 6.

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 or similar methods are also usually employed in making other surveys such as for the measurements on station coverage. Variations from the official procedure are frequently taken; some of these variations are discussed under earlier headings. The following paragraphs summarize the present requirements of the Commission's Standards.

FCC Standard Method For the Collection of Propagation Data

The following discussion summarizes the FCC procedure in making field strength measurements for propagation studies. The forms for recording and submission of data and other technical requirements are presented in Section 73.314(b) and 73.686(b) of the Rules for FM and TV respectively.

The Commission's Technical Standards require field strength measurement surveys to be made with mobile equipment along at least eight radial lines from the transmitter. The radials need not be laid out along bearings separated by 45°, beginning with true North as is standard for contour prediction. Measurements are required to be taken from 16 kilometers (10 miles) in increments of 3 kilometers (2.0 miles) in each direction. If it is desired to establish contour location, the distance should extend somewhat beyond the field strength contour which it is desired to establish. The routes are selected to encounter representative terrain and to permit reasonable interpolation between adjoining radials. 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 3-kilometer (2-mile) intervals, beginning at exactly 16 kilometers (10 miles) from the transmitting antenna. The actual measurements are made precisely on the radial, at locations as close as possible to the exact 3-kilometer (2-mile) marks established as described. The ground elevation of the actual measurement location should be the same as that of the intended location.

The individual measurements consist of short mobile runs (at least 30 meters (100 feet) along the road) at each location so chosen, with the receiving antenna at the 9 meter (30 foot) height. If measurements are made on multiple stations for comparison purposes, it is desirable to mark the beginning or end points for each run to insure that the run is made over identical paths on each channel. Before making the measurement run, the gain of the field strength meter is adjusted to the meter reading and chart recorder indicating the initial calibration.

The chart recorder is used to record the field strength meter output, and the median, minimum, and maximum values of the field for each recording are determined from the chart recording. Precise determination of the median is usually made after completion of the survey; however, it is useful to use the meter's calibrating oscillator to make a trace of an estimated median value on the chart paper after each run. The median of the run is estimated and the output of a precision attenuator may be adjusted to the estimated median. This provides an additional calibration check and permits a rapid preliminary calculation of field strength that is often useful to monitor the progress of a survey.

Fig. 8 shows a sample of a typical chart recording obtained by this method. With field strength meters such as the one shown on Fig. 5 there is no built-in adjustable attenuator; however, there is an oscillator output which may be fed through an external attenuator to the input to achieve this calibration.

The chart median values are then converted to received field strength by combining the individual calibrations of the antenna, transmission line, field strength meter, dc amplifier, and chart recorder as discussed above.

Analysis of Measurements to Depict Coverage

If a measurement height of other than 9 meters (30 feet) was used, the received fields must be adjusted to the field expected at a receiving antenna height of 9 meter (30 feet) above ground if it is desired to obtain the location of standard contours. An antenna height of approximately 10 feet is often used when the results will not be filed

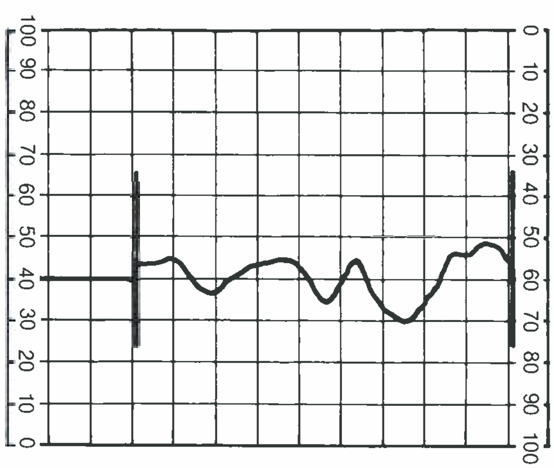

Fig. 8. Sample of field strength chart recording of a short mobile run showing traces marking beginning, ending and calibration.

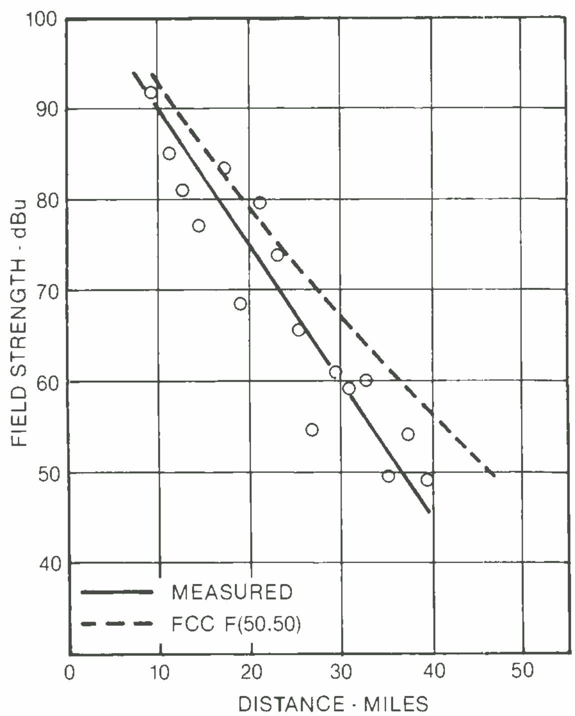

Fig. 9. Graph of measured field strength versus distance for a typical radial series of measurements. The results of each mobile run are shown. The solid line is best fit curve through the points. The dashed line is the predicted field strength from the FCC curves.

with the FCC. It has been common practice to assume the field strengths to increase linearly with antenna height, as indicated by classical plane earth propagation theory. For this assumption the relationship between the field, E30, which would be expected at 30 feet and the field EH, which would be expected at 30 feet and the field EH, measured at a receiving antenna height Hr is E30/EH = 30/Hr. For example, the ratio of the field at 30 feet to the field at 10 feet is 30/10 = 3.0, or 9.5 db.

The application of the linear height-gain function discussed above is recommended only in relatively flat terrain. In rolling or rough terrain the following height-gain factors (in decibels) were recommended by TASO to convert from 3 meter (10-foot) to 9 meter (30-foot) fields. The values were preliminary and are not based upon measurement programs designed for this purpose.

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

The median fields as established in accordance with a radial or modified radial procedure described above are plotted as a function of distance from the transmitter, and a smooth curve is drawn through the plotted points. Fig. 9 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. 9 is the predicted field strength calculated using the propagation curves and prediction methods specified in the FCC Television Broadcast Technical Standards.[19]

Individual graphs of median field strength versus distance as shown in Fig. 9 are prepared for each of the directions along which the measurements were made; the distances to the desired field strength contours, selected from Table II, 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. 1.

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 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 9 meter (30-foot) 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 9 meter (30-foot) mast presents safety hazards which require the exercise of utmost caution in the use of an elevated mast. In addition to proper grounding discussed earlier, the TASO field-strength measuring specification includes a special appendix (included here as Appendix A) dealing with overall safety requirements. When measurements are made with an elevated antenna, the need for caution must be borne in mind at all times.

Time Variation of Field Strength

Fairly substantial variations in field strength with time are frequently noted particularly near and beyond the radio horizon although significant variations occur at other distances. Factors for time variation are included in several references.[10-12] These variations may be relatively rapid, occurring over a period of a few minutes, or slow variations may appear over periods of several hours. There are also long term seasonal variations. 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 strength 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 of the measurement program 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.

APPENDIX A

Safety Precautions Recommended by TASO for Mobile Field Strength Measurements With Antennas Elevated 30 Feet Above Ground.

Some broadcast equipment uses high electrical voltages which are extremely dangerous to personnel that may come in contact with them. We have all been familiar with the locations of many of these high voltages in the past, particularly in radio and TV transmitters and, to a lesser appreciated but equally dangerous extent, video power supplies and some audio and test equipments. Personnel involved with the construction, operation or maintenance of these equipments should be fully aware at all times of the potential danger. One should never take chances with these high voltages. It has been demonstrated through a series of unfortunate accidents that the measuring of field strength at television frequencies can also be extremely dangerous where observations are made at a 30 foot level. The danger here is not with the field strength measuring equipment being used but with hazards of contact with primary electrical power circuits and, to a lesser extent, potential traffic hazards. In view of the dangers associated with the field strength measuring work outlined above, there are certain general precautions everyone should take in addition to the specific precautions included within this memo for safety in operation of the field strength measuring vehicle. These general precautions include the following:

(1) Never take chances.

(2) Do not service or work on equipment when the power is turned on.

(3) Never work on electrical equipment containing high voltages unless there are at least two persons present.

(4) If in doubt keep one hand in a pocket at all times.

(5) Everyone who has occasion to work on such electrical equipment must have a knowledge of the best methods of artificial respiration.

I. EMERGENCY PROCEDURE

If the procedures outlined in this memorandum for the safe operation of field strength measuring vehicles are followed, there should be no need for emergency procedures. In spite of this, it is felt worthwhile to outline some emergency procedures to be followed in the event of some unforeseen accident. Assuming that some accident has arisen involving overhead obstructions, the following precautions should be observed:

(1) The obstruction you are entangled which may carry HIGH VOLTAGE.

(2) The vehicle you are in may be at a high potential with respect to ground, so STOP AND THINK.

(3) Under no circumstances should the transmission line (associated with the field strength measuring gear) be touched. The grounding connections may have broken due to mechanical strain or have burned up due to extremely high currents.

(4) The precautions you have taken in inspecting the vehicle before starting the day's work should prevent any high voltage from entering the vehicle.

2.8

AM Field Strength Measurements and Proof of Performance

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INTRODUCTION

The directional antenna is composed of two or more radiating elements. These elements are arranged in a specific physical configuration and energized with RF energy of known magnitude and phase relations. The electrical and physical arrangement causes the individual fields of each element to interact, adding and cancelling, to produce the desired directional pattern shape. Each directional pattern is customized to provide the optimum service to the desired area while rendering the required suppression in area(s) of protection to other stations' service area(s) in accordance with the FCC Rules.

The phase and current relationships are produced by the RF distribution system. The distribution system transfers the RF energy from the transmitter to the radiating tower. The RF distribution system outside the transmitter building is generally composed of a matching network at the base of each tower enclosed in a weatherproof environment and an RF transmission line extending from the input of each tower-matching network to the transmitter building. Inside the transmitter building, the transmission line is connected to other distribution and matching networks. These distribution and matching networks are usually housed in a metal cabinet. This item is usually designated as the 'phasor'. The ground system is connected securely (electrically and mechanically) to the phasor cabinet and its components and the tower matching networks. The phasor typically will incorporate a matching input network between the distribution circuits and the transmitter in order to present the transmitter with a suitable load impedance. This network will help provide the optimum RF energy transfer from the transmitter and allow adjustment of the common point impedance. It is at the common point that the power of the directional array is determined. For more information on the design and contruction of AM antenna systems, see Chapter 2.4, "AM Broadcast Antenna Systems." As described in Section 73.51 of the FCC Rules, directional arrays having a nominal power of 5 kW or less shall exceed the nominal power by 8%. This additional factor for power is an allowance for system losses. Nominal powers greater than 5 kW are permitted a system loss factor of 5.3%. This factor, multiplied by the nominal power, provides the value used in the determination of the license common point current.

The directional antenna parameters are monitored by a system composed of an antenna monitor, sampling line(s) and sampling devices. The antenna monitor requires FCC-type approval. Sample lines are used to transmit the energy from the sampling device to the antenna monitor. In planning and building a sampling system, care must be exercised in the selection of the sampling element and its placement and in the selection of the type of line, size, length, and its installation.

Appropriate grounding of the sample system with the station ground system is essential. This system must be built to provide reliable service, and proper installation will benefit the station in the long term.

The ground system about the bases of the towers must be installed in accordance with that proposed in the application authorized by the FCC. Typically, the ground system is copper; although in unique situations, other materials have been permitted by the FCC. All connections should be properly made using a recognized method of electrical RF connection. Silver solder is typically used since this type of connection will withstand years of service with a minimum amount of maintenance. Rosin or acid core solder is not acceptable. While installing a ground system, detailed plats should be prepared, and it is recommended that pictures be taken for future use. These pictures will assist in directing an investigation of various parts of the ground system in later years.

Deviation in ground system composition may require prior FCC approval or, at the minimum, alternate configurations will require advising the FCC in a letter or an FCC Form 302 with supporting information.

If the radiating elements are guyed, then the electrical continuity of each guy wire must be interrupted with insulators at intervals sufficient to permit the antenna to act as a free-standing radiator.

The selection of a point to serve as a monitor point along each radial specified in the construction permit is required. Each point must be reachable in inclement weather and must be free of surrounding objects, such as underground pipes and overhead wires. Schoolyards, churches, and cemeteries often provide useful monitor-point locations because the surrounding area generally is free from alteration. Prior to the submission to the FCC, possible sites for monitor-point selections should be observed over a period of time until a degree of confidence in the measured field strength values has been established. The reading at each point must be in the direction of the station. The direction of the station can be established by using a U.S. Geological quadrangle or by switching the pattern to the non-directional mode (if available).

Once the directional array is operating, one of the often overlooked items is the monitoring of the area for new construction. Vertical structure construction or new construction authorized by governmental authorities is often very difficult to detect in the advance stage of planning. New power-line construction and construction of other communication structures can act as additional, parasitic reradiators of the directional energy if placed sufficiently close to the array. Such reradiated energy can lead to situations whereby the directional pattern is altered.

Security (especially if the transmitting site is remote controlled or is located in a remote area) is definitely an item that should be considered. The location of a transmitter building in a secluded area without adequate security is an invitation for all kinds of crime or vandalism. Fences, including those about the tower bases, should be of rugged construction to serve as a deterrent. It is recommended that adequate night lighting be positioned around vulnerable areas, and an alarm system may be installed to warn of unauthorized entry and fire. Local authorities such as police and fire can be a great source of assistance in matters of security and fire prevention in individual situations.

Requirements to conform with the FCC Rules are broader for directional than non-directional operations; however, regardless of the operational mode, the FCC Rules must be observed. One approach is the acquisition of the current edition of the AM & FM Broadcast Station Checklist from the FCC field office having jurisdictional responsibility. The booklet is useful in identifying non-technical as well as technical areas of the FCC Rules where compliance must be maintained. The 1985 edition is reproduced at the end of Chapter 1.2, "FCC Field Operations Bureau," of this *Handbook*.

One item of importance, regardless of the power level or the status of the operation, is the evaluation of exposure to radio frequency energy. The FCC, in General Docket 79-144, released a Report and Order that specified that human exposure would be an area for consideration of potential environmental impact. While Docket 79-144 deals with FCC responsibility in considering effects for human exposure to radio frequency energy, the Report and Order specified that the 1982 protection guidelines of the American National Standards Institute be used in evaluating compliance.

The Rule, which became effective January 1, 1986, in general requires the broadcast station to demonstrate its effect on its surroundings at the time when the applicant or licensee applies for a construction permit and when a licensee files for renewal.

The FCC has released an OST Bulletin No. 65 entitled, "Evaluating Compliance with FCC-Specified Guidelines for Human Exposure to Radio Frequency Radiation." The bulletin covers different areas and can be of assistance in determining the facilities' potential impact. Accompanying the release of that document was an FCC Public Notice entitled, "Environmental Processing Rules for Broadcasters". A copy of that Public Notice is provided on page 2.8-233.

(5) Study your predicament carefully to determine your best course of action. It may be one of the following:
  (a) Back the vehicle up.
  (b) Drive the vehicle ahead.
  (c) Lower the mast.
  (d) Raise the mast further.
  (e) Get away from the car—IF YOU DO THIS, REMEMBER THE CAR MAY BE AT A HIGH POTENTIAL WITH RESPECT TO GROUND SO DO NOT TAKE CHANCES—JUMP CLEAR.

(6) Be sure no one else approaches the scene or comes in contact with the vehicle.

II. CONSTRUCTION SAFETY PRECAUTIONS

Since there is a remote possibility of the mast or antenna of the measuring vehicle coming in contact with extremely high voltages, the construction of the vehicle should be such as to reduce to the absolute minimum, the possibility of these electrical voltages entering the vehicle. The secure electrical bonds referred to herein must be made with a view towards the hundreds or thousands of amperes that may be involved in the event of an accident. The first of these precautions have to do with external features of the vehicle.

(1) All antenna elements which are directly connected to the transmission line must have a secure electrical bond to the mast.

(2) The outer conductor of all transmission lines used with the mast must have a secure electrical bond to the top of the mast.

(3) The vehicle shall be operated with blinking hazard lights when the mast is elevated.

The additional constructional details to be observed with the vehicle are as follows:

(1) The outer conductor of all transmission lines must have a secure electrical bond to the vehicle as soon after entering the vehicle as practical.

(2) All electrical equipment (field strength meters, recorders, receivers and signal generators) must have secure electrical bonding to the vehicle.

(3) The vehicle shall be equipped with a light readily visible to the vehicle driver which indicates that the mast is under pressure or up and/or the vehicle shall have a window in the roof from where the driver and engineer, if feasible, can directly view the mast and antenna.

The vehicle shall also be supplied with certain safety equipment as follows:

(1) A pair of high voltage rubber gloves with protecting leather gauntlets. The rubber gloves should be tested at least once a year and a memo including the date of test and the testing organization shall be included in the carrying box for the gloves. All major power companies have provisions for making these tests.

(2) A non-metallic safety pole 8 foot minimum for handling hot wires.

(3) A CO2 fire extinguisher. This should be checked annually.

III. OPERATIONAL SAFETY PRECAUTIONS

The foregoing equipment safety precautions are believed to be adequate to make the inside of the vehicle safe in the event of some unforeseen accident. These precautions will only be effective as long as the equipment is in good working condition. Therefore, it is important that all safety precautions outlined in the foregoing paragraph be checked each morning before beginning the day's work. In addition to have a safe vehicle, it must be operated in a safe manner. Therefore, the following precautions must be observed when the car is used:

(1) No night work is permitted without prior written approval. In the event this permission is given, it will include additional detailed precautions for the specific job for which the approval is given.

(2) The mast must not be erected unless two operators are present.

(3) The location for elevating the mast must be carefully chosen both to prevent contact with overhead obstructions and to avoid being a traffic hazard. The mast must not be elevated on busy urban streets or heavily traveled rural highways. The chosen area must be reasonably level and, if a mobile run is contemplated, the vehicle must traverse the path before the mast is raised.

(4) Having selected the location for measuring, the following procedure shall be used for elevating the mast. The driver and the engineer will both step out of the vehicle and examine the overhead area for obstructions. The engineer may then return to the vehicle and elevate the mast. If a mobile run is to be made, the driver must walk ahead, examining the path for overhead obstructions and leave a marker at the end of the chosen path. If

repeated measurements are to be made along the same path, the starting point should also be marked so that neither end of the examined path is passed. The vehicle may then be driven between the markers.

(5) When the measurements are completed, the driver shall, without stepping out of the vehicle, determine that the overhead area is free for the lowering of the mast. The driver must also make a personal observation that the mast has been fully retracted before driving to the next measuring area.

FOOTNOTES AND REFERENCES

1. Federal Communications Commission: FM Technical Standards, Sec. 73.311(c); TV Technical Standards, Secs. 73.683(a) and 73.685(a).
2. "Engineering Aspects of Television Allocations," Report of the Television Allocations Study Organization to the Federal Communications Commission, Mar. 16, 1959.
3. Kalagian, G.S. "A Review of the Technical Planning Factors for the VHF Television Service FCC/OCE RS 77-01," March 1, 1977.
4. LaGrone, Alfred H.: "Forecasting Television Service Fields", Proc. IRE, June 1960, vol. 48, no. 6, pp 1009-1018.
5. Brown, G. H. J. Epstein, and D. W. Peterson: "Comparative Propagation measurements; Television Transmitters at 67.25, 288, 510 and 910 Megacycles", RCA Rev., vol. 9, no. 2, pp 177-202, June 1948.
6. Bullington, K.: "Radio Propagation Fundamentals", Bell System Tech. J., May, 1957 vol. 36, no. 3, pp. 593-626.
7. Peterson, D. W., and J. Epstein: "A Method of Predicting the Coverage of a Television Station", RCA Rev., December, 1956, vol. 17, no. 4, pp. 571-582.
8. Head, H. T.: "The Influence of Trees on Television Field Strengths at Ultra-High Frequencies." Proc. IRE June, 1960, vol. 48, no. 6, pp 1016-1020.
9. Kinase, Akira, "Influences of Terrain Irregularities and Environmental Surroundings on the Propagation of Broadcasting Waves in the UHF and VHF Bands." Japan Broadcasting Corporation (NHK) Tech. Monograph No. 14, March 1969.
10. Damelin, J., W. A. Daniel, H. Fine, and G. V. Waldo, "Development of VHF and UHF Propagation Curves for TV and FM Broadcasting" FCC Report No. R-6602, September 7, 1966.
11. Norton, K. A. "The Calculation of Ground Wave Field Intensity over a Finitely Conducting Spherical Earth", Proc. IRE, vol. 29, December, 1941.
12. Rice, P. L., A. G. Longley, K. A. Norton and A. P. Barsis "Transmission Loss Predictions for Tropospheric Communication Circuits", NBS Technical Note No. 101, January 1, 1963.
13. Reed, H.R. and Russell C. M. *Ultra-High Frequency Propagation,* John Wiley and Sons, 1953.
14. Greene, Frank M.: "Calibration of Commercial Radio Field Strength Meters at the National Bureau of Standards," Natl. Bur. Standards Circ. 517, December, 1951.
15. Green, Frank M., and Max Solow: "Development of Very-high Frequency Field intensity Standards", Natl. Bur. Standards Research Paper RP2100, vol. 44, May, 1950.
16. Terman, F.E.: *Radio Engineers' Handbook,* McGraw-Hill Book Company, Inc., New York, 1943.
17. Schrack, R.A.: "Radio-frequency Power Measurements", Natl. Bur. Standards Circ. 536, Mar. 16, 1953.
18. Greene, Frank M.: "Influence of the Ground on the Calibration and Use of VHF Field Intensity Meters", Natl. Bur. Standards Research Paper RP2062, vol. 44, February, 1950.
19. Federal Communications Commission's Rules, Sec. 73.684.

each of the radials defined in the reference proof. The partial proof must contain an arithmetic or logarithmic ratio analysis of the measurement data so obtained. It must demonstrate that the antenna system is operating within its instrument of authorization. Generally speaking, the measurements should be made at an interval of 3 to 16 kilometers (2 to 10 miles). A statement that the impedance of the common point has been measured and is unchanged from the licensed value prior to making measurements should be provided. A change in common point impedance at the operating frequency requires an appropriate submission to the FCC and is to be requested, using FCC Form 302.

GENERAL REQUIREMENTS FOR MEASUREMENTS

All measurements should be made during the daylight hours in the absence of interference, and special temporary authority may be required prior to the commencement of measurements for a new authorization. For established stations, the FCC Rules permit considerable flexibility in operation during periods of making antenna system field strength measurements.

It is FCC policy that the measurement observations to be recorded and utilized as a basis of analysis of the inverse distance radiation values are those observed with the field strength meter oriented towards the station. The maximum indication can occur when the meter is oriented away from the transmitting source. This phenomenon can be caused by many factors including null depth on the measured radial. These factors vary from local effects surrounding or adjacent to the measuring point, non-uniform conditions inherent in the propagation path and can be affected by the position of the observation point on a rapidly changing portion of the directional pattern.

A record must be kept of the measurement data, including each point number, the field strength observations, dates and times of the measurements, the pattern under investigation, a description of each point location, the name of the individual taking the measurements, the general weather conditions, the field strength instrument utilized and the date of its last calibration. A sample form is provided for tabulating the field measurement data.

Graphical Analysis

The inverse distance field or unattenuated field strength at a reference distance kilometer (1 km) is the field strength predicted at that distance from the transmitting antenna if the earth were to behave as a perfect conductor. As the wave energy travels away from the antenna, the unattenuated field strength reduces by the inverse proportion to the distance from the antenna. For example, if the value of the unattenuated field at 1 km is 100 mV/m, its value at 2 km will be one-half that value or 50 mV/m, and at 10 km, its value will be one-tenth of the 1 km value or 10 mV/m. The effects of attenuation on field strength are shown by families of curves for field strength vs distance for various values of ground conductivity. These graphs are included in Section 73.184 of the FCC Rules. The actual field will be diminished by this inverse distance factor as well as the losses attributable to ground conductivity.

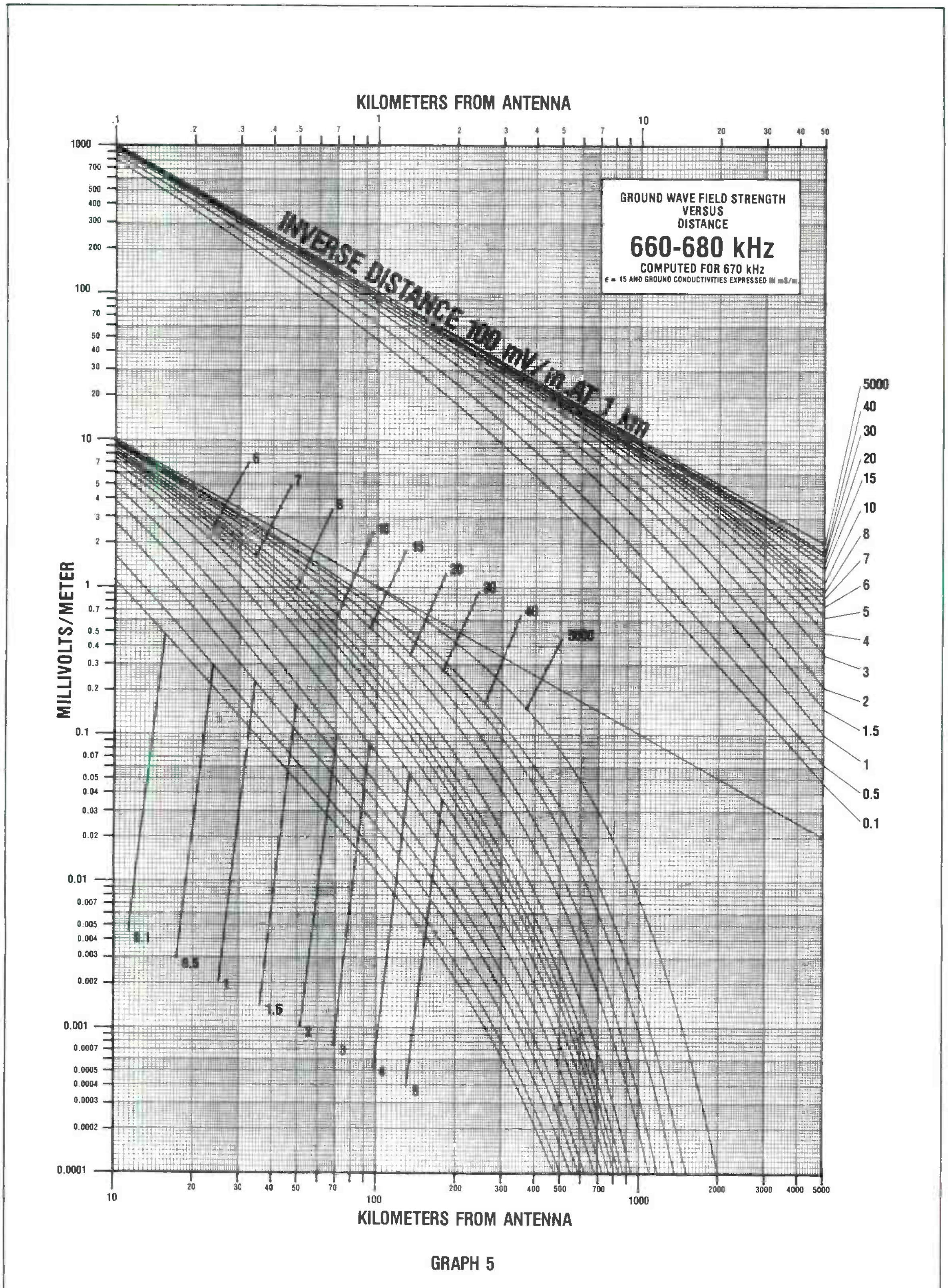
The FCC, in its conversion to the metric system, redetermined the frequency curves. In addition, the FCC used its computer program and determined additional conductivity values for each frequency chart. The dielectric constant for all curves except for sea water, is 15. For sea water the calculations are based upon a dielectric constant of 80.

There are 19 sets of frequency dependent propagation graphs that encompass the frequencies from 540 to 1610 kHz. Curves for each frequency group are drawn on two graphs. One graph shows the uppermost portion with conductivity curves normalized for 100 mV/m/km from one-tenth to 50 km and the bottom portion reflects the conductivity curves for 10 to 5000 km. The second graph is an expanded version of the uppermost portion of the first graph to allow for easier determination of the inverse distance field and conductivity values for measurements less than 50 km from the transmitting antenna.

After the distances from the transmitting antenna to each of the measuring points have been determined and tabulated opposite the observed field strength values, the measured field strength values can be plotted on log-log graph paper. The ordinate (vertical scale) is field strength, expressed in mV/m, and the abscissa (horizontal scale) is distance in kilometers. Data can be plotted on groundwave field intensity graph paper available through NAB. This paper has the same logarithmic scale as the expanded version of the FCC curves.

Plotting Data

For the logarithmic coordinate system, (log-log graph paper) the inverse distance field strength plots as a straight line. The conductivity curves are drawn for the case of an inverse distance field of 100 mV/m at 1 km, but their use is not limited to that value. If an inverse distance field strength is 200 mV/m (twice the reference value) or 50 mV/m (one-half the reference number) or some other value at 1 km, and if all points on the curve are multiplied by the ratio of the actual inverse distance field strength to 100 mV/m, the effect would be the equivalent of moving the curves by



Ground Wave Field Strength versus Distance
660-680 kHz

that amount on the logarithmic coordinate paper. This is the basis on which field strength measurements are analyzed. The appropriate conductivity values for the frequency involved are made by matching the abscissa of the data with that of the FCC graph and sliding the ordinate information data vertically to obtain the "best fit" of measured field strength values to the conductivity curves. By this method, both the unattenuated field at 1 km and the conductivity values along the radial path can be determined. The use of a light table will assist in aligning and moving the two sheets of paper.

An individual attempting to analyze measurement data for the first time and without the benefit of experienced supervision can find this a frustrating experience. One approach is to take log-log graph paper for the appropriate frequency (either the regular or expanded scale) and plot the measurement point values normalized to 100 mV/km. For example, if the non-directional 0.25 kW operation is expected to possess an RMS field at 1 kW of 91 mV/m (70 degrees [0.194 of a wavelength] electrical height tower with a normal ground system—see Figure 8, Section 73.190 of the FCC Rules), it has a field 91/100 less than the FCC log-log conductivity graph. Therefore, multiply all values (divide all values if the expected field is greater than 100 mV/m) of the measurement data by the ratio of 100/91 to normalize it to 100 mV/m. Plot the normalized data. The plotted values can be viewed in relation to the conductivity values if the assumption of the inverse distance field is correct. If the normalized data appear to be over the inverse distance line, then the radiation value is higher than assumed and conversely if the normalized data appear abnormally low, the assumed radiation value selected is too high.

This approach can be useful when the non-directional measurements out to 3 km in the various directions have been taken and a quick evaluation of the conductivity values/radiation efficiency around the site is desired. It also will help to assess whether or not the non-directional radiation pattern is being influenced by other adjacent towers in the directional antenna system.

Special Temporary Authority

Special temporary authority will generally be required with any operation which has not received prior authorization from the Federal Communications Commission. Section 73.1635 of the FCC Rules provides that special temporary authorization be requested in writing (an original and two copies) to the FCC in Washington, D.C. The authorization request should delineate the station frequency, location, and authorizing construction permit number. The request must contain the non-directional power requested. The letter should indicate the capacity of the requesting individual and his phone number so that the FCC can request additional information informally, if required.

For licensed operations, the FCC Rules provide that a non-directional operation that has been authorized in a proof-of-performance for a daytime only station, a station with a single pattern or more than one directional pattern for day and night, etc., can utilize the non-directional power set forth in the latest proof-of-performance without further authorization from the FCC. However, this privilege is permitted only for the time field strength measurements are being made. In addition, the FCC permits, without further authorization, operation of a nighttime pattern during daytime hours when field intensity measurements are being taken.

Antenna Monitor System Approval

For each new station, details of the antenna monitor system components and installation must be contained in the proof-of-performance report in order to obtain the necessary recognition from the FCC that the antenna monitor system conforms to the FCC Rules. An antenna monitor system request accompanying a partial proof should be, for prompt consideration, filed in a separate submission. During construction or revision of the monitoring system, special temporary authority for variance of parameters may be required for existing stations. This authority can be obtained by submitting a request (original and two copies) to the FCC. The purpose of the request as well as its duration should be provided. For specific situations, reference should be made to Section 73.68 of the Rules; however, with the revision in Docket 85-90, the FCC is less specific as to the detail of sampling system construction. The FCC indicates, as a matter of policy, that the procedural methods outlined in the Rules, as modified by MM Docket 83-16, would receive continued FCC acceptance. Other, less conventional methods may be subject to rigorous scrutiny, including observations over a period of time and partial proof-of-performance. For convenience, Section 73.68 of the FCC Rules is provided prior to alteration by Docket 85-90.

Whether contained in the proof-of-performance or otherwise, the request for approval must indicate information sufficient to determine compliance with the FCC Rules concerning the method of sample, type of sample line, and its electrical length and whether the sample lines are under similar environmental conditions. The submission should incorporate other descriptions as may be required to demonstrate compliance with the FCC Rules and Policy and must be accompanied by a signature of authority from the station organization. A station with an approved sampling system is permitted to establish its own schedule of monitor-point measurements based on its operating conditions.

FCC FORM FOR LICENSE

Each proof-of-performance must include the information requested in FCC Form 302. It must comply with the provisions and intent of the FCC Rules including Section 73.186 regarding the number of measurement radials, the number of non-directional and directional measurements made along each radial, the mathematical or graphical analysis, if utilized, the plot of the field versus distance measurements on semi-log or log-log graph paper, and reproductions of the quadrangle maps (or other maps as required) showing the radials along which measurements were made and locations used in making the measurements. Section 73.186 of the FCC Rules also dictates the form for the submission of non-directional antenna impedance measurements as well as the common point impedance measurements with the required graphical plots.

Furthermore, descriptions of the monitoring points as specified by the construction permit, complete with the monitor-point photographs and a route diagram must be supplied (see Section 73.158 of the FCC Rules). The station must also comply with all other conditions of the construction permit.

A diagram of the phasor, associated RF feed system, and matching network, as constructed, is to be provided. Plots of the inverse distance field at 1 km for the non-directional as well as each directional mode are to be supplied for each measured radial, showing the interpretation of the measurement data. The measured directional pattern field strength must not exceed the authorized pattern in any direction and must have the requisite RMS. In certain situations for new stations or revisions of existing facilities requiring a new reference proof-of-performance, the FCC will permit an adjustment of directional power which can be effected at the time of the license application. The FCC policy statement concerning such power adjustment is provided in its entirety, see page 2.8-229.

For each directional operation, the parameters as indicated by the antenna monitor for both loop and phase (including SIGN), as well as the base currents and the ratios are to be furnished. Each field strength instrument and its type number, make, model, and date of the last calibration should be listed. If more than one instrument is utilized, a comparison of the accuracy observed for each instrument should be made. The name, address and qualifications of the engineer making the measurements must also be provided.

LICENSE

The FCC license specifies, among other things, the licensee name; the term of the license; the station location; the main studio location, if not at the transmitter or within the boundaries of the principal community; the remote control location; the transmitter location and its coordinates; the type of antenna and ground system, if non-directional; the frequency; the nominal power; the hours of operation and any special conditions. For stations using a directional antenna system, the second page will provide a description of the directional antenna system; the spacing, orientation and height of the towers; and a description of the ground system. Also provided are the theoretical specifications authorized by the latest FCC construction permit and operating specifications determined from the most recent partial or full proof-of-performance. The descriptions of the monitor points and the maximum limits that the points must not exceed are contained on the following page(s) of the license.

Changes and modifications of any of these items require appropriate notification to and concurrence by the FCC. When a new license is received, it should be inspected for correctness as compared with the information used as a basis for the license application.

The operating parameters must be maintained in accordance with Section 73.62 of the FCC Rules and the directional antenna must be maintained with indicated relative amplitude of the antenna base currents and antenna monitor currents within 5% of the values specified in the license, unless other tolerances are specified. In addition, the directional antenna relative phase angles must be maintained within ±3 degrees of the values specified in the license unless other tolerances are required.

Monitor-point values must be maintained within the values specified in the license. An increase in an existing monitor point(s) maximum allowed value can only be accomplished by submission of a partial proof-of-performance to the FCC. A change in monitor point location requires submission of a photograph, route diagram, description of the new monitor point and a minimum of 10 field strength measurements at locations used in the last reference proof-of-performance on the radial, including the newly-designated monitor point between 2 and 10 miles that is shown in the latest reference proof. This information is to be submitted to the FCC. The FCC policy for the assignment of monitor-point values is attached.

FCC POLICY STATEMENT ENTITLED "CRITERIA FOR APPROVAL OF SAMPLE SYSTEMS FOR DIRECTIONAL AM BROADCAST STATIONS" DATED DECEMBER 9, 1985

On October 31, 1985, the Commission adopted a Report and Order in MM Docket 85-90 concerning the antenna sampling systems and proofs-of-performance for directional AM broadcast stations. The new rules are based upon performance standards in terms of accuracy and stability rather than upon construction specifications. This Notice clarifies the information required for directional AM sampling system approval under the new provisions of Section 73.68(a) of the Rules. As before, stations constructing new antenna systems pursuant to a construction permit must obtain approval of their sample system when filing for a covering license. Existing stations may obtain approval by informal request to the FCC in Washington, D.C.

To obtain antenna system approval, applicants may follow either of the procedures set forth in Paragraphs A or B below:

A. Demonstrate that the system complies with the provisions of Section 73.68(a) of the Rules in effect prior to January 1, 1986.

B. Demonstrate stability of operation by submission of the following information:

(1) A detailed and complete description of the antenna monitoring system installation.

(2) Field strength readings taken on a monthly basis at each of the monitoring points specified in the instrument of authorization for a one year period prior to the date of the application.

(3) The following readings taken daily for each directional pattern use during the thirty-day period prior to the filing of the application:
a. Common point current.
b. Base currents and their calculated ratios.
c. Antenna monitor sample current ratios.
d. Antenna monitor phase readings.
e. Final amplifier DC input voltage and current.

(4) The results of either a partial proof-of-performance (Section 73.154) or a full proof (Section 73.186) conducted no longer than 3 months prior to the filing of the application and the common point impedance at the operating frequency measured at the time of the proof.

Additional sampling system components and configurations found by the Commission to be accurate and stable over a wide range of environmental and operational conditions will be included as acceptable under Paragraph A above and announced periodically via public notice.

Questions concerning sampling system approval may be directed to John Sadler (202) 632-7010 and questions concerning the Report and Order in MM Docket 85-90 may be directed to John Reiser (202) 632-9660.

SECTION 73.68(a) OF THE FCC RULES IN EFFECT PRIOR TO JANUARY 1, 1986-SAMPLING SYSTEMS FOR ANTENNA MONITORS

(See text on page 2.8-223)

(a) The following requirements govern the installation of systems employed to extract samples of the currents flowing in the elements of a directional antenna, and to deliver these samples, to the antenna monitor. Each new station issued a construction permit, each existing station issued a construction permit authorizing tower construction, and any existing station undertaking modification or reconstruction of its sampling system must install the system meeting the following requirements. The application for license or modification of license must describe the system in sufficient detail to demonstrate its compliance with the following:

(1) All coaxial cable from the sampling elements to the antenna monitor, including cable used in the construction of isolation coils, except short lengths of flexible cable connecting the transmitter house sampling line termination to the monitor, must have a solid outer conductor and have uniform physical and electrical characteristics. The dialectric must be either predominantly pressurized air or other inert gas, or foamed polyethylene.

(i) All sampling lines for a critical antenna array (i.e., an array for which the station authorization requires the maintenance of phase and current relationships within specified tolerances) must be of the same electrical length, with corresponding lengths of all lines exposed to equivalent environmental conditions.

(ii) For other arrays, lines of differing length may be employed, provided that the difference in length between the longest and the shortest line is not so great that, over the range of temperatures to which the system is exposed, predicted errors in indicated phase difference resulting from such temperature changes will exceed 0.5 degrees.

(iii) A sampling line mounted on a tower must be adequately supported to prevent displacement, and must be protected against physical damage. Where feasible, sampling line sections between each tower base and the transmitter house is to be jacketed and buried: lines run above ground must be firmly supported, and protected against physical damage, with the outer conductor strapped to the station's ground system at such points as found necessary to minimize currents induced by antenna radiation.

(iv) All necessary connections and outdoor cable terminations must be made with waterproof fittings designed for use with the type of cable employed.

(v) For determining the permissible differences in the line lengths that may be installed, the total difference between the highest listed normal daily maximum and lowest listed normal daily minimum temperatures as shown for the nearest location shown in the most recent issue of "Local Climatological Data Annual Summaries" shall be used in the calculations. This publication is available from:

National Climatic Center
National Oceanic and Atmospheric Administration
Asheville, North Carolina 28801

(vi) The provisions of this subparagraph do not preclude the use of a centrally located impedance-matched radio frequency relay or a remotely controlled switch to provide a relative sampling currents to the antenna monitor over a single transmission line. However, the reference sampling line and the relative sampling line from the switching point to the antenna monitor must be identical in type and electrical length, and must be exposed to the same environment. The sampling line from each sampling element to the relay must conform to all relevant requirements indicated in this subparagraph. Alternatively, when such a relay is used to select signal samples from any of two or more sampling devices installed either on the tower or at its base and feed the sample to the antenna monitor through a single sampling line, the length of cable from each device to the relay shall be equal. Additionally, a licensee may install the antenna monitor at a centrally located or otherwise convenient location provided that the temperature and humidity of the operating environment are maintained within the tolerances specified by the antenna monitor manufacturer. When such an antenna monitor is to be remotely controlled and read, installation shall conform to the requirements of Section 73.67 of this Part.

(2) Except as provided below, sampling

elements must be single turn, unshielded loops of extremely rigid construction, with ample, firmly positioned gaps at the open loop end, mounted on towers at a fixed orientation. Loops must be installed to operate at tower potential, provided that for towers less than 130 degrees in electrical height, loops operating at ground potential may be used. Each loop must be mounted on the tower near the point of maximum tower current, but in no case less than three meters (10 feet) above ground.

(3) Shielded current transformers may be used in lieu of unshielded loops to extract samples from antenna feed lines at the base of each tower having a uniform cross-section and 110 degrees or less in electrical height, or a self-supporting tower 110 degrees or less in electrical height, provided it has a common feedpoint for all tower legs.

(4) Shielded current transformers may be used in lieu of unshielded loops to extract samples from the antenna feed line at the base of each tower having a uniform cross-section more than 110 degrees but not greater than 130 degrees in electrical height, self-supporting towers not exceeding 130 degrees in electrical height and having a central common feedpoint for all tower legs, and folded unipole antennas of any height having a base driving point resistance and reactance not exceeding 70 ohms, provided the following conditions are met:

(i) Stability of operation during a test period of 30 continuous days using the current transformers must demonstrate that the antenna monitor sample current ratios do not exceed five percent of those specified on the station authorization and that the relative phase indictions are with ± 3 degrees of the values specified on the station authorization, unless a more stringent tolerance is specified therein.

(ii) The following parameters shall be read and recorded as indicated during the 30 day test period for each antenna pattern:

(A) Indications at each monitoring point specified in the station authorization, weekly.

(B) Base currents and their calculated ratios, weekly.

(C) Common point current, daily.

(D) Antenna monitor sample current amplitudes and their ratios, daily.

(E) Antenna monitor phase indications, daily.

(iii) Failure to meet the stability requirement specified in paragraph (a)(4)(i) of this Section will require that the licensee seek special temporary authority to operate at variance with the terms of the station instrument of authorization until the problem can be corrected.

(iv) A certification by the licensee that the sampling system meets the stability requirement specified in this paragraph must be included in the request for approval of the monitor sampling system together with the information specified in paragraph (c) of this Section.

(v) Shielded current transformers may be used in lieu of unshielded loops to extract samples from the antenna feed line at the base of each tower greater than 130 degrees in electrical height provided the requirements set forth in subparagraphs (a)(4)(i) through (iii) of this Section are satisfied and the resulting data is included in the request for approval of the monitor sampling system together with the information specified in paragraph (c) of this Section.

(vi) The FCC may request the licensee to conduct such other tests, or measurements, or submit additional data it deems necessary to determine the stability of the antenna sampling system.

(b) Each license or modified license issued pursuant to an application containing a satisfactory showing that a sampling system has been constructed complying with the requirements set forth in subparagraphs (a)(1) and (2) of this section, and that an antenna monitor of a make and type approved or notified by the FCC has been installed, will be conditioned to exempt the licensee from compliance with the rules which require:

(1) The routine reading and logging of base currents in the array elements.

(2) That monitoring point measurements can be made more frequently than at average intervals.

(3) The readings and station log entries specified in Section 73.1830(a)(2) be made.

(4) The skeleton proof-of-performance measurements required by Section 73.61. Note not required.

(c) Any existing station with an antenna monitor sampling system meeting the specifications of paragraphs (a)(1) and (2) of this section, wishing to be exempted from the logging and measurement requirements listed in paragraph (b) may send an informal request to the FCC in Washington, D.C. The request must be signed by the licensee or officer of the licensee and contain sufficient information to show compliance with the requirements of paragraph (a), including the following:

(1) The brand and type number of the coaxial sampling line cable, with a description of the dielectric material and electrical characteristics.,

(2) The overall length of each sampling line. If cables of different length are installed, the calculations to show that the phase difference of signals at the monitor are less than 0.5 degrees between the shortest and longest cable length.

(3) A description of the sampling elements (loops or current transformers) and the position of their installation, and when loops are installed, whether bonded or insulated mounting is used.

(d) In the event that the antenna monitor sampling system is temporarily out of service, the station may be operated pending completion of repairs for a period not exceeding 60 days without further authority from the FCC, if,

(1) The base currents, their ratios, and the deviations of those ratios, in percent, from the values specified in the station authorization are determined for each radiation pattern used, as often as necessary to ensure proper directional antenna system operation and,

(2) Field strength measurements, at each monitoring point specified in the station's authorization, are read at least once each calendar week.

(e) If the antenna sampling system is modified or components of the sampling are replaced, the following procedure shall be followed:

(1) Temporary authority shall be requested and obtained from the Commission in Washington to operate with parameters at variance with licensed values pending issuance of a modified license specifying parameters subsequent to modification or replacement of components.

(2) Immediately prior to modification or replacement of components of the sampling system not on the towers, and after a verification that all monitoring point values, base current ratios and operating parameters are within the limits or tolerances specified in the instrument of authorization or the pertinent rules, the following indications must be read for each radiation pattern: Final plate current and plate voltage, common point current, base currents and their ratios, antenna monitor phase and current indications, and the field strength at each monitoring point. Subsequent to these modifications or changes the above procedure must be repeated.

(3) If that portion of the sampling system above the base of the towers is modified or components replaced, a partial proof-of-performance shall be executed subsequent to these changes consisting of at least 10 field strength measurements on each of the radials established in the latest complete proof-of-performance of the antenna system. These measurements shall be made at locations, all with 3 to 16 kilometers (2 to 10 miles) from the antenna which was utilized in such proof, including, on each radial, the location, if any, designated as a monitoring point in the station authorization. Measurements shall be analyzed in the manner prescribed in Section 73.186. The partial proof-of-performance shall be accompanied by common point impedance measurements made in accordance with Section 73.54.

(4) Request for modification of license shall be submitted to the Commission in Washington, D.C., within 30 days of the date of sampling system modification or replacement. Such request shall specify the transmitter plate voltage, and plate current, common point current, base currents and their ratios, antenna monitor phase and current indications, and all other data obtained pursuant to this paragraph (E).

(e) If an existing sampling system is found to be patently of marginal construction, or where the performance of a directional antenna is found to be unsatisfactory, and this deficiency reasonably may be attributed, in whole or in part, to inadequacies in the antenna monitoring system, the FCC may require the reconstruction of the sampling system in accordance with requirements specified above.

FCC POLICY STATEMENT ENTITLED "THE APPLICATION PROCESS AND THE USE OF NON-DISCRETE POWER LEVELS FOR AM STATIONS" DATED OCTOBER 11, 1985

By Commission Report and Order dated April 24, 1985, changes were made in the FCC Rules which eliminated the requirement that AM stations file for facilities using power levels at a limited number of discrete values (e.g.: 0.25 kW, 1.0 kW, 5.0 kW, etc.). These modifications were intended to provide greater flexibility for AM applicants. However, details regarding implementation of certain provisions of the new rules need to be further addressed.

Under the new rules, a single value will be designated for the nominal power and the antenna input power (excluding the directional antenna supplement allowed under Section 73.51(b)(1) and (b)(2)). In the past, a radiation value less than the theoretically predicted amount could be achieved by applying a power level less than the nominal value to the antenna to provide compensation and both the nominal and antenna input powers would be licensed. With the removal of the discrete power level requirement, the power actually delivered to the antenna becomes the licensed nominal power, barring the above-mentioned exclusion. Several examples of how the application process will operate under these new rules are discussed below.

Consider first, applications which propose non-directional antennas. In the case of a new station, the power will be directly derived from the proposed radiation for that allocation. The radiation will be first extracted from Figure 8 of Section 73.190 of the FCC Rules (based upon antenna height and ground system), and then, that value adjusted by the square root of the proposed power to produce the proposed radiation. Alternatively, the proposed power will be derived from the square of the ratio of the proposed radiation to the Figure 8 predicted value. For an existing station proposing a change of facilities, these same methods apply. This is a departure from the former treatment where, if, for instance, an AM antenna height was being increased to accommodate an FM antenna and the AM radiation was to be maintained at the licensed value, then the station would retain its nominal power but reduce its antenna input power and would be licensed with a restricted radiation. Under the new rules, restricted radiations are being eliminated as they are encountered in formal applications that propose changes in the antenna systems. Thus, any such application must specify the actual power to be applied to the antenna and the end result will be a licensed operation with an apparent power reduction, but, in reality, coverage and radiation equivalent to the previous operation.

For directional operations involving a new station or a proposal utilizing a new antenna system (in particular, site relocations), the provisions of Section 73.150(b)(1)(i) shall be observed and the pattern RMS shall be developed using an assumed loss of one ohm per tower and the power adjusted to meet that RMS value. Patterns proposed under these circumstances that do not meet this criterion will result in a request to the applicant for a corrective amendment.

Directional applications that propose only slight modifications of existing arrays may have a sufficient history of antenna performance and measurement data which can, in many cases, be used to demonstrate whether a particular system operates with an inherently greater loss than the one ohm method may approximate. For these specific systems, when the application proposes to modify only the theoretical parameters of the existing operation and leaves the overall system geometry unchanged, exemption from the RMS/power relationship based upon one ohm loss can be entertained. Should it become apparent after filing of the license application that a reduction of the input power is necessary to meet the pattern requirements, then that new power level will become the licensed power and any reference to the old nominal power will be deleted.

Additionally, there may be situations where a newly constructed directional antenna has been completed, and a license application has been submitted and it is demonstrated, based upon proof data, that the antenna system, due to its intrinsic shortcomings, does not perform to the level expected by use of one ohm per tower loss assumption. In such cases, an upward power adjustment can be affected at the time of license application. Such adjustment is to be made based upon a direct mathematical escalation applied to the measured values of inverse distance field while providing assurance that no adjusted value in any direction shall exceed the authorized standard pattern limitation. Requests for augmentation of the standard pattern to accommodate additional expansion once the requirements of Section 73.151(a) [regarding minimum RMS (85%)] have been met will be categorically denied. In no event will a power adjustment be allowed that would result in a power level in excess of the maximum value specified for that class of station. Upon Commission approval of the adjusted power, such value will become the licensed value and appropriate domestic and international notification procedures and data base updating will be initiated by the FCC staff. Also, at such time, the new power will be placed on FCC Public Notice. In most cases, the increase of power would normally affect the calculation of the standard pattern 'Q' factor as defined by Section 73.150(a)(1)(i) of the FCC Rules. However, since the purpose of the power adjustment is to allow for the actual performance of a constructed antenna system within the constraints of the proposed pattern, the original array design parameters should not require reconsideration. Therefore, the value of 'Q' as authorized in the construction permit will be retained and will subsequently be carried on the station license along with the modified value of nominal power. Similarly, this unchanged, but now non-standard, 'Q' value will undergo the proper international notification and data base updating processes.

Therefore, with the preponderant consideration given under the new Rules to the pattern RMS values and radiation efficiencies and their relationship to expected coverage area, no loss of service should be experienced, even though unfamiliar power levels begin to appear upon station licenses.

Related to the methods described within this Notice, examples are presented which depict some of the more frequently experienced applicational scenarios. These are included as an appendix to this document.

Further information on the matters discussed in this Notice may be obtained from James G. Ballis (202) 632-7010, or Henry A. Straube (202) 632-7010 both at the AM Branch of the Audio Services Division of the Mass Media Bureau.

EXAMPLES

Situation 1:

An existing non-directional station with a nominal power of 5 kilowatts, an antenna input power of 5 kilowatts, and an effective field of 300 mV/m/kW at one kilometer increases its antenna height while restricting radiation to the present value instead of achieving an effective field of 325 mV/m/kW at one kilometer for the new height. When the CP is issued, the nominal and antenna input power will be 4.3 kilowatts. [(300/325) squared x 5]

Situation 2:

A permittee for a new directional station with a nominal power of 5 kilowatts, a standard RMS of 700 mV/m at one kilometer, and and a Q of 25.0 mV/m at one kilometer determines via the proof-of-performance that the measured RMS is actually 800 mV/m at one kilometer. When the covering license is issued, the nominal power will be 3.8 kilowatts, the antenna input power will be 4.1 kilowatts, the standard RMS will remain at 700 mV/m, and the Q will remain at 25.0 mV/m. [(700/800) squared x 5 with an 8 percent adjustment pursuant to Section 73.51(b)(1) of the Rules]

Situation 3:

A permittee for a new Class II directional station with a nominal power of 5 kilowatts, a standard RMS of 750 mV/m at one kilometer, and a Q of 25.0 mV/m at one kilometer determines via the proof-of-performance that the measured RMS is actually 630 mV/m at one kilometer. When the covering license is issued, the nominal power will be 7.1 kilowatts, the antenna input power will be 7.5 kilowatts, the standard RMS will remain at 750 mV/m, and the Q will remain at 25.0 mV/m. [(750/630) squared x 5 with a 5.3 percent adjustment pursuant to Section 73.51(b)(2) of the Rules]

Situation 4:

A permittee for a new Class III directional station with a nominal power of 5 kilowatts, a standard RMS of 750 mV/m at one kilometer, and a Q of 25.0 mV/m at one kilometer determines via the proof-of-performance that the measured RMS is actually 630 mV/m at one kilometer. The permittee must apply for a modification of construction permit to reduce the standard RMS to 630 mV/m so that the power to be authorized does not exceed 5 kilowatts.

FCC POLICY AS PUBLISHED IN BC DOCKET NUMBER 78-28 AND MM DOCKET NUMBER 83-16 CONCERNING THE ESTABLISHMENT OF MAXIMUM MONITOR POINT VALUE

The following item addresses the current FCC Policy governing assignment of monitor point limits and has been abstracted from the Docket released December 20, 1983. The policy is in the form of a letter dated December 6, 1979 and results from a series of informal meetings with the FCC engineering staff and the Association of Federal Communications Consulting Engineers. It was signed by Richard Shiben, Chief of the Broadcast Bureau, and is included in its entirety as the FCC provides a background, essence and discussion of its views and the relationship of the monitor point in the licensing process. The policy was also formally published in Docket 78-28 released December 20, 1983. It reads as follows:

"I have your letter of October 22, written on behalf of your committee, requesting modification of certain Commission engineering practices used in assigning monitoring point limits to AM directional broadcast stations. Your letter formalizes suggestions developed in a series of meetings, begun well over a year ago, between your committee and members of the Broadcast Facilities Division's engineering staff concerning the policies and procedures governing the preparation and processing of various types of applications. The interest shown throughout this period by your committee in helping improve our processing procedures has been helpful and is greatly appreciated.

Specifically, your committee feels that, under the present policy, monitoring point limits are often assigned which are unnecessarily restrictive and urges the adoption of a policy whereby the assignment of these limits is based on the "direct ratio" method. The committee also urges the establishment of a policy whereby stations subject to seasonal conductivity changes can achieve relaxed limits upon submission of "seasonal proofs". Additionally, the committee requests that the Commission refrain from altering monitoring point limits based on partial proofs-of-performance if "substantial conformance" of radiation patterns is demonstrated and the antenna parameters are either essentially unchanged or, if changed, adequately justified.

In response to your first suggestion, I am pleased to announce that we have, on an experimental basis, adopted the policy of assigning monitoring point limits using the direct ratio method. Under the direct ratio method, monitoring point limits are obtained by multiplying the measured field strength at a monitoring point by the ratio of the authorized maximum radiation divided by the unattenuated radiation established in the proof-of-performance. This method simply restricts unattenuated radiation to within its maximum authorized value whereas the traditional method in many cases restricted radiation much more severely. Theoretically, objectionable interference is not caused if antenna radiation is maintained below its maximum authorized value. Assuming, therefore, that changes in monitoring point field strength correspond directly to changes in antenna radiation, monitoring point limits determined by the direct ratio method should be adequate to avoid interference. However, since the assumption of a linear relationship between monitor point readings and antenna radiation becomes somewhat questionable with excessive changes, we do not intend to assign limits higher than 200% above proof values. In addition, because operation with monitoring point field strength in excess of the direct ratio limit could result in objectionable interference, we will continue to deny requests to exceed those limits.

Your second suggestion addresses a problem encountered in many areas of the country where complete proofs-of-performance are done during the summer months when ground conductivity is significantly lower than during the winter months. Often monitoring point limits resulting from such summertime proofs are not sufficient to accommodate higher readings encountered during winter. In such a case increased limits are obtained by collecting supplemental wintertime data in the form of a partial proof of performance consisting of at least 10 measurements on each radial established in the complete proof (see Section 73.154(a) of the Rules). You suggest that the Commission accept "seasonal proofs" for this purpose in lieu of partial proofs. A seasonal proof would consist of "at least 20 field strength measurements, both non-directional and directional, on each of the radials specified in the construction permit and at least one radial in the major lobe".

In responding to this suggestion, it is helpful to understand the approach used by Commission engineers in analyzing complete proofs-of-performance. These generally consist of 20 or 30 measurements per radial (see Section 73.186(a)(1)) and serve as the reference for all subsequent partial proofs. As you know, the fundamental problem is distinguishing between the effects of conductivity and antenna radiation. In making this distinction, we consider it imperative to establish, as conclusively as possible, the size and shape of the non-directional radiation pattern. The non-directional radiating system is simpler (fewer variables) than the directional system and its RMS (size) can be more accurately determined since each measured radial is of more or less equal significance, particularly if the radials are evenly spaced. With a directional pattern, many of the minor-lobe and null radials do not contribute significantly toward defining the RMS, leaving the remaining main lobe radials with a disproportionate influence on the determination of the pattern size. For these same reasons, the Commission relies entirely on non-directional measurement data in determining the extent of seasonal changes in conductivity.

Because of the crucial role played by the non-directional pattern resulting from a complete proof-of-performance, extreme care is used in analyzing the measurement data. Experienced engineers who have been carefully trained are used in the work. All known external factors such as terrain features, reradiating structures, pipe lines, etc., are taken into account. Each radial is repeatedly weighed against the others with constant attention to the resulting pattern shape and RMS and the analysis is not considered complete until the importance of each element of data is understood from the perspective of the whole. Of course, the more extensive and "well behaved" the measurement data, the more precise and confident the engineer can be with his/her analysis. Once the non-directional pattern is established, analysis of the directional data can usually be done mathematically, rather than graphically, using either arithmetic or logarithmic averages. Any subsequent non-directional partial proofs which are submitted to the Commission for the purpose of documenting suspected conductivity changes are mathematically analyzed, point for point along each radial, against the complete proof non-directional data (See Section 73.186(a)(5)). If the possibilities of distortion and chanted RMS can be eliminated from the partial proof non-directional pattern, then the extent of conductivity change along each radial can be determined and applied to the directional partial proof data revealing whether, in fact, observed change in directional field strengths resulted from changes in the radiation pattern or simply from conductivity changes.

The notion of a seasonal proof, to the extent that some of the proof radials would be eliminated, strikes at the very heart of our approach which is an accurate determination of the non-directional radiation pattern. Although, under the committee's suggestion, the minimum number of measurements on some radials would be raised from 10 to 20, we do not feel the value gained from additional data on these radials would be sufficient to offset the complete loss of data on the remaining radials. This is also the case for directional patterns where changes in radiation in some directions can affect radiation in other directions and assumptions of pattern symmetry are generally unreliable. The Commission encourages supplemental measurements in addition to the minimum of 10 per radial required by the

Rules; this should not be accomplished, however, at the expense of fewer measurements on other radials.

Your last suggestion concerns the Commission's assignment of monitoring point limits in response to partial proofs-of-performance conducted following antenna repairs, refurbishment, construction or readjustment. Often such proofs result in a reduction in limits below those previously assigned because measurements were taken during periods of low conductivity or because antenna radiation in some directions was reduced. The committee suggests we not lower limits in such cases if the pattern remains in substantial conformance and the antenna parameters (phases and current ratios) are either essentially unchanged or, if changed, adequately justified. We believe this suggestion has merit and have, also on an experimental basis, ceased the practice of lowering limits based on partial proofs except when such limits would exceed measured values by more than 200%.

We feel that the current mandatory use of type-approved antenna monitors by directional stations and the widespread use of approved sample systems permit these changes in policy at this time without endangering in any way the technical integrity of our AM broadcasting system. Nonetheless, because of the significance of these changes, we intend to proceed on an experimental basis for at least a year, gaining the benefit of practical experience, before permanently adopting them. In addition, cases clearly falling beyond the scope of these policies will continue to be handled on a case-by-case basis.

We are hopeful that the changes we have initiated in response to your suggestions will provide many stations with operating tolerances sufficient to accommodate variations which under our old policy, would have required a proof-of-performance and the filing of an application with the Commission. Again, I would like to express my sincere appreciation for the work done by your committee in bringing forth these suggestions''.

Sincerely,
Chief, Broadcast Bureau

FCC POLICY STATEMENT ENTITLED "ENVIRONMENTAL PROCESSING RULES FOR BROADCASTERS" DATED NOVEMBER 14, 1985

Effective January 1, 1986, the Commission's environmental rules will be amended to provide the evaluation of human exposure to radio frequency (RF) radiation. The following information addresses several aspects of that matter which have been of particular concern in the broadcasting industry.

In the broadcast services, the Commission will routinely consider the effect of a broadcast station on the environment at the time when a party applies for a construction permit (for new or modified facilities), and when a licensee files for renewal.

With regard to applications for new facilities or operations, the Commission will be determining the potential impact, if any, of a station on its surroundings. This will normally be done in conjunction with the staff's review of the technical aspects of a proposal. Consideration of an RF radiation issue at this point in the Commission's authorization process will afford an opportunity for modification before construction has begun.

With regard to renewal applications, the Commission and licensee will be evaluating the consequences of any change in a station's surroundings, usually the construction of nearby businesses and residences. (Part 1, Subpart I of the Commission's rules sets forth the administrative procedures implementing the National Environmental Policy Act, a list of those actions which may affect the environment, and a description of those actions which are categorically excluded.)

With regard to applications for construction permits filed prior to January 1, 1986, but not acted upon by the Commission until after that date, the FCC may require an environmental assessment of RF radiation either on its own motion, or in response to an objection filed by a third party based on a proper technical showing. Environmental assessments of RF radiation will not otherwise routinely be required for those applications.

Although an applicant's affirmative responsibility to include the potential effects of RF radiation in the application's environmental evaluation does not become effective until January 1, 1986, any applicant who files prior to that date and who has reason to believe that its requested operation would exceed the American National Standards Institute's guidelines is encouraged to bring the facts to the Commission's attention so that the application can be given appropriate environmental review.

Every such applicant will definitely have the affirmative responsibility to report on RF radiation in its renewal application, and with any modification application filed after January 1, 1986. An applicant's diligence and foresight in raising and addressing the RF radiation hazard issue at an early stage in the authorization process may save substantial application processing time and modification expense in the future. The potential effect of RF radiation on the environment was not routinely considered as part of the Commission's processing of the last cycle of broadcast license renewal applications. Accordingly, all licensees must be alert for existing RF radiation problems when renewal first comes due after January 1, 1986, even if the surroundings have remained unchanged over a long period.

2.9

Radio Wave Propagation

Marty Barringer
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Radio wave propagation is the study of the transfer of energy at radio frequencies from one point, a transmitter, to another, a receiver. Radio waves are part of the broad electromagnetic spectrum that extends from the very low frequencies which are produced by electric power facilities up to the extremely high frequencies of cosmic rays. Between these two extremes are bands of frequencies that are found in every day uses: audio frequencies used in systems for the reproduction of audible sounds, radio frequencies, infrared, light, ultraviolet, and X-rays.

Electromagnetic waves travel at the velocity of light waves, which for a vacuum is 3×10^8 m/sec. The velocity of any wave is dependent upon the medium in which it is traveling, but for simplicity is usually considered with respect to a vacuum. The frequency of a wave is defined in terms of the number of cycles per second or Hertz (Hz) and is related to the wavelength λ in meters by the expression $\lambda = c/f$ where c is the velocity of light. Fig. 1 shows the ranges of various bands of frequencies within the electromagnetic spectrum in terms of frequency and wavelength.

Radio frequencies are generally confined to that portion of the electromagnetic spectrum that is between the audio frequency portion and the infrared portion. At present, the practical limits of radio frequencies lie roughly between 10 kHz and

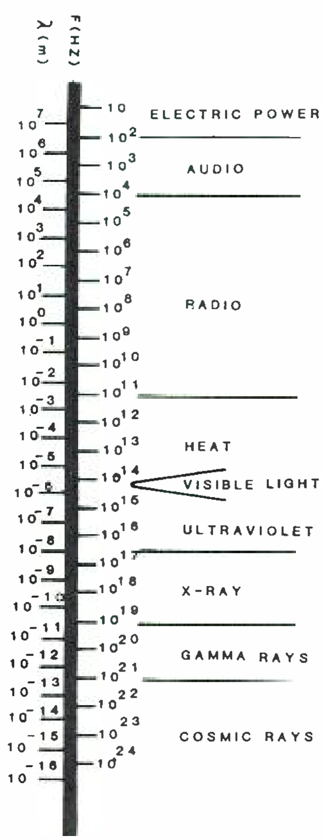


Fig. 1. Electromagnetic spectrum.

NOTE: Superscript numbers refer to references at the end of the chapter.

100 GHz.[1] Within the radio frequency spectrum are bands of frequencies that have been allocated to the broadcast service. The following discussions and methods will apply particularly to these bands of the radio frequency spectrum.

The AM broadcast frequency allotments are contained in what is referred to as medium frequencies (MF), 300 kHz to 3 MHz. The FM broadcast frequencies and a portion of the TV broadcast frequencies band are contained in the VHF band which extends from 30 MHz to 300 MHz. The remaining TV broadcast allocations are contained in the UHF band of 300 MHz to 3 GHz. Allocations for broadcast auxiliary services such as remote pickup, studio-transmitter links, intercity relays, MDS, and ITFS are interspersed within the MF, VHF, UHF and SHF (Super High Frequency) bands. Table 1 illustrates that portion of the spectrum assigned to the broadcast service. The allocations for auxiliary services may change from time to time as the needs of various services for radio frequencies change and as technology for equipment improves, so Table 1 is included as an illustration of the wide band of frequencies allocated to the broadcast services. For a discussion of the origin of the frequency allocations for broadcasting and broadcast auxiliary services the reader should refer to Chapter 1.5 of the Handbook, "Frequency Allocations for Broadcasting and the Broadcast Auxiliary Services," by Michael Rau. In order to keep abreast of new frequency allocations the most current FCC Rules and Regulations should be consulted.

TABLE 1. Broadcast Frequency Allocations.

MF 300 kHz—3 MHz	
AM:	525 kHz—1605 kHz
VHF 30 MHz—300 MHz	
FM:	88 MHz—108 MHz
TV:	54 MHz—72 MHz Channels 2-4
	76 MHz—88 MHz Channels 5-6
	174 MHz—216 MHz Channels 7-13
UHF 300 MHz—3 GHz	
TV:	470 MHz—806 MHz Channels 14-69
AM-FM SATL:	947 MHz—952 MHz
MDS:	2150 MHz—2162 MHz
ITFS:	2500 MHz—2686 MHz
Auxiliary Services:	2000 MHz—3000 MHz
SHF 3 GHz—30 GHz	
Auxiliary Services:	6.425 GHz—7.125 GHz
CARS:	12.700 GHz—13.250 GHz
TV STL:	17.700 GHz—19.700 GHz

QUANTIFYING PROPAGATION

The energy that is emitted from a transmitter may take many different paths before it is received. The path that the radio wave will take depends on many factors, some of which include: frequency, antenna type and height, atmospheric conditions, and terrain. Radio waves that propagate along the surface of the earth are commonly referred to as ground waves. All radio waves have some ground wave component; however because the earth is a lossy medium, it severely attenuates the radio wave. This attenuation increases with frequency, and so this mode of propagation is useful for only frequencies below 30 MHz. To achieve significant distances the atmosphere is preferred over ground waves as a transmission medium. The atmosphere is comprised of several different layers, as depicted in Fig. 2. The *troposphere* is the layer that extends from the earth's surface up to about 16 km. This layer is the chief mode of propagation for frequencies above about 30 MHz, and propagation through this layer is dependent upon weather conditions. The next layer is the *stratosphere* which extends to about 40 km above the earth. But has no drastic effect on the propagation of radio waves. The *ionosphere* extends upwards of 400 km above the surface of the earth. This region is a charged environment where the air is sufficiently ionized, mainly by the sun's ultraviolet radiation, to reflect or absorb radio waves below about 30 MHz. The ionosphere is constantly changing and is usually considered as consisting of the following sublayers.[2]

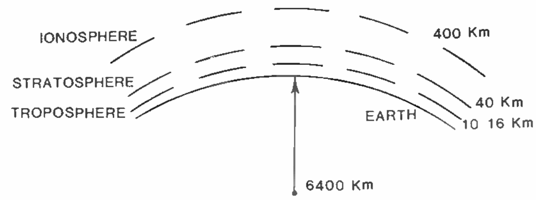


Fig. 2. Atmosphere layers.

- **D layer**—This layer exists at heights from about 50 km to 90 km and is present only during daylight hours. The electron density is directly related to the elevation of the sun. This layer absorbs medium and high frequency radio waves.

- **E layer**—This layer exists at a height of about 110 km and is important in the nighttime propagation of medium frequency radio waves. The ionization of this layer is closely related to the elevation of the sun. At certain times irregular cloud-like areas of high ionization may occur. These areas are known as sporadic E and occasionally prevent frequencies that normally penetrate the E layer from reaching higher layers. [The sporadic E layer is prevalent during the summer and winter months. The sporadic E layer formed during the summer is the longest, lasting from

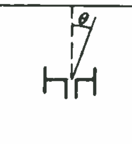
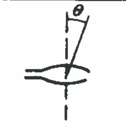
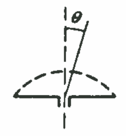
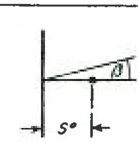
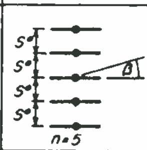
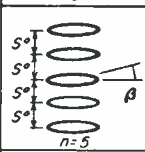
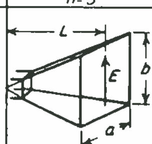
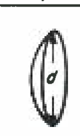
TYPE	CONFIGURATION	PATTERN	POWER GAIN OVER ISOTROPIC	EFFECTIVE AREA
ELECTRIC DOUBLET		$\cos\theta$	1.5	$1.5\frac{\lambda^2}{4\pi}$
MAGNETIC DOUBLET OR LOOP		$\sin\theta$	1.5	$1.5\frac{\lambda^2}{4\pi}$
HALF WAVE DIPOLE		$\frac{\cos(\frac{\pi}{2}\sin\theta)}{\cos\theta}$	1.64	$1.64\frac{\lambda^2}{4\pi}$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

Fig. 3. Patterns, gains, and areas of typical antennas.

May to August, and the winter layer lasts about half as long beginning in December. During the mid-summer months when the electron density is at its greatest levels, TV signals in the lower VHF band can be transmitted over distances of hundreds or thousands of kilometers.[3]

• **F1 layer**—This layer exists at heights of about 175 to 200 km and is present only during the day. Waves that penetrate the E layer (3 to 30 MHz) will be reflected by the F2 layer. The F1 layer introduces additional absorption of these waves.

• **F2 layer**—This layer exists at the upper boundaries of the atmosphere, 250 to 400 km, and is present at all times though the height and electron density will vary from day to night, with the seasons, and over sunspot cycles. During the night the F1 layer merges with the F2 layer at about 300 km. This, in addition to the reduction of the D and E layers, causes nighttime field intensities and noise to be generally higher than during the day.

FREE SPACE PROPAGATION

In beginning the study of the means of how radio waves propagate and how the field strengths may be calculated it is necessary to adopt a simple standard of reference. It is customary to consider as a standard the theoretically calculated loss for waves propagated in free space between two idealized antenna. The simplest case is the radiation emitted from an isotropic source: an ideal antenna which radiates energy with uniform intensity in all directions. An analogy to an isotropic antenna is a point source of light, such as a candle. The intensity of the energy varies proportionally to the inverse of the distance squared from the source, the "inverse square law." The power flux per unit area $P_a(W/m^2)$ at a distance $d(m)$, from a loss-free isotropic antenna radiating a power $P_t(W)$, is given by:

$$P_a = P_t/4\pi d^2 \qquad [1]$$

where $4\pi d^2$ is the surface area of a sphere at a distance d(m) from the source. The power available from a loss free antenna P_r is the product of the power flux per unit area P_a and the effective aperture area of the receiving antenna A_e. This area is related to the gain of the antenna by the expression:

$$A_e = G\lambda^2/4\pi \qquad [2]$$

Aperture areas and gains for specific antennas are given in Fig. 3. For a loss-free isotropic antenna $G = 1$ the basic free space transmission loss is defined as:

$$L_{bf} = P_t/P_r = (4\pi d/\lambda)^{||} \qquad [3]$$

where d and λ are in the same units. This equation can be rewritten in its more common form by solving for the common logarithm of both sides (10 log (P_t/P_r)):

$$L_{bf} = 32.44 + 20 \log F + 20 \log d \ [dB] \qquad [4]$$

where F is the frequency in megahertz (MHz) and d is the distance between antennas in kilometers. In the above equation it should be remembered that ideal loss-free isotropic antennas are considered. In real world systems, antenna gain is a significant factor. The equation that incorporates antenna gains is known as the transmission loss and is defined as:

$$L = L_{bf} - (G_t + G_r + L_d) \ [dB] \qquad [5]$$

where G_t and G_r are the free space antenna gains with respect to isotropic for the transmitting and receiving antenna respectively. The term L_d is the aperture-to-medium coupling loss or polarization coupling between the antennas. The term L_d will have a value of 0 dB when the transmitting and receiving antennas have the same polarization.

In considering the potential service area coverage for a broadcast station, it is usually more desirable to express measurements in terms of field strength rather than transmission loss as previously presented. The root-mean-square (RMS) field strength, E in volts per meter, at a point where the power density of a plane wave is P_a in watts per square meter is given by:

$$E = (120\pi P_a)^{1/2} \qquad [6]$$

where the term 120π is the impedance of free space. The power available from a loss free isotropic antenna is determined from equations [1], [3], and [6] above:

$$E = (480\pi^2 P_r/\lambda^2)^{1/2} \qquad [7]$$

or in logarithmic terms:

$$E = 107.2 + 10 \log P_r + 20 \log F \ [dBu] \qquad [8]$$

The electric field produced by a transmitter radiating a power $P_t(W)$ at a distance $d(m)$ in free space can be derived from [1] and [6] and is given by:

$$E = (30P_t/d^2)^{1/2} \qquad [9]$$

A more useful form of the free space field can be expressed in logarithmic terms above 1 microvolt per meter (dBu) when d is in kilometers, P_t is expressed in decibels above 1 kW (dBK), and a transmitting antenna has a gain G_t in decibels above isotropic:

$$E = 105 + P_t + G_t - 20 \log d \ [dBu] \qquad [10]$$

Using the same units the field strength $E(dBu)$ for non-free space environments can be related to the basic transmission loss by:

$$L_b = 137 + 20 \log F + P_t + G_t - E \ [dB] \qquad [11]$$

These equations form the basis of propagation. They do not, consider such real world factors as the presence of the earth, atmosphere, or obstructions. To describe an actual radio system, additional losses will need to be added to the free space equations derived above.

Propagation over Earth's Surface

When the transmitting and receiving antennas are placed over ground, the propagation of radio waves is modified from the free space models presented above. Radio waves that strike the earth are partially absorbed and partially reflected. Waves that are reflected by the earth experience changes in the phase of the wave which affects the distribution of available energy. The extent to which the waves are reflected or absorbed is dependent upon frequency and the ground constants: conductivity (σ) and permittivity (ε_r) the product of materials relative capacitance and the electric constant of free space.

Propagation Over Plane Earth

The geometry of the idealized situation of propagation between two antennas placed above a plane earth is shown in Fig. 4. This geometry is valid for antennas that are sufficiently close so that the curvature of the earth is not a factor, yet removed from each other enough so that the energy may be described as a plane wave, and ray theory can be applied. The resultant received electric field can be represented as the sum of the direct and reflected rays:

$$E = E_d\ [1r|R|e^{j(\Phi_\Delta + \Phi_r)}] \qquad [12]$$

This equation is valid for small angles of θ. The term E_d is the free space electric field that is produced at a distance d(m), and is known as the direct ray. The terms |R| and Φ_r are the magnitude of the complex reflection coefficient and its phase. This term is dependent upon the nature of the surface, i.e. conductivity (σ) and permittivity (ε_r), the angle between the surface and incident wave, the wavelength of the radio wave, the polarization of the wave, and the curvature of the earth. The magnitude of the reflection coefficient varies between -1 and 1. Several sources have derived the equations for the reflection coefficient and plotted the effects of changing variables, and the reader is referred to these for further study.[3,4] The term Φ_Δ is the phase delay due to the longer path that must be taken by the reflected wave, and has the form of:

$$\Phi_\Delta = 4\pi h_1 h_2/\lambda d \qquad [13]$$

It is usual to assume the ground approximates a large flat surface. In such a case a sufficiently accurate expression is given by Martin Hall in

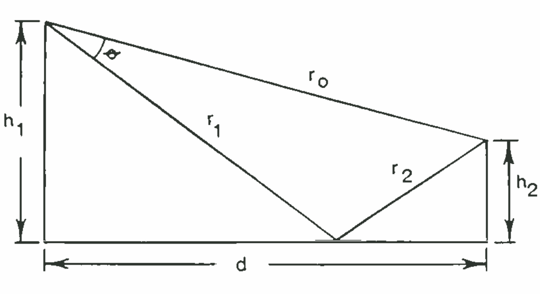


Fig. 4. Path rays for plane earth.

Effects of the Troposphere on Radio Communications.

$$E = 2E_d^{\sin(2\pi h_1 h_2/\lambda d)} \qquad [14]$$

Some cases of special merit that can be derived from equation [14] are:

Case I

$$h_1 h_2 = d\lambda/2 \qquad E = 0$$

When the product of the transmitting and receiving antenna heights equal half the product of the path distance and wavelength the received electric field strength will be completely cancelled.

Case II

$$h_1 h_2 = d\lambda/4 \qquad E = 2E_d$$

When the product of the transmitting and receiving antenna heights equal a quarter of the product of the path distance and wavelength the received electric field strength will be double that which could be achieved from a free space field.

Case III

$$h_1 h_2 = d\lambda/12 \qquad E = E_d$$

When the product of the transmitting and receiving antenna heights equal a twelfth of the product of the path distance and wavelength the received electric field strength will equal the free space field strength.

The above cases assume an ideal plane earth model. In a real world environment undulations in the path between the transmitting and receiving antenna will cause scattering and shadowing of the radio waves. Thus, the above cases will only be approximated in a real world environment. The variation of signal strength due to multipath effects can be minimized in point-to-point applications through the use of antennas with narrow beam widths.

When considering the case of VHF antennas that are close to the ground the effective antenna heights, $h_t(m)$ and $h_r(m)$, will need to be substituted for h_1 and h_2 respectively for [14]. The new antenna heights h_t and h_r allow for the effects caused by the relative permittivity and conductivity of the ground. The effective antenna heights are related to the physical antenna heights above ground level by the work by Martin Hall cited previously.

$$h_t = (h_1^2 + h_o^2)^{1/2} \qquad [15.1]$$
$$h_r = (h_2^2 + h_o^2)^{1/2} \qquad [15.2]$$

the term $h_o(m)$ is dependent upon the type of polarization being considered:

Vertical Polarization

$$h_o = (\lambda/2\pi)[(\varepsilon_r + 1)^2 + (60\lambda\sigma^2)]^{1/4} \qquad [16.1]$$

Horizontal Polarization

$$h_o = (\lambda/2\pi)[(\varepsilon_r - 1)^2 + (60\lambda\sigma^2)]^{-1/4} \qquad [16.2]$$

Table 2 lists values for conductivity and permittivity for various soil conditions. As an example, assume that an antenna is placed 3 meters (9.8 feet) above dry, sandy, flat coastal land ($\sigma = 2 \times 10^{-3}$ S/m, $\varepsilon_r = 10$) and operated at a frequency of 100 MHz ($\lambda = 3$ m). Then, h_o in [16.1] and [16.2] will be 1.59 m and 0.16 m respectively. The effective height of the antenna will then be increased to 3.4 m (11.1 feet) for vertical polarization and will remain unchanged at 3 m (9.8 feet) for horizontal polarization. As the frequency increases above VHF, the wavelength becomes increasingly small and the distinction between true antenna height and effective height is immaterial.

TABLE 2. Ground Conductivity and Dielectric Constants.

Terrain	Conductivity σ (S/m)	Dielectric Constant ε_r (esu)
Sea Water	5	80
Fresh Water	8×10^{-3}	80
Dry Sandy, flat coastal land	8×10^{-3}	10
Marsh, forested flat land	8×10^{-3}	12
Rich agricultural land, low hills	1×10^{-2}	15
Pasture land, medium hills and forest	5×10^{-3}	13
Rocky land, steep hills	2×10^{-3}	10
Mountainous	1×10^{-3}	5
Residential Area	2×10^{-3}	5
Industrial Area	1×10^{-4}	3

MEDIUM FREQUENCY PROPAGATION

Medium frequency (MF) waves lie in the frequency range of 300 kHz to 3 MHz and are characterized by their long wavelengths, 1000 meters to 100 meters. The AM Broadcast band of frequencies is within this range, and the transmitting antenna is frequently located right at the surface of the earth. The typical receiving antenna is also very close to the earth's surface with respect to a wavelength. In this case the direct and ground *reflected* waves are cancelled and transmission is by means of the *ground* wave (also known as the surface wave) as well as by the sky wave.

Ground Waves

These waves are characterized by the fact that the wave is guided along the earth's surface, similar to a transmission line. The field is attenuated in this propagation mode by losses in the ground. Therefore the composition of the soil, ε_r and σ, have a direct bearing on the attenuation of the wave and subsequently the distances for reliable communications. The attenuation is also dependent upon the frequency and polarization. Thus the attenuation factor is a measure of the amount of attenuation present and can be determined for a ground wave using the chart of Fig. 5. The term p is the numerical distance and b is the phase constant. The term x related the conductivity of the soil to the frequency of the radio wave expressed in megahertz. Values for these terms can be calculated from the following equations:[4]

$$p = (\pi d/\lambda x)\cos b \qquad [17.1]$$

$$b = \tan^{-1}[(\varepsilon_r + 1)/x] \qquad [17.2]$$

$$x = 18 \times 10^3 \sigma / F \qquad [17.3]$$

To determine the electric field strength, the attenuation factor must be added to equation [11]:

$$E = E_d\,[1 + Re^{j(\Phi_\Delta + \Phi_r)} + (1 - R)Ae^{j(\Phi_\Delta + \Phi_r)}] \qquad [18]$$

It is interesting to note that the same earth which acts as a conductor at very low frequencies will act as a small loss dielectric at very high frequencies. Note also that the losses for horizontally polarized waves are greater than for vertically polarized waves. Thus, for all practical purposes, vertically polarized waves should be (and normally are) considered for medium frequencies. For more detailed and accurate representations of the effects of ground wave the works of Norton and Jordan should be consulted.[5,4]

Sky Waves

The ground wave provides the major path for medium frequency propagation. Ground waves attenuate rapidly with distance and reliable communications are limited to only a few hundred kilometers. Medium frequency waves are propagated via the ionosphere, are known as sky waves, and can provide sufficient signal strength at distances up to a few thousand kilometers.

The *ionosphere* is a constantly changing environment that begins approximately 65 km (40 miles) above the earth and extends to about 400 km (250 miles). This region of the atmosphere is composed of three major sub-layers D, E, and F. These layers are not present at all times. The D layer, present only during the day, absorbs medium frequency waves. The E layer, above the D layer, reflects medium frequency waves. Thus, during the day, most medium frequency waves are absorbed by the D layer, but at night the D layer is not present allowing the medium fre-

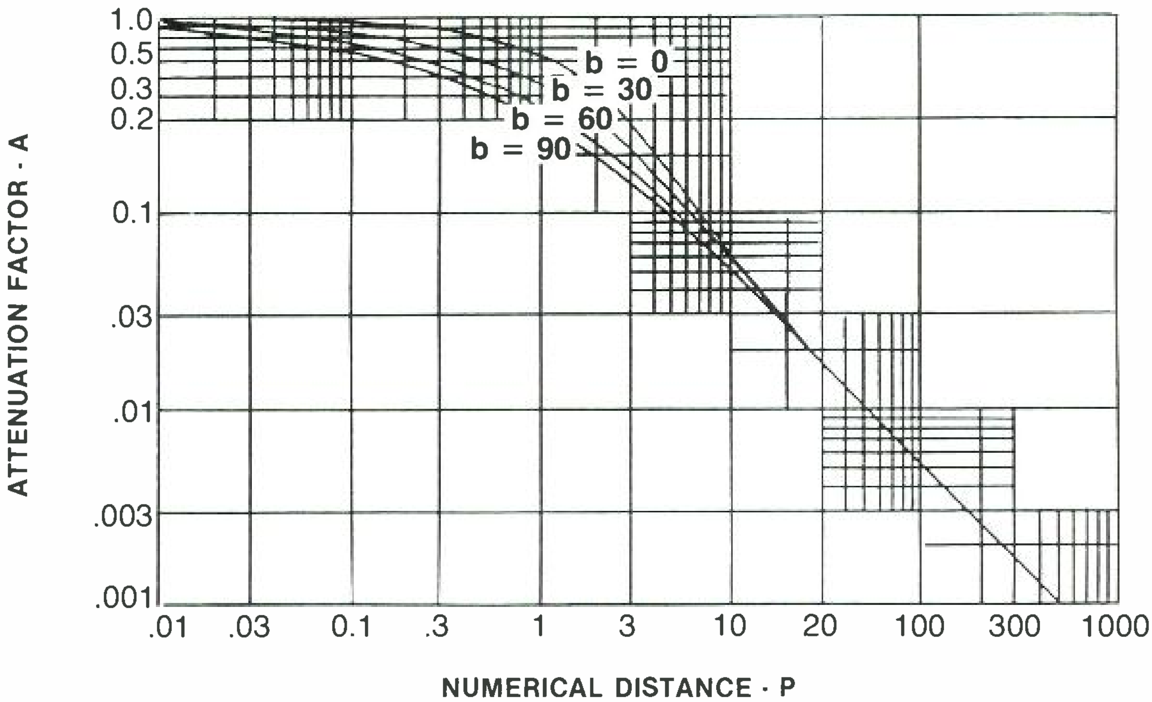


Fig. 5. Attenuation factor of ground waves.

quency waves to be reflected by the E layer permitting long distance transmission.

Interference Between Ground Waves and Sky Waves

Interference can occur from co-channel stations located many kilometers from the desired station, and because of the sky wave sufficient signal strength may be received to interfere with the local station. This effect has been minimized by the FCC by limiting two factors in the operation of some AM stations: the operating power and time of operation. The directional antenna is a selective limitation on operating power. That is, the antenna system is designed and located so as to radiate power toward the population area(s) while reducing radiation in the direction of other stations on the same or adjacent frequencies. For more information see Chapter 2.4 "AM Broadcast Antenna Systems," in this *Handbook*.

Multipath interference occurs when the waves from the same transmitting antenna reach a receiver from different paths in such a manner as to cancel or severely limit each other. The geometry of this is similar to that shown in Fig. 4. The direct ray will be from the ground wave and the reflected sky wave will be from the ionosphere. This effect occurs at those distances where both the ground wave and sky wave will interact. At distances relatively close to the transmitter the ionosphere will not reflect waves back to the earth, so the ground wave is dominant. At distances beyond a few hundred kilometers the sky wave will dominate and the ground wave will be too weak to interfere. Multipath interference can also occur where the sky wave follows two different paths.

Effects of Solar Activity

Interference to medium frequency waves can also be caused by solar activity such as sunspots and flares caused by a reduction or increased emission of radiation from the sun. This in turn causes changes in the ionospheric layers that may result in unusual sky wave patterns called "skip" which can cause inter-station interference. (The effects of such activities as solar storms and high solar flare activity, will have the strongest influence on propagation of the AM band during the first five to ten days after the start of a solar storm. This has the effect of reducing sky wave field strengths. The effect has been observed to increase with increasing frequency at higher frequencies.)[12]

PROPAGATION ABOVE 30 MHz

Smooth Earth Conditions

At frequencies above about 30 MHz the principal propagation mode is the troposphere. The ground surface wave is attenuated too severely

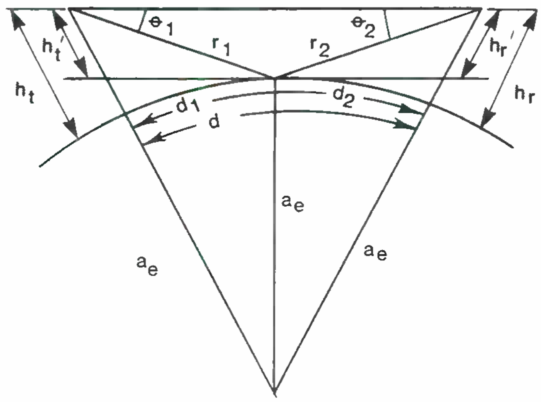


Fig. 6. Reflection from smooth earth on line-of-sight path.

to be of any practical long distance use and, though mildly attenuated, the sky wave is usually passed through the ionosphere to space.

For waves that propagate close to the earth's surface the curvature of the earth will introduce additional effects that must be included in the plane earth model that was considered earlier, Fig. 6 shows the geometry of a smooth earth model. First, the reflection coefficient R of the reflected wave has different characteristics than that of a plane surface. Since the wave is reflected against a curved earth the energy diverges more than that predicted by the inverse square law and the reflection coefficient R, in equation [12], must be multiplied by the divergence factor D, given by[3]

$$D = [1 + 2d_1d_2/2a_e\ (h_t' + h_r')]^{1/2} \quad [19]$$

It should be noted that for smooth earth conditions, the heights h_t', and h_r', for the transmitting and receiving antennas above the plane tangent to the earth at the point of reflection, are less than the antenna heights h_t and h_r, above the surface of the earth.

Under normal propagation conditions the refractive index of the atmosphere decreases with height, so that radio waves near the surface of the earth travel more slowly than at higher altitudes. This variation in velocity as a function of height results in a bending of the radio waves. This may be represented as a modified earth radius or more commonly known as the effective earth radius a_e, which allows the radio waves to be represented as straight lines. The ratio of the effective earth radius to true earth radius is commonly known as the *k factor*. Values of k can vary between about 0.6 to 5.0 depending on the climate of the area between the transmitter and receiver being considered. For temperate climates, the average value of k is 1.33 and most works refer to this as the 4/3's earth model when used in calculation.[2] Additional values of k for the United States can be obtained from the map in section 4.2, page 63 of this *Handbook*.

Beyond Line-of-Sight Conditions

In order to predict when conditions exist to be termed beyond line-of-sight, the distance from the respective transmitter and receiver to the radio horizon must be calculated. The radio horizon is the distance the horizon appears from an antenna, as defined by a plane from the antenna to the tangent of the earth's surface and is depicted in Fig. 7. The equation for the radio horizon in terms of $d_{lt}(km)$ and $h_t(m)$ and the k factor is of the form:

$$d_{lt} = 3.57(h_t k)^{1/2} \quad [20]$$

When the sum of the distances to the radio horizon for the transmitter and receiver is less than the total distance of the path being considered then a beyond line-of-sight condition exists. The amount of attenuation can be determined by "diffraction." This effect makes it possible for radio waves to travel beyond line-of-sight although an additional loss term must be added to the free space loss equations. The geometry of beyond line-of-sight propagation is shown in Fig. 8.

The exact calculation of the field strength at any point beyond the line-of-sight for a smooth earth is rather complex and the presentation of such a method is beyond the intent of this text. However, nomograms have been developed that apply to a large number of cases. For the reader interested in the prediction of the losses to be expected for smooth earth diffraction the National Bureau of Standards publication may be consulted.[8]

Fig. 9 is a nomogram that can be used to determine the loss for beyond line-of-sight that must

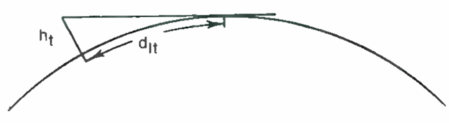


Fig. 7. Distance to radio horizon.

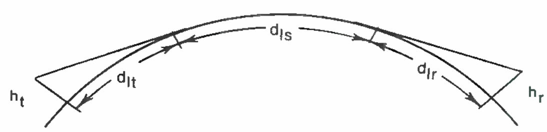


Fig. 8. Beyond line of sight.

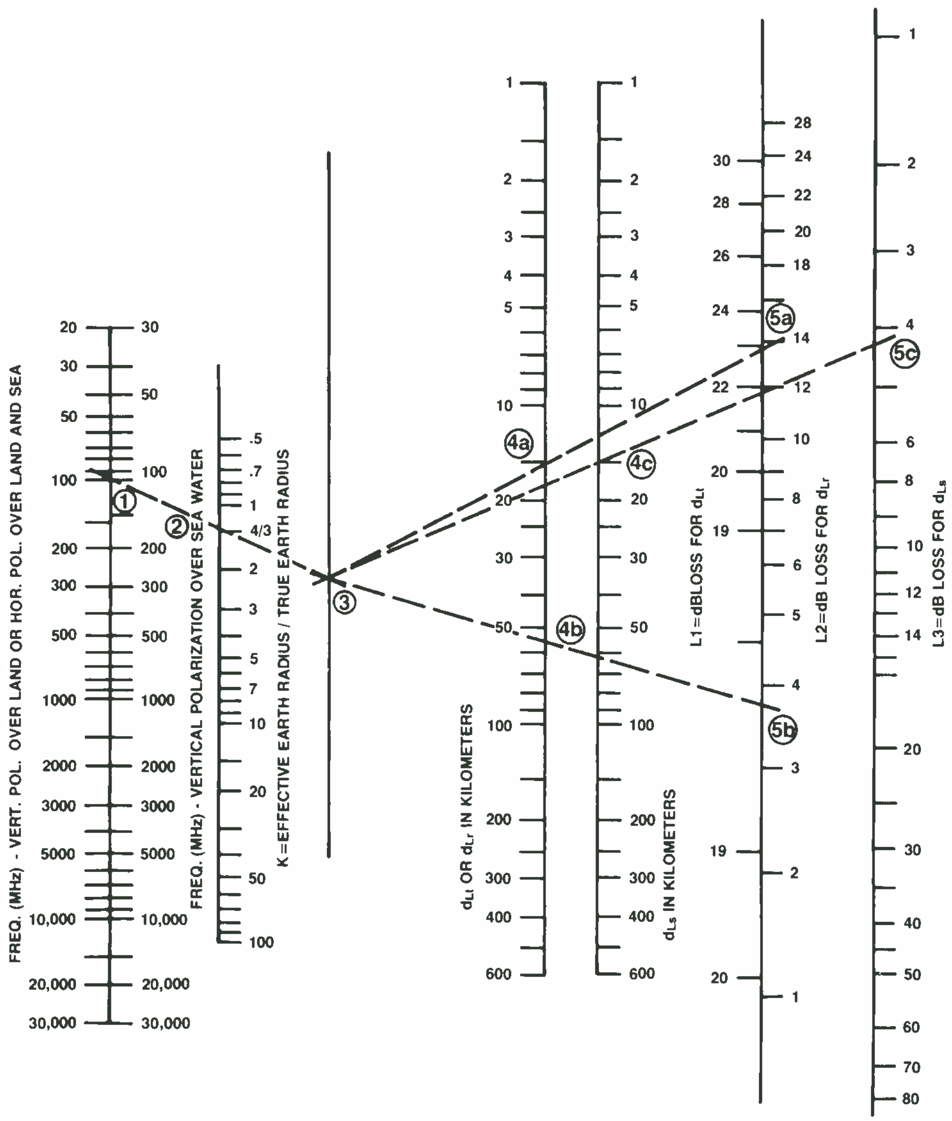


Fig. 9. Diffraction loss over smooth earth.

be added to the free space loss. In order to use the nomogram, the distance d_{lt} must be less than d_{lr}. The total loss L is the sum of the three losses $L1$, $L2$, and $L3$. By way of example assume a system that has the following parameters: h_{lt} = 14 m (45.9 feet); h_{lr} = 178 m (583.8 feet); F = 100 MHz; k = 4/3; total path length of 85 km and the wave is vertically polarized over land. The distances are calculated to be: d_{lt} = 15 km (9.3 miles), d_{lr} = 55 km (34.2 miles) and d_{ls} = 15 km (9.3 miles). The total loss relative to free space is thus $L = L1 + L2 + L3 = 18.5 + 12.0 + 4.3 = 34.8$ dB.[6]

Effects of Obstacles on Propagation

So far only a perfectly smooth sphere has been assumed for earth. The only effect of an atmosphere was accounted for in the *k factor*. These conditions allowed for a relatively simple calculation of the expected field strengths and transmission losses at various points within the line-of-sight and regions beyond the line-of-sight. However, the real world is much less than ideal and the presence of hills, buildings, vegetation as well as the atmosphere have a bearing on the computation of field strengths. The higher the frequency the more the effect buildings and terrain will have on the propagation of the wave between transmitter and receiver. Because these obstacles have a complex effect on the propagation of radio waves, it is extremely difficult to predict the field strength or transmission losses at discrete points close to these obstacles. However, the path under consideration may be quantized by use of elevation profiles: and, through the use of some simplifying assumptions, predictions of the field strength which are more accurate than smooth earth calculations can be performed

Hills

Hills are the single most common form of obstruction that will appear in the path of a radio wave. The distance from the antenna and height of the hill can be determined by constructing a path profile and plotting the terrain features on special graph paper that includes the effect of refraction. The most common charts are defined for a factor of k of 4/3. A typical path is shown in Fig. 10. Terrain elevations necessary to construct a path profile can be obtained from topographical maps of the area, or from computer databases. To obtain the best accuracy, topographical maps the smallest scale available should be used, such as 1:24,000. These maps can be obtained from the United States Geological Survey in Arlington, Virginia 22202 or from any of its branch dealerships. Computer models exist which use a terrain data base that can map the terrain along a propagation path and are available from many sources.

In order to determine when a hill is sufficiently removed from a path to allow free space conditions to exist the Fresnel zone equation can be used. This equation was initially developed to explain the diffraction of light around knife edged obstacles and has since been applied to radio theory. This equation describes a radio path as an ellipsoid with the transmitting and receiving antenna located at the focal points of the ellipse. As Fig. 11 depicts, the curves for various reflection coefficients intersect at 0 dB from free space at a value equivalent to six-tenths of the first Fresnel zone. Thus free space conditions exist when obstacles are outside the $0.6F_1$ zone radius. This distance can be calculated by:

$$h = 0.6F_1 = 328.6(d_1 d_2/Fd)^{1/2} \qquad [21]$$

where the height of the $0.6F_1$ zone is in meters; d_1 is the distance from one antenna to the obstacle in kilometers; d_2 is the distance from the second antenna to the obstacle in kilometers; d is the total path distance in kilometers; and F is the frequency in megahertz. When determining whether a path clears an obstacle such as a hill, additional height should be added to account for any trees that may be present. A typical value for the tree height is 15 meters.

If the hill lies within the calculated Fresnel zone radius then non-free space conditions exist and additional losses will occur. When the frequency is high enough for the hill to appear as a sharp ridge and the transmitter and receiver are distant from the hill, then the loss may be calculated using diffraction from a knife edge, as shown in Fig. 12. The height of the hill H(m) is measured from the line joining the centers of the two antenna to the top of the ridge. The amount of attenuation or shadow loss with respect to free

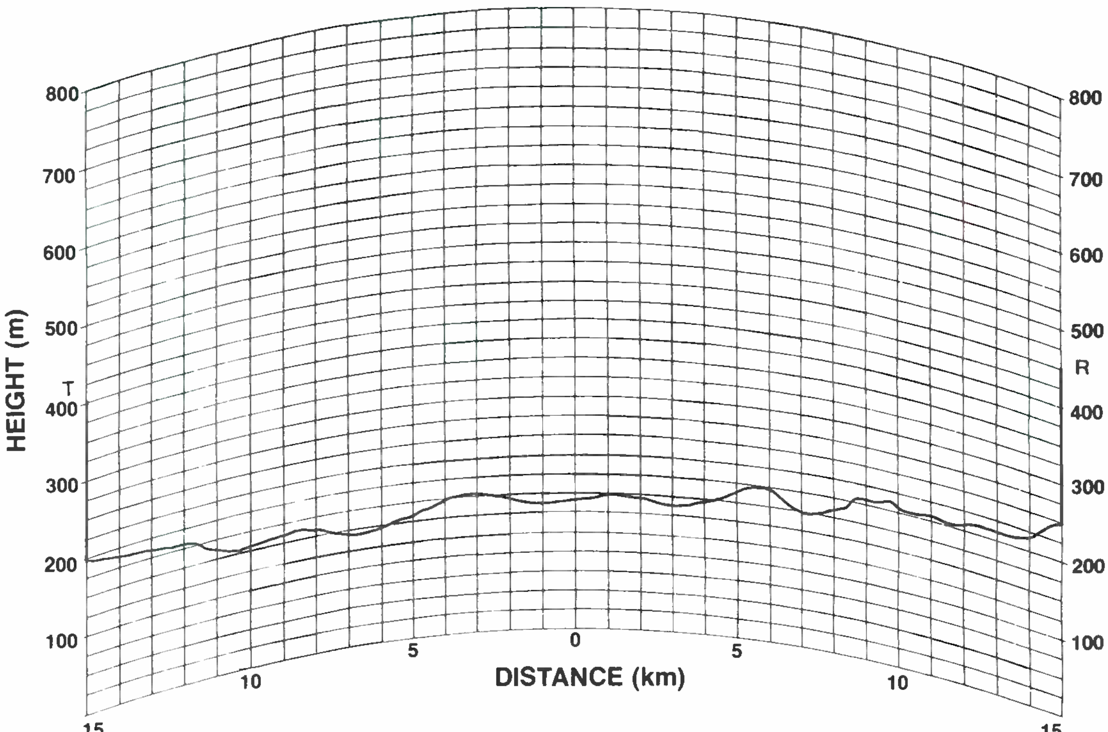


Fig. 10. Typical 4/3 earth path profile.

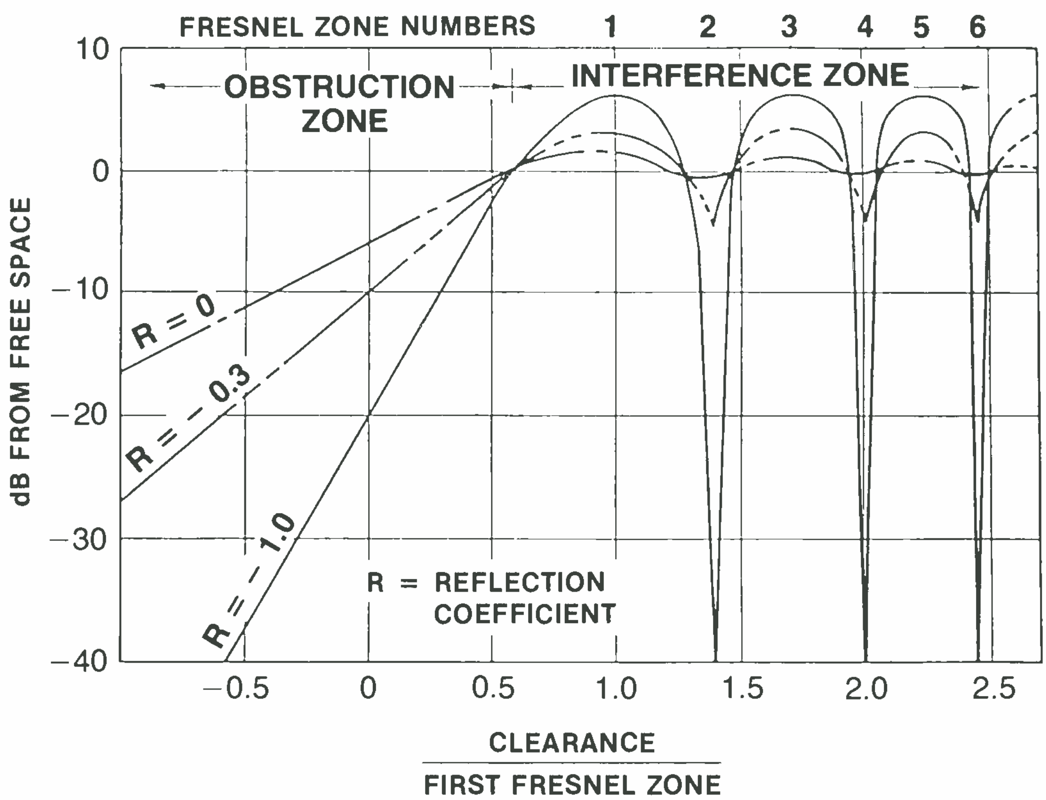


Fig. 11. Effect of path clearance on radio propagation.

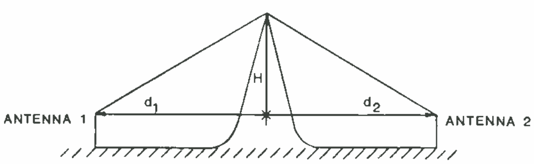


Fig. 12. Ray path for knife edge diffraction.

space may be read from the graph shown in Fig. 13. The value of the v, diffraction parameter, can be calculated, with respect to the distances measured in kilometers and the frequency F(MHz).[3]

$$v = 0.00258H[dF/d_1d_2]^{1/2} \qquad [22]$$

When considering paths that are obstructed by hills that appear rounded rather than knife edged, the attenuation can be calculated using diffraction around a cylindrical surface, as depicted in Fig. 14. This condition will be prominent when the elevation of the hill changes drastically within a wavelength. This can be found when investigating paths at the lower end of the VHF spectrum that pass over older mountain ranges, i.e. Appalachian, Blue Ridge, Catskill.

The amount of attenuation can be found from the chart of Fig. 13. The term p from the chart

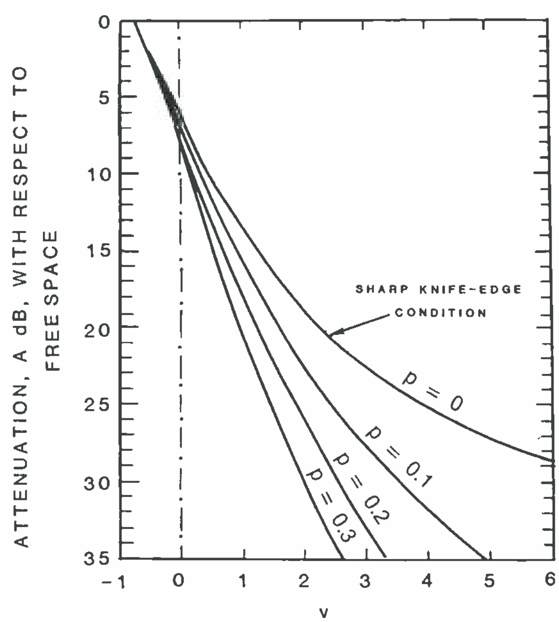


Fig. 13. Attenuation due to various diffraction conditions.

is a dimensionless quantity known as the index of curvature of the cylinder's radius R and is calculated from[3]

$$p = 0.83R^{1/3}\lambda^{1/4}[d/d_1d_2]^{1/2} \quad [23]$$

where all distances are in the same units. For those interested in incorporating the calculation of losses due to diffraction over knife edge and rounded obstacles into digital computers, more exact equations can be found in Rice, et al.[8]

While the method for calculating the loss due to a single obstacle is relatively straight forward, there are times when successive obstacles are present in a radio path as shown in Fig. 15. In order to determine the loss associated with multiple diffraction regions, an approximate method has been developed based on an extension of single edge diffraction. The obstacle which by itself would produce the greatest diffraction loss is determined using the methods discussed above. The summit of this obstacle should be joined to the antenna locations. The additional attenuation caused by the remaining obstacles should be added to the loss of the main obstacle using the heights they are above the lines so drawn, h_a and h_b. It is important to note that even if h_a and h_b are slightly negative, i.e. below the lines, they may still produce a small amount of attenuation due to the Fresnel zone clearance requirements.[3]

Buildings

When planning for radio locations within built-up areas of cities or residential areas, buildings will have an effect on radio propagation. For radio relay stations such as studio-to-transmitter links, it is the normal practice to select sites that will be clear of buildings. However, where this is not feasible and the path geometry is known, i.e. height and location of buildings, then the diffraction methods discussed for hills may be applied. In planning for broadcast systems it is not practical to relate attenuation measurements made in built-up areas to the particular geometry of buildings. Therefore, it is more conventional to treat the losses in a statistical manner dividing the general classifications of building types into loss groups, so that a loss can be derived for a particular type of building, i.e. multistory structures made of concrete and steel versus single story residential buildings made of wood.

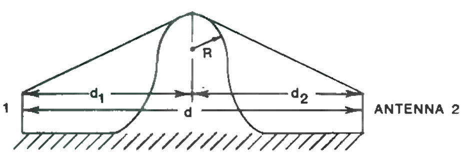


Fig. 14. Diffraction due to cylinder.

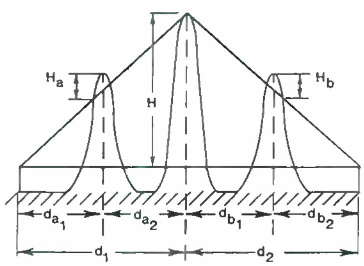


Fig. 15. Multiple knife edge diffraction.

Within built-up areas there is much more back scatter than in open country. Additionally, due to the fact that buildings are more transparent to radio waves than the earth, there tends to be less shadow loss caused by buildings. However, the angles of diffraction due to buildings are usually much greater than in open country for natural terrain and thus the loss resulting from the presence of buildings tends to increase. Measurements indicate that at 100 MHz the median field strengths are 4 to 6 dB below that expected for a plane earth and up to 10 dB for 200 MHz. These measurements were made in areas comprising of some large buildings and open areas, but were mainly residential areas. Some recent measurements conducted in the 850 MHz band indicate values of 20 to 34 dB below that expected for free space for path distances of from 1 km to 25 km.[9]

Vegetation

Among the many factors that have an effect on the determination of the losses present in a propagation path, effects of vegetation are sometimes the most overlooked. Depending on the type of terrain in consideration, i.e. open or forest, the effect of vegetation can add several dB loss to the system. The amount of attenuation present is dependent upon the frequency and polarization of the wave, see Fig. 16. For example, the attenuation for a horizontally polarized wave for frequencies below about 1000 MHz is much less than that for a vertically polarized wave. At around 1000 MHz trees that are thick enough to block the field of vision can be modeled as an obstruction and the attenuation over or around these obstructions can be predicted from knife edge diffraction methods.

The effect of vegetation on a radio path varies seasonally in the case of deciduous trees. During the winter months the losses due to shadowing and absorption are less than those during the spring and summer. It is interesting to note that the greatest losses will occur during the spring since new growth has more sap and moisture content which increases the absorption losses. When the antenna is raised above trees and other vegetation, the prediction of field strengths depend upon the estimation of the height of the antenna above areas of reflection and the reflection coefficients.

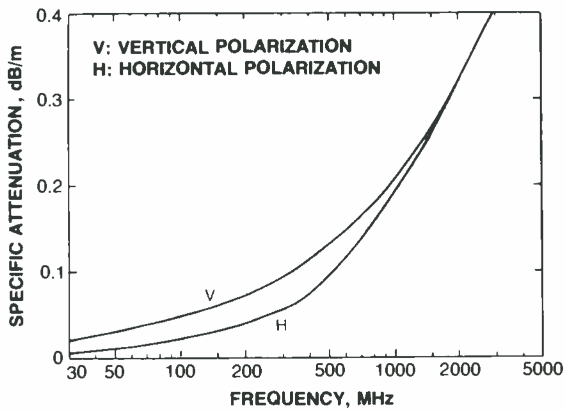


Fig. 16. Attenuation through woodland.

Atmospheric Refraction

The refractive index of air is approximately one. It is dependent upon the dielectric constant, and can vary depending on the pressure and temperature of the air and on the amount of water vapor present. Therefore, the refractive index of the atmosphere can change with weather conditions and with the height above the earth. The velocity of radio waves is dependent on the refractive index of the atmosphere. As a general rule the velocity of a radio wave is slower at the earth's surface than at higher altitudes. So, a horizontally polarized wave will be refracted back towards the earth, though unusual atmospheric conditions may change this. Because there are numerous constantly changing variables involved in the prediction of field strengths due to atmospheric conditions some simplifying assumptions are generally needed to obtain a solution under known meteorological conditions.

The refractive index *(n)* of the atmosphere has a value near unity (typically 1.00035). Changes of only a few parts per million of the refractive index can have dramatic effects on radio waves, therefore it is usually more convenient to refer to the refractive index in terms of the refractivity n:

$$N = (n-1)\times 10^6 \qquad [24]$$

and the typical value would then be $n = 350$.

Ducting

Under meteorological conditions where the refractive index decreases rapidly with height over a large horizontal distance, radio waves can become trapped and experience low loss propagation over long distances. This phenomena is known as ducting. Although ducting is frequent at some locations and under certain meteorological conditions, due to its randomness and the inability to predict range, it is not a reliable mode for communications. However, due to the strong fields ducting can cause beyond the horizon, co-channel interference can result. In addition, line-of-sight paths may be affected by severe fading caused by ducting.

In order for atmospheric ducts to occur two conditions must exist. First, the refractive index gradient must be equal to or more negative than -157 N/km. The refractive index gradient is a measure of the change of the refractivity across a vertical height h, dN/dh. When this condition is present, the radio waves will remain close to the earth's surface beyond the normal horizon. Secondly, the refractive index gradient must be maintained over a height of many wavelengths. The duct may be thought of as similar to a transmission line waveguide. Unlike metallic waveguides, natural ducts do not have sharp boundaries, although there is a wavelength cut-off above which waves will not propagate. Since the duct does not have sharp boundaries, the thickness (t) will not be rigid. The cut-off wavelength λ therefore, will not be rigid, but an estimate can be obtained from.[3]

$$\lambda = 2.5\text{X}10^{-3}\left(\frac{\delta N}{t} - 0.157\right)^{1/2} t^{2/3} \qquad [25]$$

where the wavelength and thickness are in meters. The term δN is the refractive index change across the duct. As an example, a duct near the ground that is 25 meters thick and has a refractive index change of 10 N, i.e. -400 N/km, (-10/0.025 km) will have a cut-off wavelength of 0.15 m (2 GHz). However, a duct with the same refractive index gradient will have to about 87 meters thick to propagate a wavelength of 1 meter (300 MHz).

A duct spreads the energy within it in the horizontal direction, but is constrained in the vertical direction as the distance from the transmitter is increased. Thus, in principle, it is possible for the field strength within a duct to be greater than the free space field at the same distance. However, a duct will 'leak', or allow energy to escape at the boundary, adding to the transmission losses so that field strengths are seldom greater than free space values.[3]

Radio waves that leave the transmitting antenna at an angle greater than a certain vertical angle, the critical angle, will not become trapped in a duct. These radio waves will propagate through the duct, though they will experience some bending due to the change in the index of refraction at the duct's boundaries. There are typically two types of ducts: ground based and elevated. A ground based duct, as its name implies, forms close to the earth's surface. Energy is propagated in this duct by being refracted back to the earth, then reflected off the earth, then refracted again, see Fig. 17A. An elevated duct forms above the earth's surface and is generally very short lived.

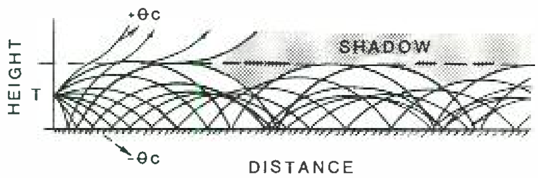


Fig. 17A. Ray propagation in a ground based duct.

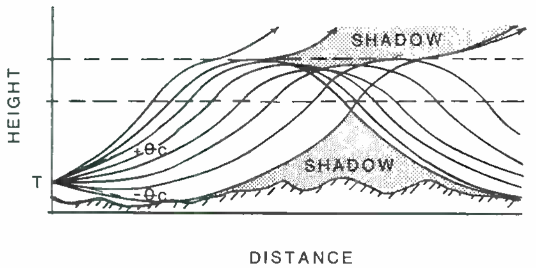


Fig. 17B. Ray propagation in an elevated duct.

Energy in this duct is refracted back and forth between boundaries without coming in contact with the earth, see Fig. 17B.

Shadow regions are formed along a duct where, due to the nature of the duct, radio waves are not present. Receiving antennas placed in such a region will experience a loss of signal. Fig. 17A and B shows these regions can not only form above the earth's surface, as in a ground based duct, but can also form along the earth's surface in the case of an elevated duct. Therefore, a shadow region that can result in loss of communications can form at a receiver that is located relatively close to the transmitter.

Rain Attenuation and Absorption

The use of radio systems using frequencies above 1 GHz adds another loss that must be accounted for when planning the system. Inadequately engineered systems, such as relay and STL links, may experience outages during periods of heavy rainfall. The amount of attenuation due to rain is dependent upon three factors: 1) the rate the rain is falling, 2) the frequency of the wave, and 3) the length of the rain cell through which the wave must propagate. For adequate planning purposes, if the path length is only several kilometers, the length of a rain cell may be approximated by the total path distance. The average rainfall rate varies from one section of the country to another section, however typical rainfall amounts are shown in Table 3. The specific attenuation γ_r is given by *Transmission Loss Predictions for Tropospheric Communications Circuits*, by Rice, Longley, Norton and Barsis.

$$\gamma_r = KR_r^{\alpha} \ [dB/km] \qquad [26]$$

TABLE 3. Rainfall Amounts.

Characteristics	Rate
Drizzle	0.25 mm/hr
Light Rain	1.00 mm/hr
Moderate Rain	4.00 mm/hr
Heavy Rain	16.00 mm/hr
Very Heavy Rain	100.00 mm/hr

where R_r is the rainfall rate in millimeters per hour, and the terms K and α are found from material cited previously.

$$k = [3(F-2)^2 - 2(F-2)] \times 10^{-4} \qquad [27.1]$$

$$\alpha = [1.14-0.07(F-2)^{1/3}]\ [1+0.085(F-3.5)e^{(-0.0066F^2)}] \qquad [27.2]$$

where F is the frequency in GHz. These equations give a good approximation to attenuation curves published by the CCIR for frequencies below 50 GHz.[13] As an example assume F = 12 GHz and a rainfall rate (R_r) of 16 mm/hr. The terms K and α will them be: K = 0.0280 and $\alpha = 1.2655$, yielding a specific attenuation (γ_r) of 0.9353 dB/km.

In addition to rain, radio wave absorption can also occur from water vapor and oxygen that is present in the air. The attenuation is less than that for rain and usually can be neglected below 20 GHz. However, at higher frequencies, attenuation due to absorption losses can become significant.[8]

COVERAGE AREAS

Engineering a radio or television broadcast station using the methods presented previously is far too cumbersome to be of any practical use in determining the service area of the station. While radio waves actually behave in the manner described in the previous sections, it is too complicated to calculate the signal at every point surrounding a station. Therefore other quantitative methods are needed to quickly and reliably determine field strengths. Considerable work has been conducted in this area and is still being carried out.

The received field strengths are subject to several natural and man-made phenomena described earlier which can cause the field strengths to vary over periods of time and from one location to another. These changes can be long term such as seasonal changes, i.e. weather, temperature, and foliage, or short term changes such as weather disturbances, i.e. storms and fronts, and vehicles passing in front of the receiver. These variations have an effect on radio systems that is difficult to account for when determining service areas. Thus, it is appropriate to describe the field strength by statistical means: the percentage of locations that will receive a particular field strength for some percentage of time. By describing field variations in this manner it is possible to arrive quickly at a satisfactory determination of the service area of a station. However, the general terrain in the area still must be considered. In preparing propagation curves, this is accomplished by incorporating a terrain roughness factor Δh. The terrain roughness factor is a generalization of the local terrain and is defined as the difference in elevation between the levels exceeded for 10 and 90 percent of the terrain along a path. The average value of h for the United States is 50 meters.[10] In using the propagation curves found in the FCC Rules and Regulations for FM and television stations the local terrain is accounted for by determining the height of the antenna above average terrain along a radial.[11]

To simplify field strength prediction, curves have been developed to determine the service area of a station. These curves are generally developed using measured values taken from different geographical areas over certain periods of time. The median values are incorporated into a family of curves that describe the field strengths for various antenna heights, frequencies, and distances. A detailed discussion of how to perform field strength measurements may be found in Chapter 2.7, "FM and TV Field Strength Measurements" and Chapter 2.8, "AM Field Strength Measurements and Directional Antenna Proof" of this *Handbook*. The FCC curves for FM and television broadcast stations were derived in this manner. The curves used by the FCC for FM and TV describe the field strengths for service at 50 percent of the locations for 50 percent of the time. These curves are referred to as F(50,50) and are based on an effective power of 1 kW radiated from a half wave dipole in free space. The F(50,10) curves used by the FCC describe the field strength for 50 percent of the locations for 10 percent of the time. These curves can be used to estimate the service provided by FM and television stations.

Through the use of a computer, field strength estimates can be made quickly permitting designers to try more options and see the effect on the service area. The designer can change transmitter locations, power levels and tower heights to optimize the station. Computer methods rely on terrain databases and user supplied technical information of the station, i.e. frequency, power, location, and height, to derive the service contours.

REFERENCES

1. *IEEE Standard Directory of Electrical and Electronic Terms*, ANSI/IEEE Std 100-1977, Wiley-Interscience.
2. Reference Data For Radio Engineers, 6th ed., Howard W. Sams & Co., 1982.
3. Hall, Martin. *Effects of the Troposphere on Radio Communications*, Peter Peregrinus Ltd. New York, 1979.
4. Jordan, Edward C. *Electromagnetic Waves and Radiating Systems*, (Englewood Cliffs: Prentice-Hall, Inc., 1950), pp. 608–688.
5. Norton, K.A. "Ground Wave Intensity Over a Finitely Conducting Spherical Earth," *Proceedings of the IRE*, December, 1941, p. 623.
6. Bullington, K. "Radio Propagation Variation at VHF and UHF," *Proceedings of the IRE*, January 1950, p. 27.
7. "Wave Propagation," *The ARRL Antenna Book*, 14th ed., 1982, American Radio Relay League pp. 1–19.
8. Rice, Longley, Norton, and Barsis. "Transmission Loss Predictions for Tropospheric Communication Circuits," *National Bureau of Standards Technical Note 101* (Rev.)
9. Okumura, "Field Strength and its Variability in VHF and UHF Land-Mobile Radio Service," *Review of the Electrical Communication Laboratory Volume 16,* (Tokyo) 1968, pp. 825–873.
10. Damelin, Daniel, Fine, and Waldo. "Development of VHF and UHF Propagation Curves for TV and FM Broadcasting," *FCC Report No. R-6602.*
11. Federal Communications Commission, Rules and Regulations, Section 73. See most recent edition.
12. Wang, John C.H. "A Skywave Propagation Study in Preparation for the 1605–1705 kHz Broadcasting Conference," *IEEE Transactions on Broadcasting*, vol. BC-31, March 1985, pp. 10–17.
13. "Attenuation and Scattering by Rain and Other Atmospheric Particles," *CCIR Report 721*, Vol. V.

2.10

Radio and TV RF Systems

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INTRODUCTION

In this chapter, several methods of connecting the output of the transmitter(s) to the external transmission line system, utilizing either coaxial transmission line or waveguide, will be presented. Various components ranging from the simple patch panels, that have been in existence for quite some time, to the recently developed "switchless" combiner-routing systems will be discussed as to their operation and implementation into the transmitter system. Filters and filter networks, such as diplexers and multistage multiplexers, will also be covered.

SWITCHING

Every transmitter installation requires some type of switching in the transmission line system. The amount of switching utilized will depend on the individual needs of the station. It can be as simple as a 3-port patch panel to connect the output of the transmitter to the station load, or as complex as a multiple transmitter-antenna installation.

Patch Panels

Patch panels provide a convenient method of rerouting the interconnecting transmission lines between various inputs and outputs in the transmitter plant. Since they are manual devices and cannot be changed very rapidly, their use is limited to maintenance type functions or as a secondary source of switching.

Coaxial Patch Panels

Coaxial patch panels can be configured in any number of ports, however the more common are 3,4, and 7-ports. They consist of the appropriate number of quick disconnect connectors mounted on a panel, and interconnecting transmission lines, usually in the form of "U-links". The connectors are spaced such that the "U-link" may be utilized to interconnect any two adjacent connectors. For example: the connectors of a 3-port patch panel would form an equilateral triangle (all sides equal and all angles are 60 degrees).

Interlock switches are utilized to prevent transmitter power from being applied until the "U-links" are in the proper positions and properly seated. Power handling capabilities of the patch panels are essentially the same as the mating transmission line.

Waveguide Patch Panels

Waveguide patch panels are utilized much the same way as their coaxial counterparts. However, since waveguide is larger, and most transmitter installations use rectangular waveguide inside the transmitter building, the patch panels aren't quite as versatile. Generally, the waveguide patch panel is only available as a 3-port unit.

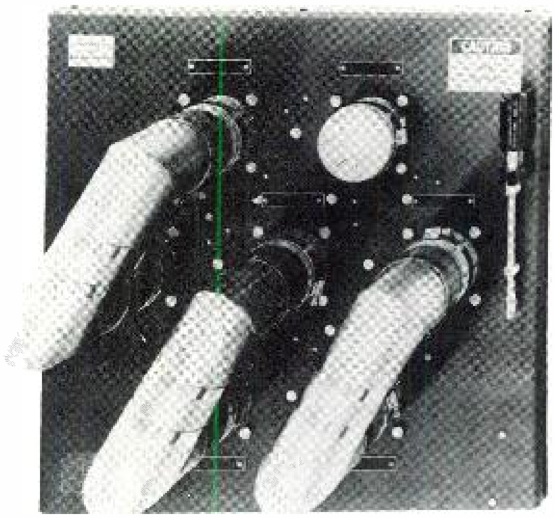


Fig. 1. 7-port coaxial patch panel.

Fig. 2. 3-port "E" plane waveguide patch panel.

Since the waveguide is rectangular, the ports need to be oriented in a straight line in either the broad wall or narrow wall plane. Fig. 2 illustrates a 3-port E plane patch panel.

Manual Coaxial Switches

Manual coaxial switches are generally available in either single pole double throw (spst) or 4-port transfer type configurations. They have two distinct advantages over the manual patch panels, which are ease of operation and speed of switching.

Most manual coaxial switches have either a lever or knob that is turned to change positions of the switch, which can be accomplished in a few seconds as compared to minutes for the manual patch panel. Like the patch panels, the manual coaxial switch is equipped with interlock switches for turning off the transmitters during switching.

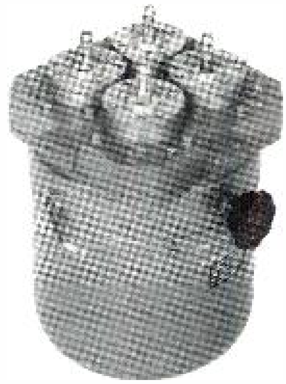


Fig. 3. Coaxial rotary switch.

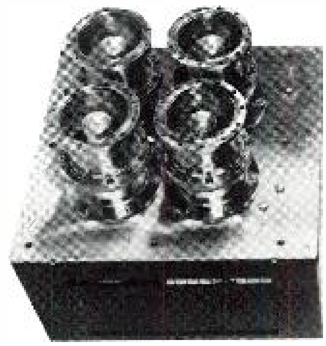


Fig. 4. High power coaxial switch.

Power ratings of the coaxial switches are approximately 80% of the equivalent coaxial transmission line. Since they are more complicated to build, they cost more than a patch panel. In order to get the same functions of a 7-port patch panel, several switches will be required as they are only available in 3-port spot and 4-port transfer configurations.

Motorized Coaxial Switches

Generally, the motorized coaxial switches will be very similar to the manual type switches. To reduce production costs, a lot of the parts will be the same.

Usually, the RF portion of the switch will be the same for either the manual or the motorized switch. The manual drive is replaced with a motor drive assembly. The motor drive system requires some type of control system to start and stop the motor in the switching sequence.

Most motorized switches will offer a choice of motor voltages, with 115 vac being the more common, and various control circuit voltages. A small control relay is provided to isolate the switch from the control circuits of the transmitter system. Generally, both sides of the control relays are available in the electrical connector. Therefore, the user must supply a source to energize the control relay.

Rotary type motorized coaxial switches are available in 1 5/8″, 3 1/8″, 4 1/16″, and 6 1/8″. These switches will switch positions in approximately 2 seconds. Their frequency range is good up through the high band TV frequencies. Some of the larger switches are limited in their use at the UHF range because of possible moding problems. The power ratings of most of the types of switches is limited to approximately 80% of the comparable transmission line.

For use at higher power levels and higher frequencies, another type of switch was developed. This is a motorized "U-link" type of switch. Its power ratings are essentially the same as the comparable transmission line and its problems at the higher frequencies have been greatly reduced. Sizes of 3 1/8″, 4 1/16″, 6 1/8″, 8 3/16″, and 9 3/16″ are available. Because of the mass of the moving parts of the larger switches, the switching time is increased to approximately 10 seconds or less. A switch of this style is shown in Fig. 4.

Open Wire Switches

Open wire switches can be utilized in lower frequency applications, such as the AM and short wave bands. These switches often resemble high power relays or contactors. The major differences would be the type of dielectric material and the proximity of the contacts. An open wire RF contactor is shown in Fig. 5. The configuration shown is a 30 ampere unit, that would handle 10 kW. It is a double pole-double throw type ZZ relay, which allows several configurations including a transfer type switch. Various types and sizes are available for use from a few watts to several hundred kilowatts.

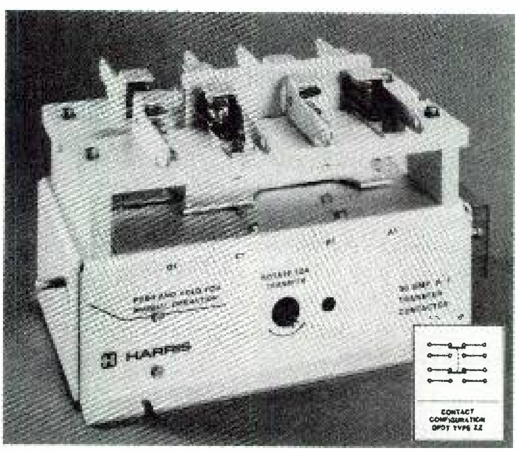


Fig. 5. RF contactor for AM & short wave applications. (Courtesy Harris Corp.)

Waveguide Switches

Waveguide switches are available in 3, 4, and 5-port versions, both manual and motorized. The RF sections of the manual and motorized switches are usually the same. Manual units will have a knob or handle to change the positions of the switch. Motorized units have the manual drive replaced with a motor drive assembly. Some type of motor control circuits will also be required.

The 4-port transfer switch shown in Fig. 6, is an E-plane type of switch. Both E-plane and H-plane units are available. The 4-port units usually take the form of crossed waveguide, with the ports 90 degrees apart. Within the switch is a metal back plate that has fingerstock around the four sides, which contact the waveguide case. The back plate is positioned at a 45 degree angle to the ports of the switch. Thus, two ports of the switch will be connected together in the form of an elbow. In one position, the top port will be connected to the right hand port, while the bottom port is connected to the left hand port. In the other position the opposite is true.

The control circuits of the waveguide switch are very similar to the ones utilized in the coaxial switches. Various motor and control voltages are available. The waveguide switch will be equipped with some type of interlock switches to turn off the transmitters during the switching process.

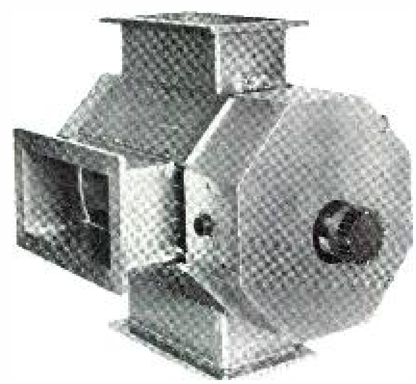


Fig. 6. 4-port motorized waveguide switch.

FILTERS

Filters are used in broadcasting to limit the undesirable emissions of transmitters. More specifically it is necessary to limit the harmonic content of transmitters to prevent interference at higher frequencies with other services. In addition it is also necessary to limit the intrusion of other RF signals into the final stage of transmitters as a result of antenna coupling.

The FCC addresses these requirements in Volume III, subpart B, section 73.317, paragraph 14 for the FM broadcaster by stating that "Any emissions appearing on a frequency removed from the carrier by more than 600 kHz shall be attenuated by 43 dB + 10 log (power) dB below the level of the unmodulated carrier or 80 dB, whichever is the lesser attenuation." If a broadcaster is operating above 5 kW the 80 dB requirement applies. For comparison, a broadcaster operating at 100 watts would be required to meet a 63 dB requirement under these rules.

The TV requirement is addressed in Volume III subpart D section 73.687 paragraph i,1. It, in part, states "...all emissions removed in frequency in excess of 3 MHz above or below the respective channel edge shall be attenuated no less than 60 dB." It goes on to say that this requirement should be considered temporary and that the state of the art might be the more appropriate limit and broadcasters are encouraged to seek this limit in order to meet future rulemaking requirements.

Harmonic Filters

Harmonic filters are commonly used on the output of all transmitters used for broadcast applications. They can be built in coax or waveguide. The decision to use one form over the other is a matter of convenience (i.e. size), performance and cost.

The coax form is used in the lower portions of the broadcast spectrum namely VHF, FM and portions of UHF bands. For low band VHF and FM where the maximum ERP is limited to 100 kW, coaxial harmonic filters are used since the common EIA line sizes from 3-1/8 to 6-1/8 inch coax can handle the power levels without degradation due to higher order modes. Waveguide would have to be in excess of 60 inches wide to operate in the fundamental mode at these frequencies.

Harmonic filters will pass the fundamental frequency with efficiencies of about 98% or—.1 dB insertion loss. They will reject the second through the fifth harmonic (i.e. frequencies 2 times through 5 times the fundamental) with attenuation of -40 to -50 dB. This limits the passage of these harmonic frequencies to 1/10000 to 1/100000 of the harmonic power level before filtering. By virtue of their function of attenuating harmonics they are of necessity designed to handle a limited segment of the band containing less than an octave. Table 1 lists the typical way in which the band is divided.

The skirt of the attenuation curve must have a slope sufficiently large to pass the highest fundamental frequency and reject the lowest frequency in the 2nd Harmonic. A filter with nine to eleven stages will normally provide 40 to 50 dB rejection at the low end of the 2nd harmonic.

Table 1

Channel	Fundamental	2nd Harmonic	Typical Construction
2-3	54- 66 MHz	108-132 MHz	Coax
4-6	66- 88 MHz	132-176 MHz	Coax
FM	88-108 MHz	176-216 MHz	Coax
7-13	174-216 MHz	348-432 MHz	Coax
14-43	470-650 MHz	940-1300 MHz	Coax
44-52	650-698 MHz	1300-1396 MHz	Coax or Waveguide
52-69	698-806 MHz	1396-1612 MHz	Waveguide

The waveguide form of the harmonic filter is usually utilized at frequencies on the high end of the UHF band. This is necessary for a combination of reasons. Larger coax sizes will support the generation of higher order modes near the high end of the frequency spectrum for UHF TV. Higher order modes will be sustained at a frequency where the:

$$\text{Wavelength} = \pi\,(a+b)$$

where a and b are the radii of inner and outer. Larger coax sizes are also needed to handle the power levels authorized in the UHF band. 8-3/16—75 ohm line will support higher order modes at frequencies just above channel 56 and 9-3/16—75 ohm at frequencies just above channel 40. But the construction of a coax filter is a cascade of larger and smaller diameter inner conductors. The larger inners essentially cause the moding to occur at larger wavelengths or lower frequencies. This phenomenon lowers the effective frequency at which coax filters can be used.

The waveguide filter must therefore be used for channels above 40 when transmission line power levels exceed the rating of 6-1/8 coax. One example of the solution in waveguide is commonly called a waffle iron filter because the broad walls of the waveguide appear as the top and bottom plate in a waffle iron. A waffle iron harmonic filter in WR 1150 waveguide can be utilized for all those channels between 40 and 69.

Usually harmonic filters of appropriate type are supplied with the transmitter since the transmitters cannot meet FCC rules with regard to harmonic content without a harmonic filter. The broadcaster will seldom find the need to acquire a harmonic filter unless he has experienced a severe transmission line failure or acquired a used transmitter.

Band Pass and Band Stop Filters

Band pass filters are used sometimes in combination with band stop filters to control another class of spurious emission problems. The transmitter with its harmonic filter is capable in the absence of other RF signals of producing transmissions which are free of any spurious emissions. Potential problems arise however when two or more broadcast channels are located very close to one another physically.

Assume, for the sake of illustration, that Channel A consists of an entire system (i.e. transmitter, transmission line and antenna). Assume, also, that Channel B is similarly constructed and that both antennae are on the same tower. This is a common scenario in today's broadcast site. Each antenna in addition to transmitting its primary signal is also capable of receiving. Therefore, Channel A is capable of receiving some of Channel B's signal. The magnitude of this received signal is dependent on the gain and bandwidth of Antenna A at the frequency of Channel B as well as the distance between the two antennas. Several spurious signals can be generated in Transmitter A and transmitted on the air as a result of the presence of RF from Channel B. The transmitter will usually, because of its limited bandwidth, provide several dB turn-around loss for this spur. The most troublesome spur will occur at a frequency which is

$$F = 2A\text{-}B$$

A comparable problem could occur in transmitter B where

$$F = 2B\text{-}A$$

The magnitude of the spur will be equal to the power level of the coupled signal minus the turnaround loss. So, if Channel B is present in Channel A's transmission line at a level of -40 dB down from Channel A's power level and transmitter A provides -10 dB turn-around loss, then a spur will likely exist at $(F = 2A\text{-}B)$ with an amplitude of -50 dB from Channel A's amplitude. In order to bring this situation into compliance with FCC rules at FM, for example, a filter would have to be installed in Channel A's transmission line which would pass Channel A with a minimum insertion loss (usually—.15 dB) and provide -30 dB rejection at Channel B. This would lower the spur level to -80 dB below Channel A's transmission line level.

The broadcaster must first determine if such a problem exists. This can be done by inserting a dual directional coupler in Channel A's transmission line. Then connect a spectrum analyzer through a suitable attenuator and monitor the system to determine the presence of any undesirable RF signal. Check the reflected power coupler to detect incoming signals and the forward coupler for any resulting spurious emissions. If spurs are detected in the forward coupler at levels higher than the -80 dB level the reverse measurements can be used to determine the offending source.

The decision to use band pass versus band stop filters should be based on the nature and extent of the problem. Each has virtues and limitations which make them suitable for certain problems.

The typical response curves for several combinations are presented in Fig. 7 through 10. The band stop as depicted in Fig. 7 is characterized by rapidly rising skirts which make these filters particularly suited to rejecting frequencies that are extremely close to the desired frequency (i.e. frequencies displaced by as little as .8%). However, due to their sharp response they are more prone to drifting with temperature than the band pass configuration if not properly designed. It must be emphasized that they can be built so that drifting does not affect their desired performance. But, manufacturers must design to minimize this tendency. Band stop cavities are commonly used in the FM band. They are also used in VHF or UHF diplexers but not to protect one TV channel from another since their band stop widths are generally too narrow to reject an entire TV channel.

The band pass response is depicted in Fig. 8 and 9. The skirts of these filters rise much more slowly than the reject curves. They rise at 6 dB per octave per stage. Again using the FM band for comparison at 100 MHz with a usable bandwidth of .3%, the reject will rise to -30 dB when displaced from the pass band by approximately 3% for a 2 stage, and by 1.5% for a 3 stage filter. This suggests that more stages will be needed in band pass to obtain the same attenuation as a band stop cavity. The band pass, however, has some advantages; since the pass band is broad it is not affected by drifting due to temperature changes. The reject curves are also symmetrically located about the pass band. The formula for determining the location of the spur

$$F = 2A\text{-}B$$

will always place the spur at exactly the same distance, frequency wise from the pass but on the opposite side of the pass band. So the band pass is attenuating the incoming RF on one side and the resulting spur on the other side of the pass band. It also has the advantage of attenuating all frequencies sufficiently removed from the pass band. This is especially useful when multiple interferences are detected.

The combinations of band pass and band stop are depicted in Fig. 9 and 10. These can be produced with mirror images or with the reject ap-

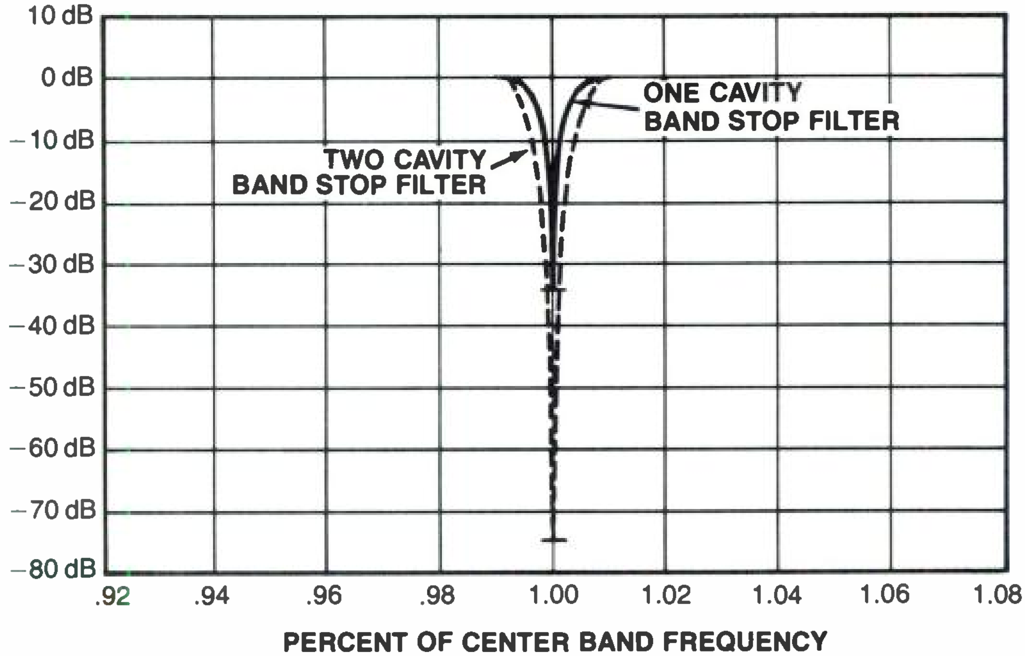


Fig. 7. Band stop filter frequency response characteristics for one and two cavity filters.

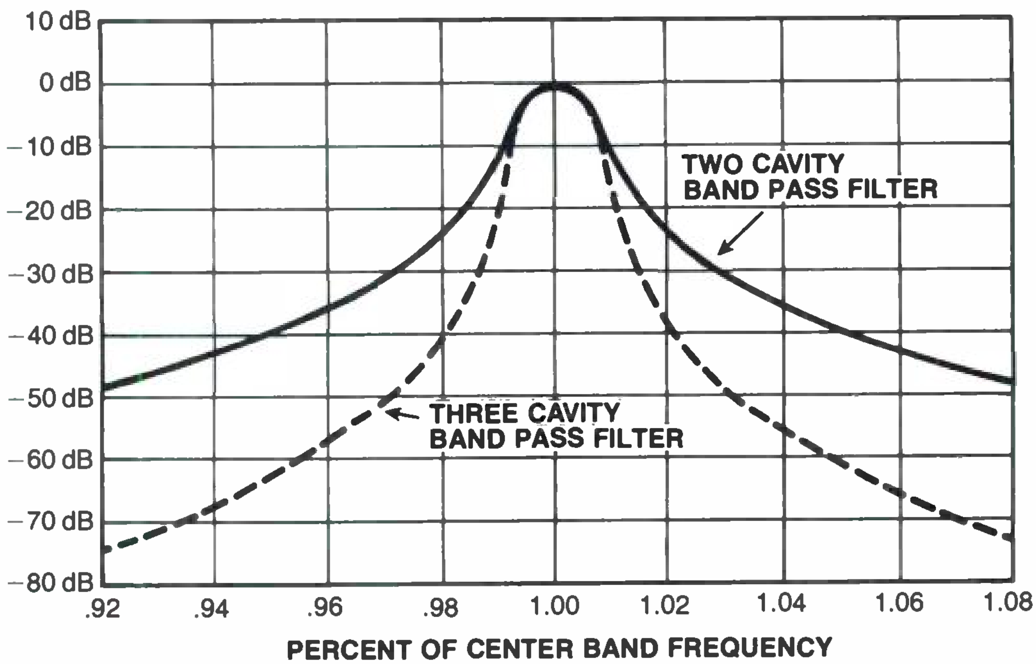


Fig. 8. Band pass filter frequency response characteristics for two and three cavity filters.

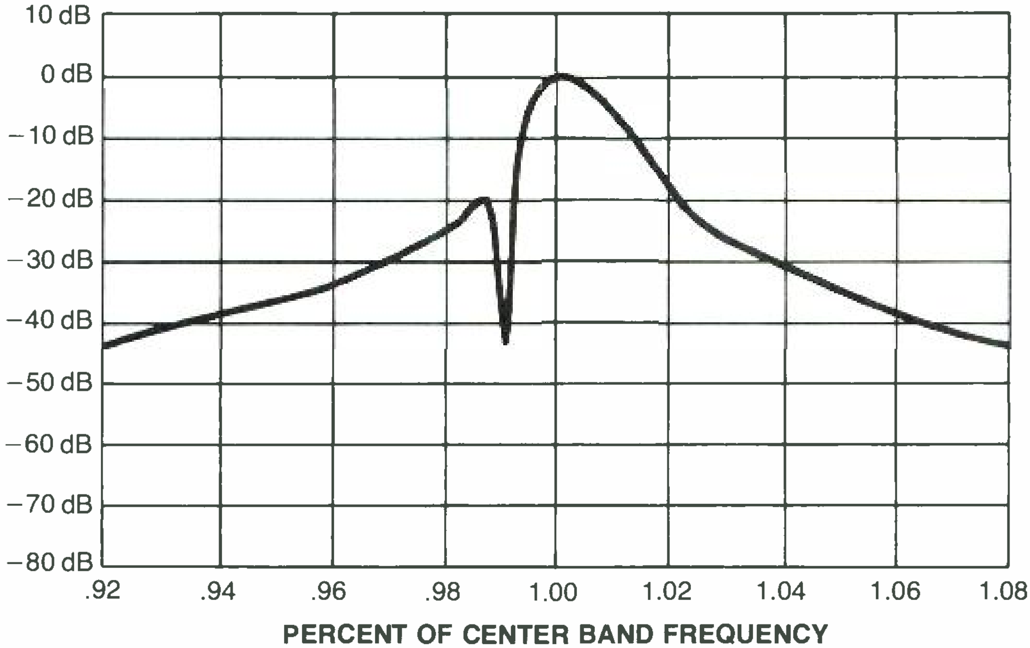


Fig. 9. Two cavity band pass-one cavity band stop filter.

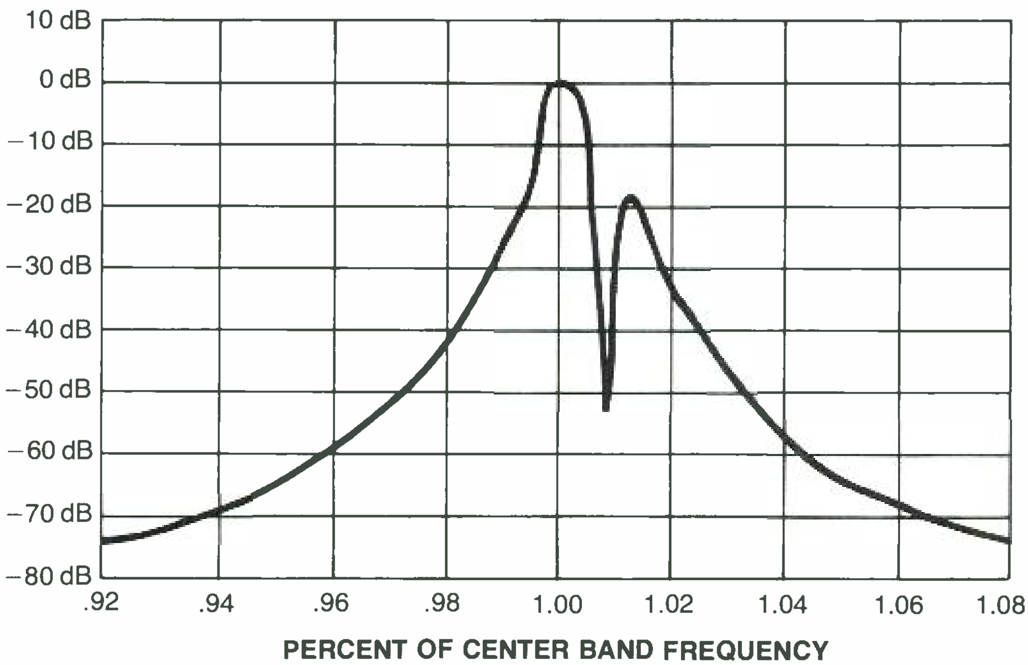


Fig. 10. Three cavity band pass-one cavity band stop filter.

pearing on both sides. These are useful when interference is caused by a combination of one frequency closely spaced and multiples further removed.

All of these responses in the VHF and FM bands are generated by coaxial cavities approximately 3/8 of a wavelength long and 12 to 24 inches in diameter (See Fig. 11). In the UHF band they can be produced by coaxial cavities or waveguide cavities. They also serve as building blocks for the diplexing and multiplexing systems discussed in the next section.

Once a decision is made to use band pass, band stop or a combination of both for a particular application, it is important to specify a few additional parameters to insure that the filter does not introduce degradation to the audio or visual content of the broadcast signal.

For example, if a filter is used to prevent Channel B from entering the transmitter of Channel A. The filter will pass Channel A and reject Channel B. But the reject curve of Channel B must not infringe upon the bandwidth of Channel A. Therefore, an insertion loss variation must be specified across the operating bandwidth and perhaps beyond. At FM, where these filters are commonly used, insertion loss variation can be kept within

0 to − .1 dB, +/- 75 kHz
0 to − .3 dB, +/-150 kHz
0 to − 1.0 dB, +/-200 kHz

when either the notch is sufficiently removed or the band pass is broad enough. The edge of the reject skirt in either configuration is also characterized by a large deviation in group delay. Group delay is defined as a change in phase divided by a change in frequency.

Fig. 11. Dielectric 1 CAV band stop for FM application.

$$\textit{Group delay} = \frac{\textit{change in phase}}{\textit{change in frequency}}$$

Since the maximum excursion in the group delay occurs at the 3 dB point for filters with Butterworth or Chebyshev amplitude response, it is difficult to determine whether the group delay or the lack of bandwidth causes deterioration in cross talk and separation of stereo signals.

A paper delivered at the 1983 NAB Engineering Conference by Spencer Smith and Robert Weirather cites actual measured data of an FM multiplexer with group delay of +/- 100 ns for +/- 200 kHz resulting in stereo separation greater than 50 dB and crosstalk equal to 50 dB. The issues of bandwidth and group delay which they address are equally important for simple filter systems as discussed here. Some broadcasters are, however, requiring +/- 25 ns for +/- 150 kHz. This latter specification approaches the state of the art limits when two FM channels are separated by only 800 kHz. Since group delay can exceed either of the above specifications at frequencies well inside the 3 dB points of a band pass filter if improperly tuned, the specification of group delay is desirable to assure proper audio performance.

Diplexers and Multiplexers

Diplexers and multiplexers are devices which allow broadcasters to combine two or more frequencies into a common transmission line while providing the necessary isolation between transmitters. The isolation is needed to prevent either transmitter from generating spurious emissions. Fig. 12, 13 and 14 provide schematic examples of three configurations which can provide in varying degree the necessary response.

Fig. 12 will be called a Tee Diplexer. In the Tee Diplexer each input leg contains either a band pass or a band stop filter. For the band pass, each of these filters is characterized by a good VSWR and low insertion loss within the pass band. The slope of the reject curve away from center band is completely dependent on the number of cavities in each leg. Therefore, F1 and F2 must be separated sufficiently frequency wise to allow the reject skirt to reach a suitable rejection to obtain isolation. All of the isolation other than the 3 dB split of the tee must be provided by the filter cavities. Fig. 8 is an example of the rejection to be expected with deviations from center band. In general F1 and F2 must be widely separated for band pass legs and each operating band must be narrow for band stop legs. In addition, this configuration has limitations when multiple frequencies must be combined.

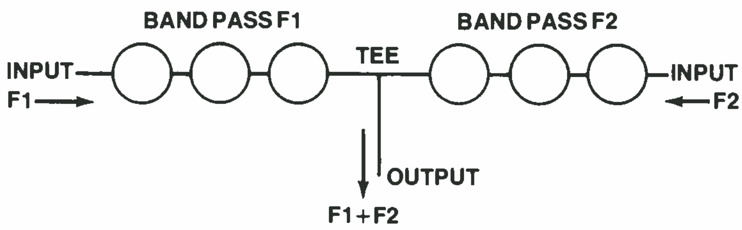


Fig. 12. Tee diplexer.

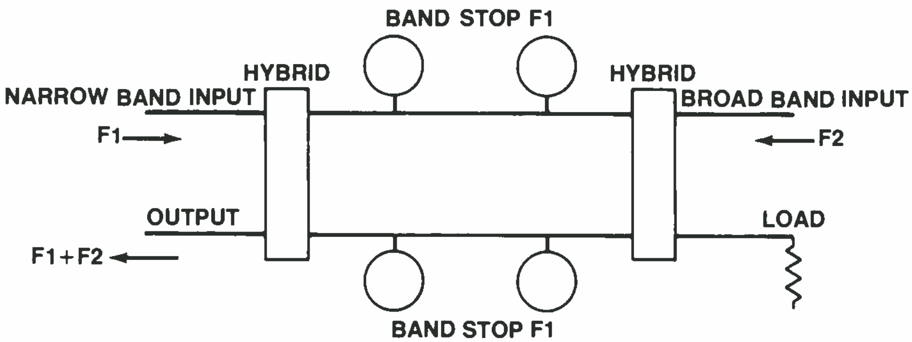


Fig. 13. Band stop.

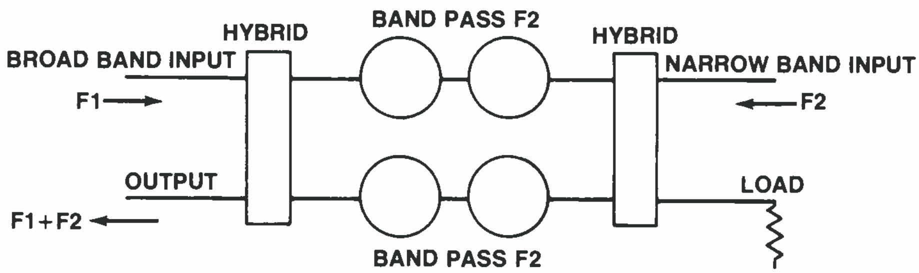


Fig. 14. Band pass

Fig. 13 and 14 respectively are band stop and band pass versions of a diplexing configuration in common usage today at VHF, UHF and FM frequencies. In both configurations 3 dB hybrids are used on both ends of the system and there will be an equal number of cavities in each leg between the hybrids. With the exception of the load on the isolated port and possible differences in line size, each system is electrically symmetrical about lines running through the center both vertically and horizontally. These systems have similar response in both coax and waveguide configurations.

In either band pass or band stop systems the hybrid on each end, when fed with an RF signal in one port, will split the power equally between two outputs with 90 degrees phase difference between the outputs. In addition, the fourth or isolated port will only pass the signal reduced by 35 dB. A matrix analysis of the magnitudes and phase of a signal such as F2 entering from the upper right port of these figures will show that it will pass through the parallel lines unattenuated by the cavities tuned to reject F1 and due to phase characteristic of hybrid will recombine in the lower left side port or output of system. It must be noted, however, that due to the isolation characteristics of the left hybrid, the entry port for F1 is isolated from F2 by 35 dB (F2 to F1). This isolation is strictly due to the presence of the hybrids and works similarly for F1 to F2 since the signal from F1 passing through the cavities aside from being attenuated by the cavities would recombine into the load port with 35 dB isolation to the F2 port due to the hybrid.

The 35 dB mentioned is a nominal figure and with the one side being a narrow band input, some additional isolation can usually be gleaned from the hybrid possibly 40 to 45 dB. The input frequency at F2 can be any frequency within the bandwidth of the hybrid and unattenuated by the cavities so it is generally called the broad band input in Fig. 13 and the narrow band input in Fig. 14. Without the presence of the cavities, the signal input at F1 would recombine into the load, so the cavities are used to create a short circuit at F1, which reflects the power back to the left side and due to phase considerations combines into the output port of the system. Because the cavities in Fig. 13 stop only F1, it is a narrow band input. In Fig. 14 the cavities will stop any frequency sufficiently removed from F2 so the F1 input is the broad band input.

The differences in the response of the two systems stem from the differences in the response of the cavities. As in the filters discussed earlier, the band stop cavities rise quickly to a high attenuation rate but the width of the attenuation band is narrow. The response of band stop cavities is used extensively in TV Diplexers (See Fig. 15 and 16) where the narrow band port accepts the audio which is reflected usually by a single notch (band stop) cavity back to the output port of the diplexer. In the UHF portion of the band where the visual transmitter is actually capable of amplifying the audio if diplexed low level, special motor driven devices are used in waveguide to de-tune the notch so that the entire content of the TV channel can be amplified by the visual transmitter, fed into the broad band port and recombined into the output without being attenuated by the notches. This is an emergency configuration when an audio transmitter fails. In the FM band two cavities in each leg will generally provide adequate bandwidth to reject the entire content of an FM channel fed into the narrow band port. For this FM application the isolation of Fig. 13 is 70 dB nominal for F1 to F2 and 40 dB nominal F2 to F1. This is adequate for a diplexer but additional cavities can be added to the narrow band input which will reject all frequencies input at F2 and thereby increase the isolation from F2 to F1 to 65 to 70 dB when modules are connected in cascade to create a multiplexer.

The band pass configuration of Fig. 14 does not find extensive use in TV since it would require several cavities in each leg to obtain the sharp skirts necessary to pass visual and reject audio components. It, however, has been used in FM diplexers as well as multiplexers. With four cavities in each leg this configuration will provide 70 dB isolation F1 to F2 for frequencies separated by as little as .8 MHz and 40 dB isolation F2 to F1; the latter not being dependent on frequency separation but only on isolation of the hybrid. These isolation figures are adequate for diplexers. When multiple modules are connected in cascade the output of one module fed into the broad band input of the next, the resulting multiplexer has greater isolation F2 to F1. This occurs because F1 is in fact introduced to the network through its own narrow band port in the previous module in the chain. So that the isolation F2 to F1 is the combination of the 40 dB previously mentioned plus the additional isolation provided by the reject skirt of the band pass cavities in the module used to introduce F1 into the system. This analysis assumes 1 module for each frequency in the system leaving a spare broad band input which through proper patching can be used as an emergency port in the event of a failure of one of the modules.

If redundancy with the spare port is not deemed necessary, the first port in the series can be sup-

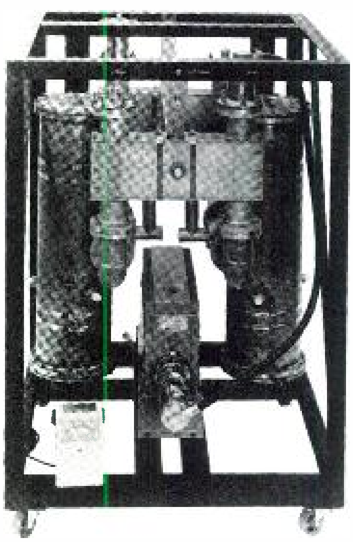


Fig. 15. High band VHF diplexer.

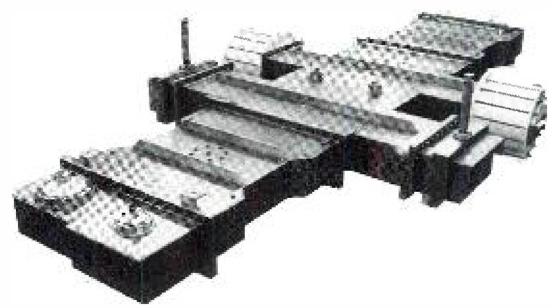


Fig. 16. UHF diplexer.

plemented with additional input cavities to provide the necessary isolation for proper system performance. This reduces the number of modules to one less than the number of frequencies.

TRANSMITTER SYSTEMS

In the following section, several methods of connecting one or more transmitters to the antenna system will be discussed. It would be impossible to cover all the possible combinations that could be conceived, therefore, only some of the basic configurations will be discussed. They can be modified or expanded to suit the individual station requirements. Most of the broadcast manufacturers will be happy to assist in designing custom systems.

When designing an RF output system with motorized coaxial switches, it is essential to make sure that the transmitter is not producing RF power when the switch contacts open. Most coaxial switches are constructed so that the interlock switches function before the RF contacts open. However, this timing will vary between different types of switches. Also, the time it takes a transmitter to stop producing RF after the interlock signal is applied will vary. Therefore, it is a good idea to check this timing. It may be necessary to turn off the transmitter a short time before commanding the coaxial switch to change positions. If the transmitter is still producing RF power, when the RF contacts open, the RF contacts of the coax switch will be burned.

Single and Alternate Main Transmitter Systems

Fig. 17 illustrates a single TV transmitter system utilizing a 7-port patch panel. The patch panel would allow the visual, aural or the diplexer output to be terminated in station load. If the transmitter has multiplex capability (amplifying both the visual and aural signals in the visual amplifier), the visual amplifier could be connected directly to the antenna, bypassing the diplexer.

An alternate main transmitter with a coaxial switch is shown in Fig. 18. A single ended transmitter like an AM or FM unit, would connect as shown. A TV transmitter would require two switches. Fig. 19 shows wiring for the interlocking of the transmitters. Notice that the station load interlocks will transfer to the transmitter that connects to the station load. Also, during switching, both transmitters will be interlocked off.

Parallel Transmitters

Parallel transmitters are two complete transmitters that are combined on the output to double the available output power. In addition to the increase in output power the parallel transmitter has additional advantages, such as redundancy and reduction of ghosting in TV applications.

When the parallel transmitter is operating normally, and one of the transmitters fail, the output power will drop to quarter power. If switching is provided in the output system, the output power can be increased to half power by bypassing the

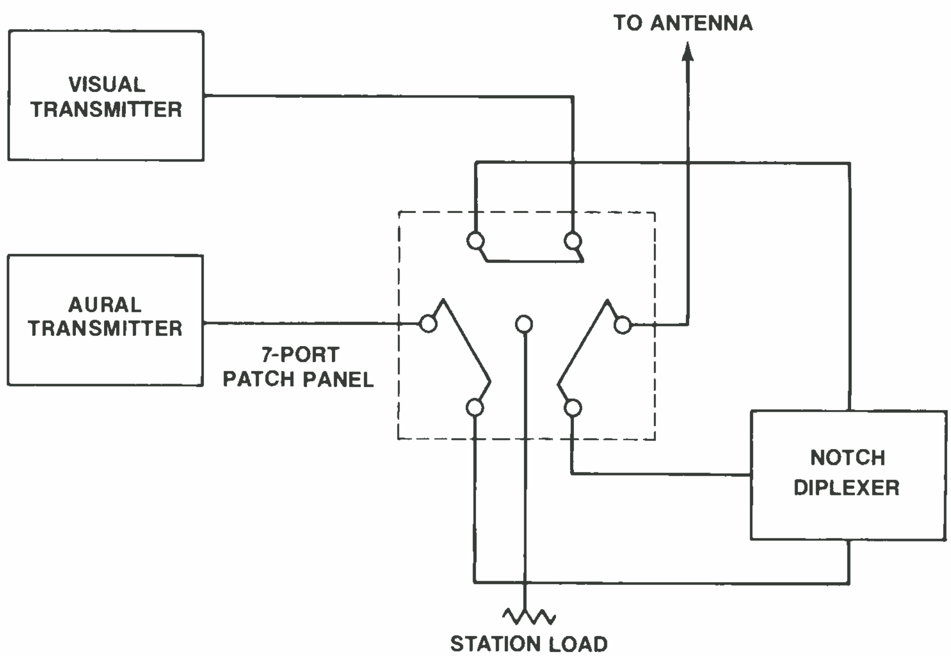


Fig. 17. RF flow diagram TV transmitter with 7-port patch panel.

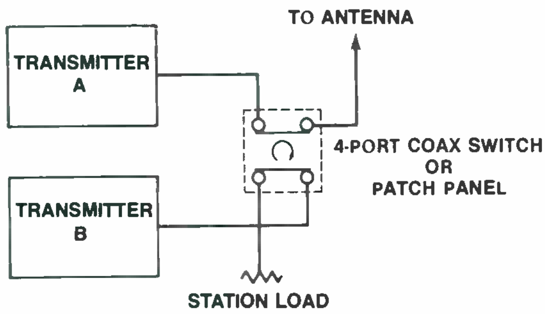


Fig. 18. RF flow diagram alternate main transmitter.

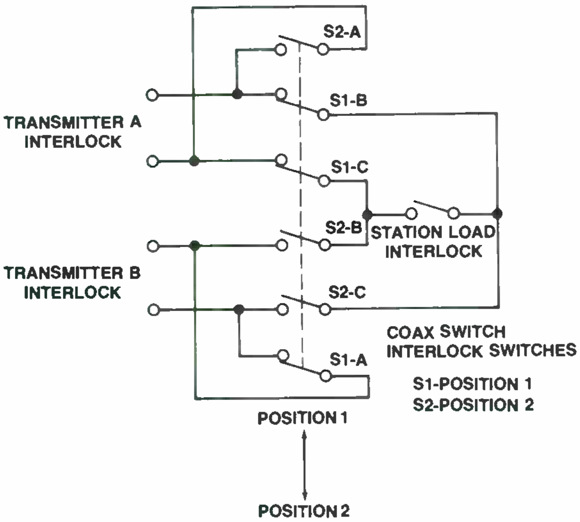


Fig. 19. Schematic alternate-main transmitter interlocks.

output combiner. The switching can take place at any convenient time.

In its simplest form, a parallel transmitter consists of an exciter-modulator, input power divider, two amplifier sections, output combiner, and reject load as shown in Fig. 20. In order to properly combine the input signals to the output combiner, they must be of the proper phase and amplitude. These relationships vary with the various types of combiners.

AM and Short Wave Parallel Transmitters

Parallel transmitters in the AM and short wave broadcast bands are not as common as in the higher frequency bands. They are generally used only to double the output power available.

Combiners used at these lower frequencies are usually a bridge type of circuit. The bridge circuit is usually made up of four π circuits with a characteristic impedance of 70.7 ohms and are constructed with lumped elements (capacitors and inductors). The bridge circuit is shown in Fig. 21A. The phase shifts produced by each leg can either be a positive or negative 90 degrees depending on the elements used. If the shunt elements are capacitors, a negative phase shift will be produced. Using shunt inductors will produce a positive phase shift.

If the two transmitters are fed to the two inputs in-phase, the two signals will be in-phase at the antenna output, Thus they will combine. The two input signals will be 180 degrees out-of-phase at the reject load output, therefore, there will be no power dissipated in the load. When one of the transmitters stop producing power, the power from the remaining transmitter will be split equally to the reject load and the antenna.

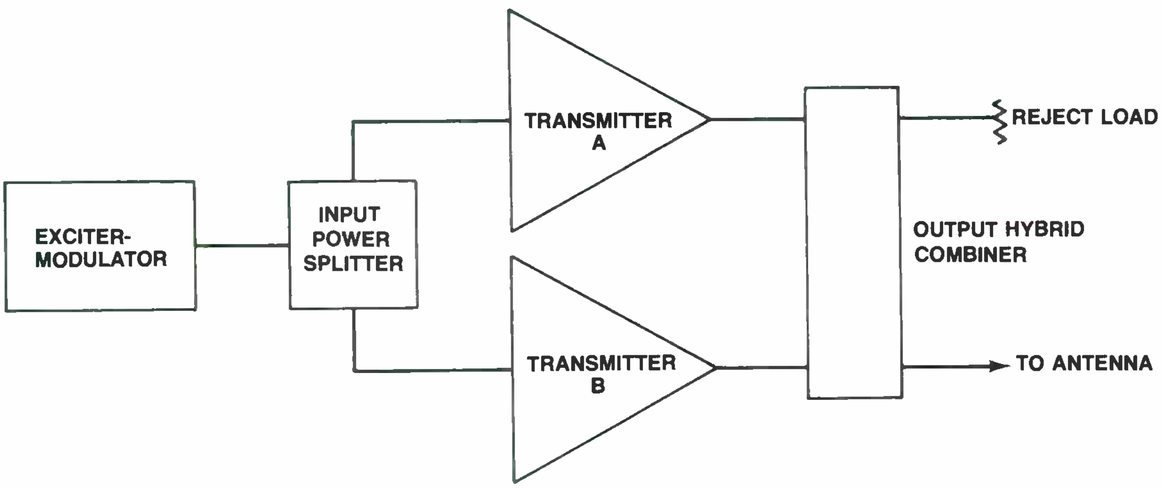


Fig. 20. Basic parallel transmitter.

By making three of the legs of the bridge a positive phase shift, the number of circuit components can be reduced. This simplified circuit is shown in Fig. 21B. The two parallel capacitors across the antenna output and transmitter 1 input can be combined so that only one capacitor is required at each point. The capacitor and inductor that are in parallel across the reject load and transmitter 2 input, will have equal reactance and thus cancel, so neither are required. The bridge combiner can be built with only three capacitors and three inductors, thereby reducing the costs of the unit. As an added advantage the high current carrying devices are the series elements, of which three are inductors.

Ferrite core transformers have been used in lower power applications. One parallel transmitter using such a device is shown in Fig. 22. This unit is used to combine two 5 kilowatt transmitters.

The combiner can be thought of as a center tapped autoformer that operates at these RF frequencies. If equal amplitude signals that are in-phase are applied to the ferrite combiner, with a common ground, the center tap will contain the sum of the two signals. Since the two signals are in-phase, there will be no voltage differential across the reject load resistor.

If each input is 200 watts for example, there will be 100 volts, at 2 amperes across the 50 ohm input of the ferrite transformer. When the two signals are added, there will be a total of 4 amperes. Since the center tap of the transformer has an impedance of 25 ohms, the 4 amperes will produce 400 watts of power. A "L" network is used to match the 25 ohm center tap of the transformer back to the 50 ohm output.

When only one transmitter is operating, the power it produces will be split equally between the antenna and the reject load. The operating transmitter will produce 200 watts, or 100 volts at 2 amperes as in the example above. Therefore, there will be only 2 amperes at the center tap of the transformer, which will produce 100 watts of power. Since the other transmitter is not operating, there will be 100 volts across the 100 ohm reject load, which will be the remaining 100 watts produced by the operating transmitter.

VHF Parallel Transmitters (Coaxial)

In VHF parallel transmitters' the output combiner is usually a 3 dB 90 degree hybrid. In order to properly combine the two transmitter signals, the hybrid requires the signals be equal amplitude and phased in quadrature (90 degrees). If we assume that the amplifier sections of the transmitters are identically tuned and the electrical path lengths and gain are the same, then the input power divider must provide two signals that are equal amplitude and phased in quadrature. A

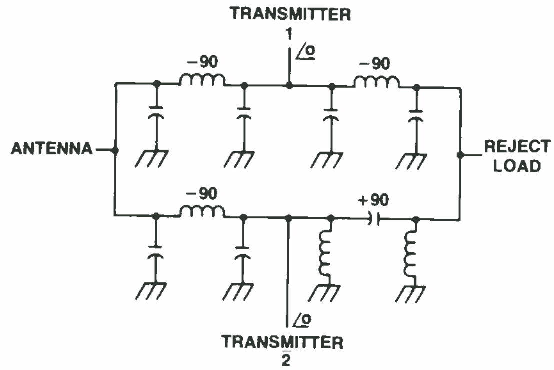


Fig. 21A. Bridge combiner - π networks.

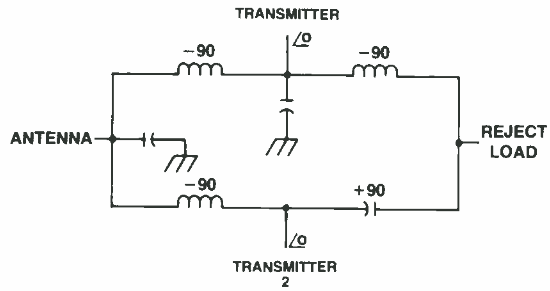


Fig. 21B. Bridge combiner simplified.

3 dB hybrid will provide this type of power division. Other types of power dividers could be used. An "in-phase" power divider with a 90 degree delay in one output would work just as well.

Fig. 23 shows the relative phase relationship to the output power of the parallel transmitter system. With no phase error, input signals to the output hybrid in quadrature, 100% of the available transmitter power will be delivered to the antenna. If there is a 90 degree phase error, both signals in-phase, the power will be divided equally between the antenna and the reject load. All the available transmitter power will be dissipated in the reject load if the phase error is 180 degrees. A phase error of 20 degrees will only result in an output power reduction of approximately 3%. This would indicate that the phasing is not critical for output power considerations.

The relative amplitude relationship to the output power is shown in Fig. 24. The graph assumes that one of the transmitters is operating at full power and output power of the second transmitter is varied from 0 to full power. If only one transmitter is operating the output power will be only 25% of the normal combined output power. With only one input signal, the output hybrid acts as a power divider, applying half the power to the antenna and the other half to the reject load. The power being fed to the antenna is 25% of

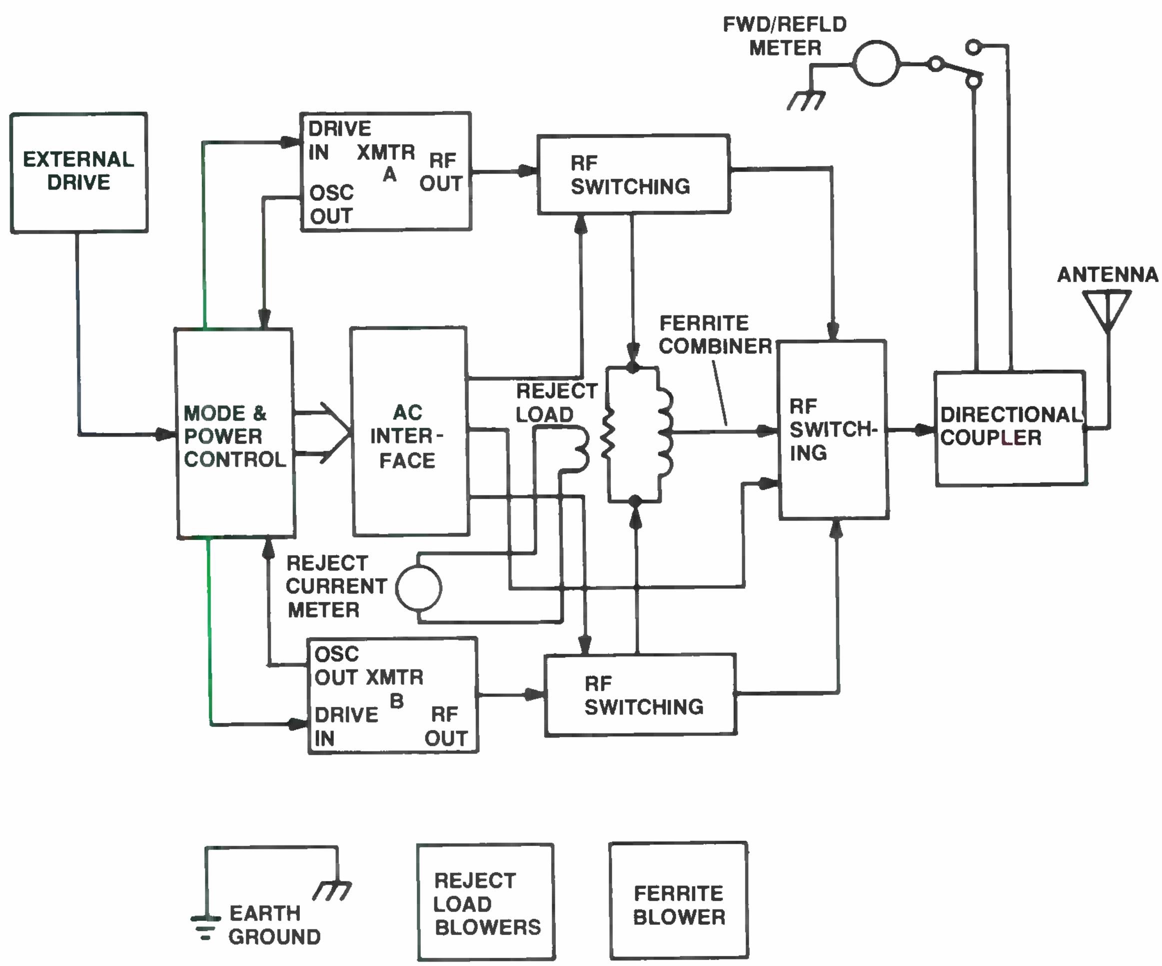


Fig. 22. Simplified block diagram, combiner and RF switching. (Courtesy Harris Corp.)

the normal combined transmitter power. If one of the transmitters is operated at half its normal output power, while the other transmitter is operated at full power, the combined output power will be approximately 73% of the normal combined power. Since the two transmitters are only generating 75% of the normal combined power, only about 2% of the power is being dissipated in the reject load. Therefore, there is not a great amount of power being wasted in the reject load. The maximum power that the reject load should be required to dissipate is half of one transmitter's power.

Thus far only the basic parallel transmitter system has been discussed. It was assumed earlier that the amplifier sections of the transmitters were identically tuned, having the same electrical path lengths and gain. From a practical view point this could be done, but with difficulty. Therefore, most parallel transmitter systems will provide a means of controlling the phase and gain of the transmitters that are independent of the tuning. It usually is an attenuator for gain and a phase shifter for the phase. Some transmitters may use a gain control within the amplifier section for the gain control and one of the input matching controls of the power amplifier for phasing. This practice is probably more common in FM than TV since the bandwidth is smaller.

One of the major advantages of a parallel transmitter is the reduction of ghosts or reflections from the antenna. Ghosts are reflections from the antenna that are re-reflected from the transmitter and radiated from the antenna. The distance between the original image and the ghost on a TV receiver can be used to determine the approximate location of the reflection in the antenna system. Since the horizontal frequency of the TV is 15734 Hz. The full horizontal line would be equal to 63.6 microseconds. The length of the visible portion of the horizontal line is 53.1 microseconds, therefore, the time between image and the ghost can be measured. This time, when compared to the speed of light, will yield the

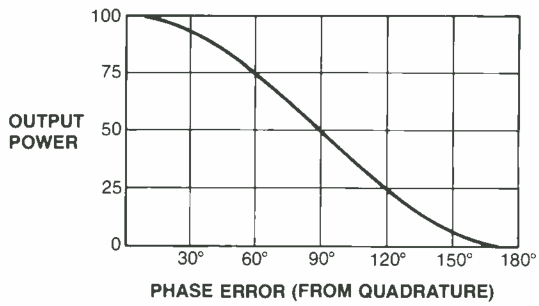


Fig. 23. Relative phase error verses output power.

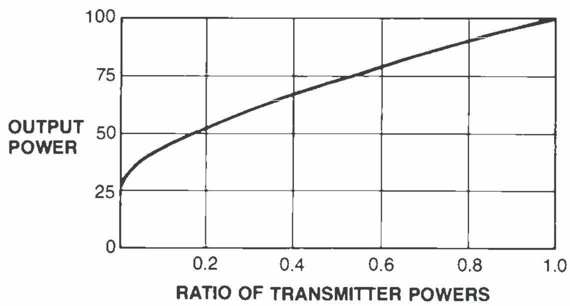


Fig. 24. Relative amplitude error verses output power.

distance the reflected signal had to travel to produce the ghost. It must be kept in mind that the signal had to travel from the point of origination down the transmission line to the transmitter and back up the transmission line to the antenna to be radiated. The velocity of propagation of the transmission line must also be taken into account.

The use of the 3 dB hybrid in the parallel transmitter will reduce the reflected signals that produce the ghosts. When the reflected energy from the antenna is applied to the output of the 3 dB hybrid, it is split into two signals at the two transmitter inputs. These signals will be phased 90 degrees apart and will continue until they are re-reflected by the output circuitry of the transmitters. The signals will be applied to the inputs of the 3 dB hybrid, however, their phases are such that instead of combining in the antenna output, they will combine in the reject load of the parallel transmitter. For optimum ghost reduction the electrical path lengths between the hybrid and transmitter inputs must be the same. The use of slugs or other tuning devices can upset the phase balance or electrical length of the system. One method to measure the performance of a system for ghost reduction, is to measure the reverse VSWR of the system. This is accomplished by placing open or short circuits on the transmission lines that would connect to the transmitter outputs and measuring the VSWR looking in the output of the combining system. Thus the path of the ghost signal is being measured. Ideally, this path should be as good as the forward VSWR of the system, however, from a practical standpoint a VSWR of 1.1:1 or better will reduce the ghosting. It should be noted that the equal electrical line lengths are needed for quadrature type combining networks. For systems using in-phase type combining networks there needs to be a 90 degree delay in the proper input. To offset this delay, a 90 degree delay can be inserted in the input circuitry of the opposite transmitter.

Fig. 25 shows a complete output switcher for a parallel television transmitter. For single ended transmitters such as FM, only half the system would be required. This figure shows the output switching around the output hybrid combiner. There are normally four modes of operation:

1. A&B Combined to the Antenna
2. A&B Combined to the Station Load
3. A to the Antenna and B to the Station Load
4. B to the Antenna and A to the Station Load

The RF flow diagram is shown in the A&B to the antenna mode. By rotating S3 and S6 the system is changed to the A&B to the station load mode. If S1, S2, S4, and S5 are changed, transmitter A will be connected to the antenna while transmitter B will be connected to the station load. If S3 and S6 are rotated, the transmitters will switch transmitter A to the station load while transmitter B is connected to the antenna.

Since a parallel transmitter is two complete transmitters, there should be two exciter-modulators. Some manufacturers may offer the second exciter-modulator as an option. By adding a switch on the input of the input power divider, either exciter-modulator could be selected. This would provide redundancy, should the active exciter-modulator fail. Since the power levels of the exciter-modulator is usually fairly low, the switching could be done under power which would allow the switching to be automatic. By using relatively fast switches, the transfer could be done with only a small carrier interruption.

Automatic switching of the output switching system is not usually done. Stations would rather choose when the carrier break occurs, since it will be noticeable to the audience. In lower power installations, the carrier break will be 2 seconds or less. With higher power switches the break could be up to 10 seconds.

Again referring to Fig. 25, the combined output of the visual hybrid must pass through S2 and S3. Therefore, these switches must be sized to carry the combined power. Some systems will add another coaxial switch (S7) on the output of

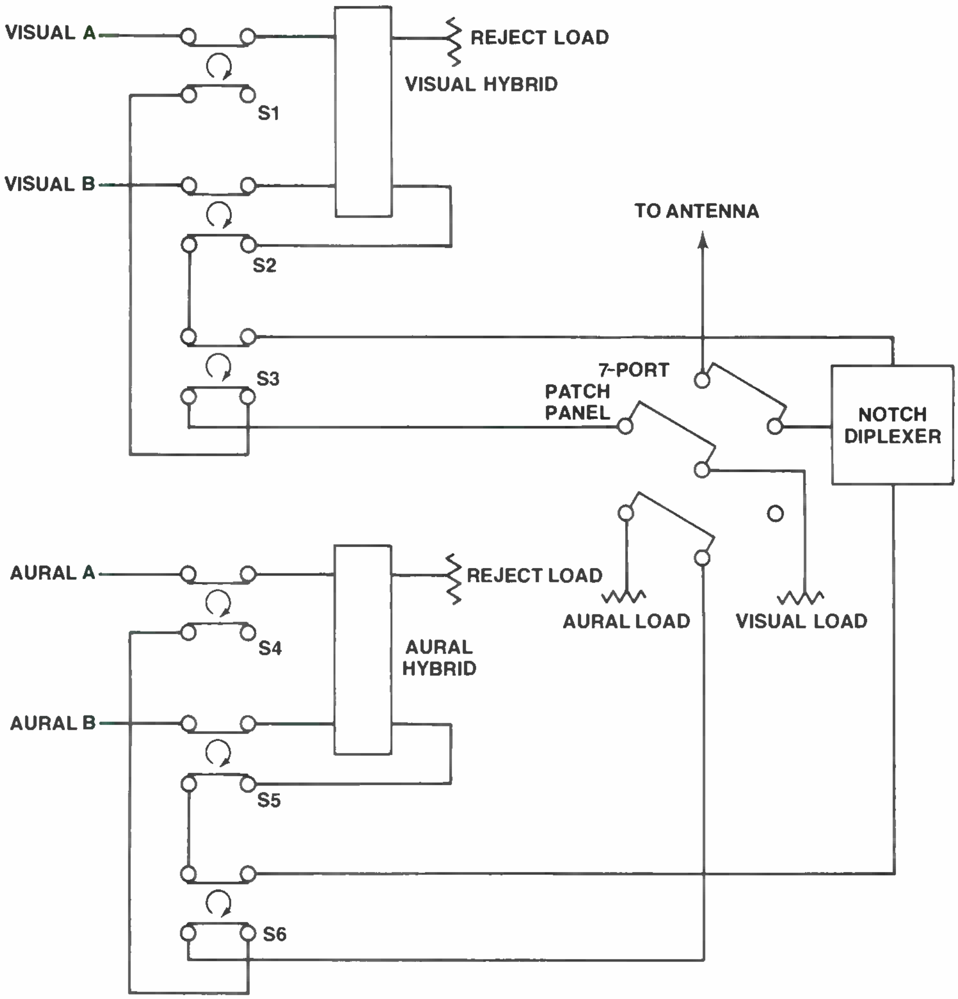


Fig. 25. RF flow diagram output switcher.

the visual hybrid as shown in Fig. 26. This higher power switch will allow the other three switches to be a smaller size, since the combined power will only be applied to S7. It will also be necessary to add another station load for the combined signal at S7. Generally, this will reduce both the package size and the cost of the parallel transmitter system. A television system requires a diplexer of some type in order to combine the aural and visual signals. The output switching system usually contains a patch panel which allows the output of the diplexer to be routed to either the antenna or the station load. The output switching system must also contain the necessary monitoring points for combined power and reject power.

VHF "Switchless" System (Coaxial)

The "switchless" phase shifter system for VHF frequencies is probably the most recent development in RF switching systems. At the time of writing, the writer is not aware of these systems operating in the field. The "switchless" system is designed to combine the outputs of two transmitters operating in parallel. It is intended to replace the switch type output switchers previously used.

As with the switch type output switchers, it is desired to have four basic modes of operation which are:

1. A&B Combined to the Antenna
2. A&B Combined to the Station Load
3. A to the Antenna and B to the Station Load
4. B to the Antenna and A to the Station Load

There are several methods to accomplish the mode changes performed by the "switchless" system. The basic system is shown in Fig. 29, and consists of two 90 degree hybrids, a reject load, and some type of phase shifting device. It is the method used to do the phase shifting that makes the systems different. Therefore, the basic system will be presented and then the different methods

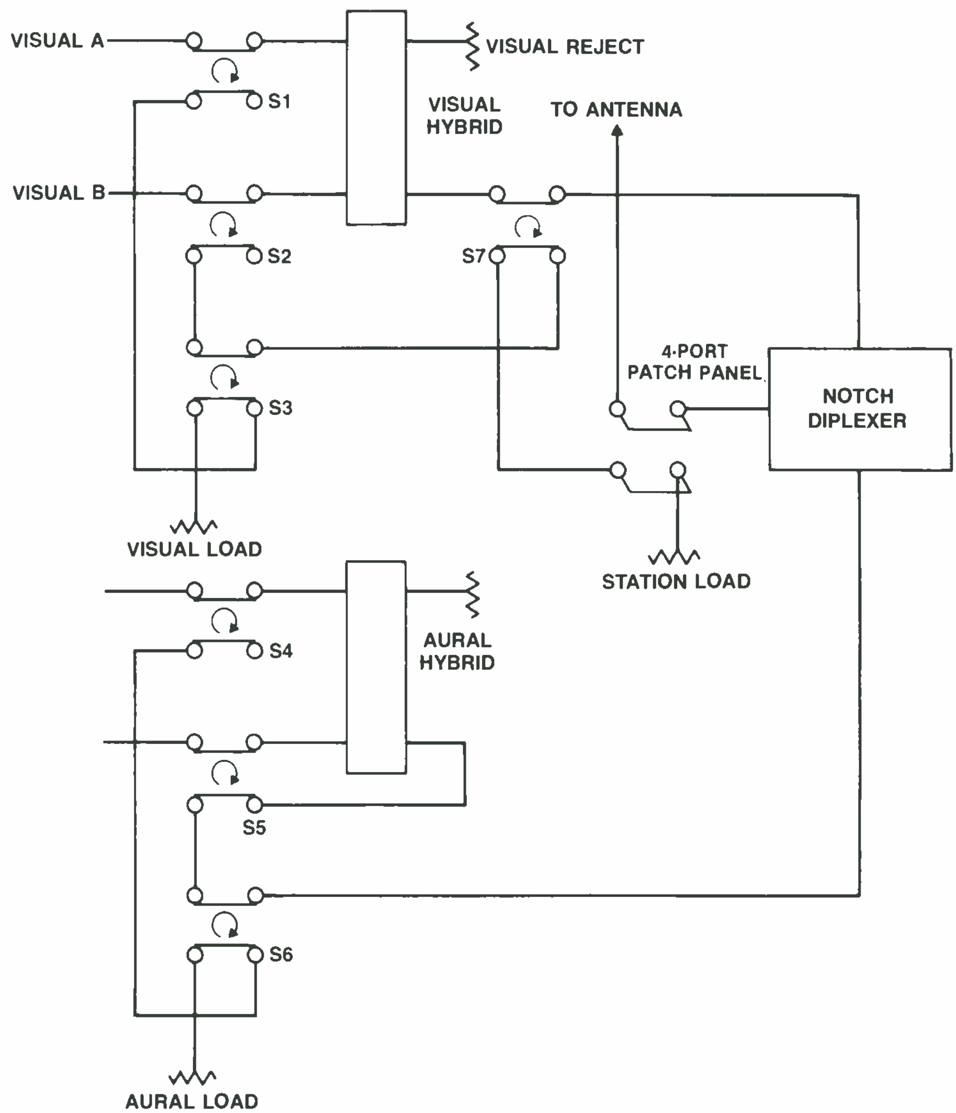


Fig. 26. RF flow diagram high power output switcher.

of accomplishing the phase shifting will be discussed.

Since the "switchless" system contains two hybrids, it is necessary to understand how the hybrid operates. The 90 degree hybrid can be utilized as either a power divider or a power combiner. In the "switchless" system both are used.

When used as a power combiner, the hybrid will combine two signals that are equal amplitude and phased in quadrature. Again referring to Fig. 29, if two equal amplitude signals are applied to points E and F, with the signal at F lagging in phase by 90 degrees, the signals will be combined into the antenna. Conversely, if the signal at point E is lagging by 90 degrees, the signals will be combined into the load.

If a signal is applied to the A input of the hybrid, being used as a power divider, it will be split into two signals of equal amplitude that are phased 90 degrees apart. The signal appearing at point C will be in-phase with the input signal (point A), while the signal at point D will lag the input signal by 90 degrees. The converse is true for a signal being fed into the B input. The signal at point D will be in-phase, while the signal at point C will lag 90 degrees. If two signals that are in-phase are applied to inputs A and B, then each of the outputs (points C and D) will have two signals, one in-phase with the inputs and one lagging by 90 degrees.

If the "switchless" system is set in the A&B to the antenna mode, phase shifter #2 must have 90 degrees more phase shift than phase shifter #1. The two signals at point F will lag the two signals at point E. In this situation, the signals will combine in the antenna output.

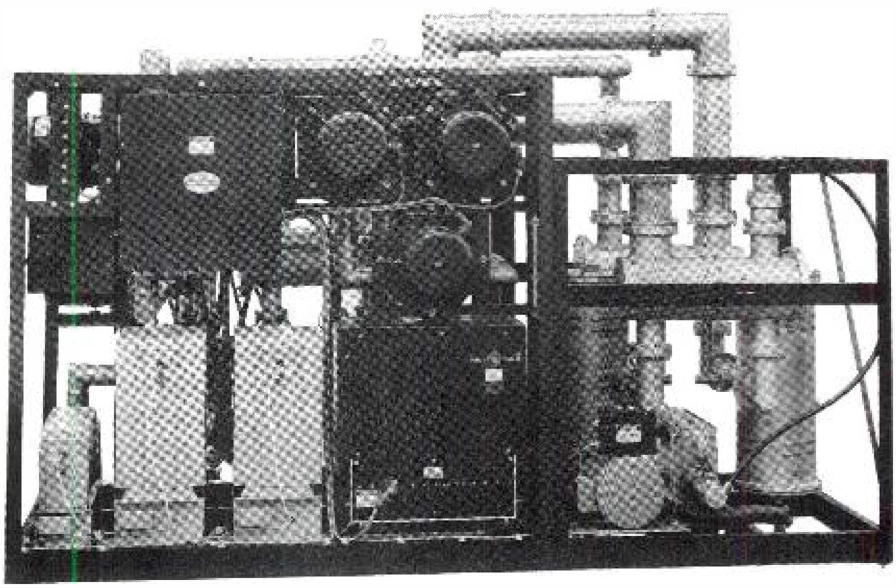


Fig. 27. VHF output switcher parallel TV transmitters front view.

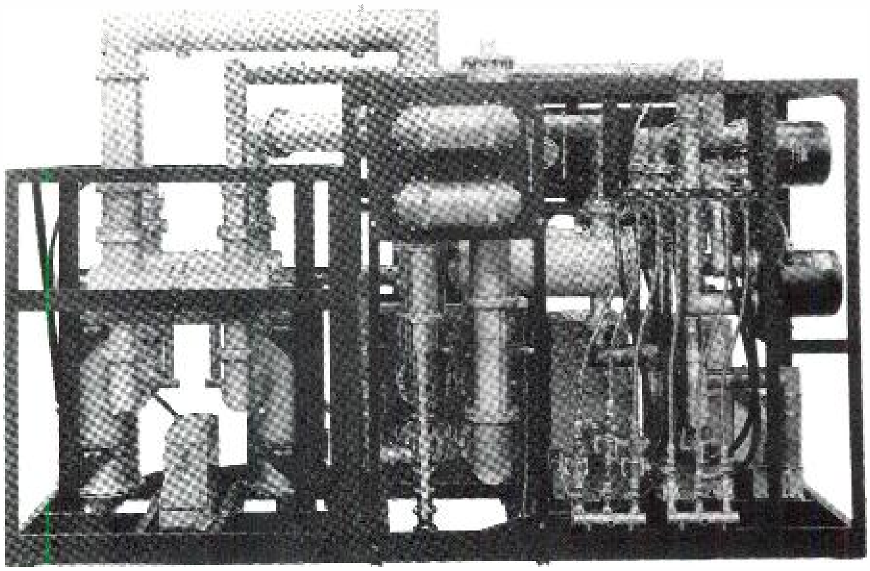
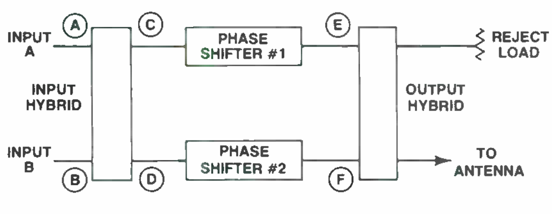


Fig. 28. VHF output switcher parallel TV transmitter rear view.



MODE	PHASE SHIFTER #1	PHASE SHIFTER #2
A+B ANTENNA	0	90
A-ANTENNA B-LOAD	90	90
B-ANTENNA A-LOAD	0	180

NOTES:

1. INPUTS A + B ARE IN-PHASE
2. PHASE SHIFTER #2 WILL USUALLY CONTAIN A FIXED 90° SECTION AND A VARIABLE 90° SECTION

Fig. 29. Basic switchless combining system.

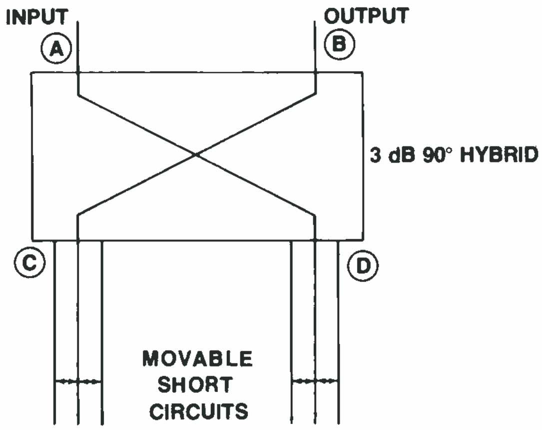


Fig. 30. Variable phase shifter.

If either of the phase shifters are set for an additional 90 degrees of phase shift, the system will be in one of the single transmitter modes of operation. If phase shifter #1 is changed, then transmitter A will be routed to the antenna, while transmitter B will be terminated in the station load. Should phase shifter #2 be changed, transmitter B will be routed to the antenna, while transmitter A is terminated in the station load.

There are three methods of getting the combined transmitters routed to the station load.

1. A coaxial switch or patch panel could be used on the antenna output to route this output to a separate station load.
2. The combined transmitters could be routed to the reject load by moving the additional 90 degree phase shift in phase shifter #2 to the #1 phase shifter.
3. The transmitter outputs could also be combined into the reject load by changing the input phases to the "switchless" system. By adding 180 degrees delay to the A input the combined transmitter will be routed to the reject load.

The later two methods will require that the power rating of the reject load be increased to the combined power level instead of that of a single transmitter. They also require the antenna to function as the reject load for any power that is not absorbed in the reject load.

There are several methods of changing the phase of the RF signals in the "switchless" system.

1. Probably the most familiar method of changing the phase at higher power levels is the line stretcher. It is a piece of transmission line, whose length can be changed. For convenience, it often takes the form of a "U-link", or trombone, so that the connectors can be mounted and the "U-link" moved to change the length.
2. Another method is to use a 90 degree hybrid with movable short circuits on two of the arms. This device is shown in Fig. 30. If a signal is applied to the input (Point A), the hybrid will divide it into two equal signals that are phased 90 degrees apart. The signal at Point D will lag by 90 degrees. The short circuits attached to Points C and D will reflect the two signals back to the hybrid. The phase of the two signals will be delayed by twice the electrical length of the short circuits. If the two short circuits are the same length, the relative phases of the two signals will still be 90 degrees. Since the signal at Point D is lagging by 90 degrees, the two signals will combine into the output (Point D). By changing the length of the short circuits, the delay or phase shift through the circuit will change. If the short circuits are moved 90 degrees, the phase shift through the circuit will be 180 degrees. The signal must travel from the hybrid to the short circuit and then return to the hybrid, twice the distance of the short circuit. The two short circuits must be moved together in order to make the hybrid combine the reflected signals properly.
3. There are several methods of making a short circuit needed in the above circuit, which are shown in Fig. 31. It could be the traditional short (i.e. a piece of metal contacting the inner and outer conductors of the transmission line, employing finger stock, allowing it to be moved). A "deep short" could be used which moved the ringer contacts one quarter wave length away from the short. This greatly reduces the amount of current that the fingers are required to carry. A "non-contacting" short may be used. It is a pair of cylinders that are a quarter wavelength long and shorted at one end. The sizes of the cylinders are such that they fit between the inner and outer conductors of the transmission line. The shorted cylinders are insulated from the transmission line, thus forming a capacitor. The capacitor is large enough so as to have very little impedance to the operating frequency, therefore, it appears as a short circuit.

Another method of creating phase shift is to change the short circuit to an open circuit. A short section of the center conductor is removed from a shorted piece of transmission line. The transmission line appears as an open circuit, since there is very little capacitance between the two pieces of cut center conductor. By moving an insulated metal probe across the gap in the cut center conductor, a large amount of capacity is created. This causes the

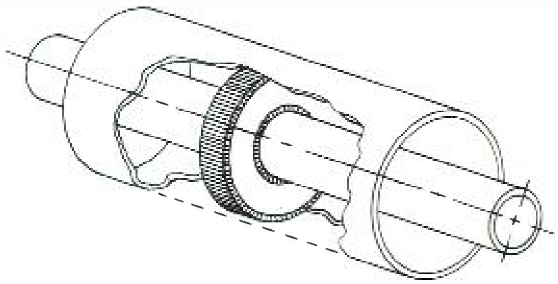


Fig. 31A. Traditional short.

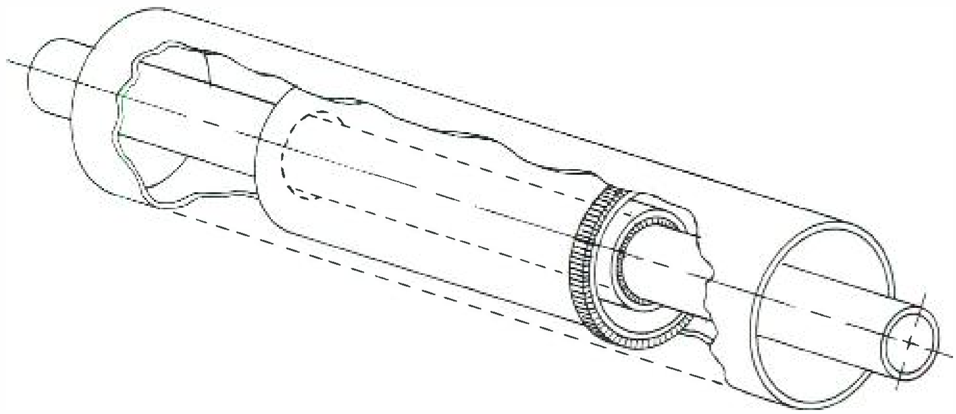


Fig. 31B. "Deep short".

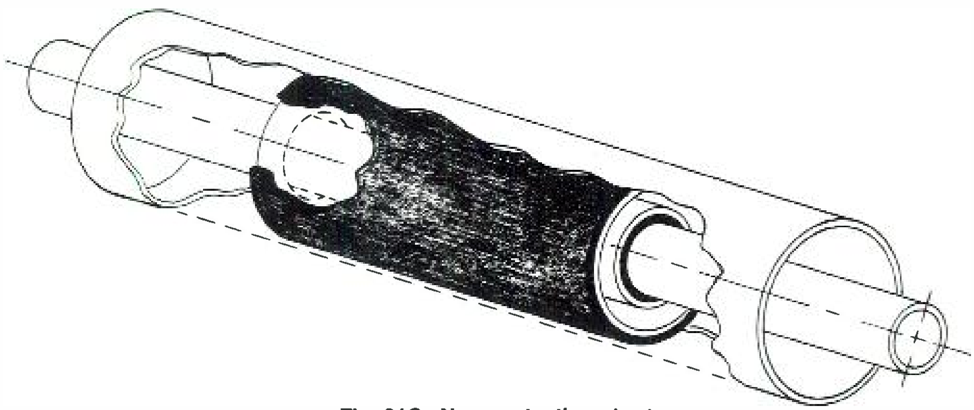


Fig. 31C. Non-contacting short.

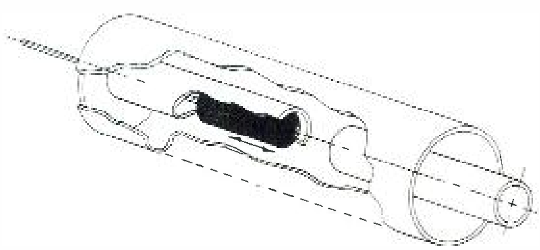


Fig. 31D. LC short.

transmission line to appear as a short circuit, thus changing the phase.

All the above methods will accomplish changing the phase and allow the "switchless" system to operate. Each of the methods have advantages and disadvantages that should be taken into consideration upon purchasing a "switchless" system.

The "switchless" system does not require that the transmitters be turned off during the switching process. Since there is no carrier break, the length of switching is not important. It also allows the switching to be done with no regard to program content. Switching can be done while the commercial is on the air.

The "switchless" system will offer the same ghost reduction as the other types of parallel transmitters. Since the two signals from the transmitters are applied to the "switchless"system in-phase, there needs to be an external phase shift to take advantage of the ghost reduction feature. A 90 degree phase shift has to be added between the output of one of the transmitters and the "switchless" system. This will delay the reflected signal in that path 90 degrees as it passes from the output system to the transmitter, and another 90 degrees as it passes from the transmitter back to the output system. The two reflected signals will now be 180 degrees out-of-phase, thus be combined in the reject load. Since a 90 degree delay was added to one of the transmitter signals it will be necessary to add an equal phase shift to the other transmitter so that the transmitter signals will combine in the antenna output. This delay can be added to the input circuits thus allowing the ghost reduction circuit to operate properly.

There are some differences in the "switchless" system that were not common to the switch type systems. In a switch type system, the transmitters were isolated by the mechanical switch when operating in the single transmitter mode. The "switchless" system does not have that isolation. The isolation is provided only by the two hybrids of the system. Therefore, the 60 dB or better isolation provided by the coaxial switches, is not present in the "switchless" system. It is possible that voltages could be present on the input, even though the transmitter driving that input is turned off. It is necessary to make sure safety devices are utilized to protect individuals. It would be a good idea to delay maintenance on the system until both transmitters could be turned off.

UHF Parallel Transmitters (Waveguide)

UHF Parallel transmitters are a little different than their VHF counterparts. Because of the power rating of the klystron (30 kW to 60 kW), complete parallel transmitters are not as common as in VHF. A 220-240 kW transmitter is the more common parallel UHF transmitter. There are quite a few 110-120 kW transmitters operating, but these aren't complete parallel transmitters, as only the visual klystrons are operating in parallel. The UHF transmitters also have aural multiplex capabilities, which reduce the need for parallel aural amplifiers.

A typical RF flow diagram for a waveguide output switching system is shown in Fig. 35. It contains four waveguide transfer switches, a hybrid combiner, and a reject load. S1 and S2 switch the input of the system around the hybrid for single transmitter operation. S3 determines

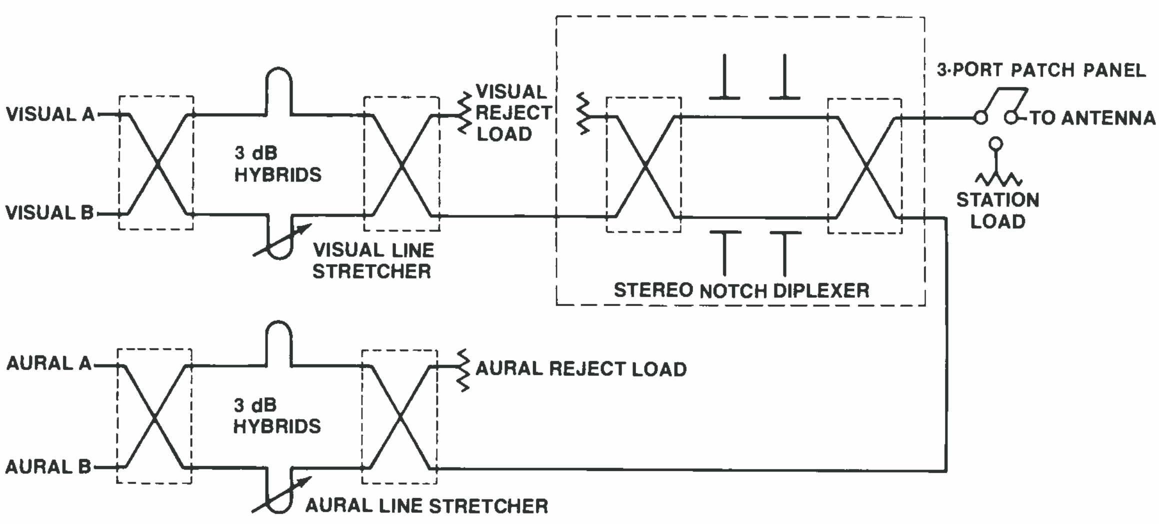


Fig. 32. RF flow diagram VHF "switchless" system with phase shifters.

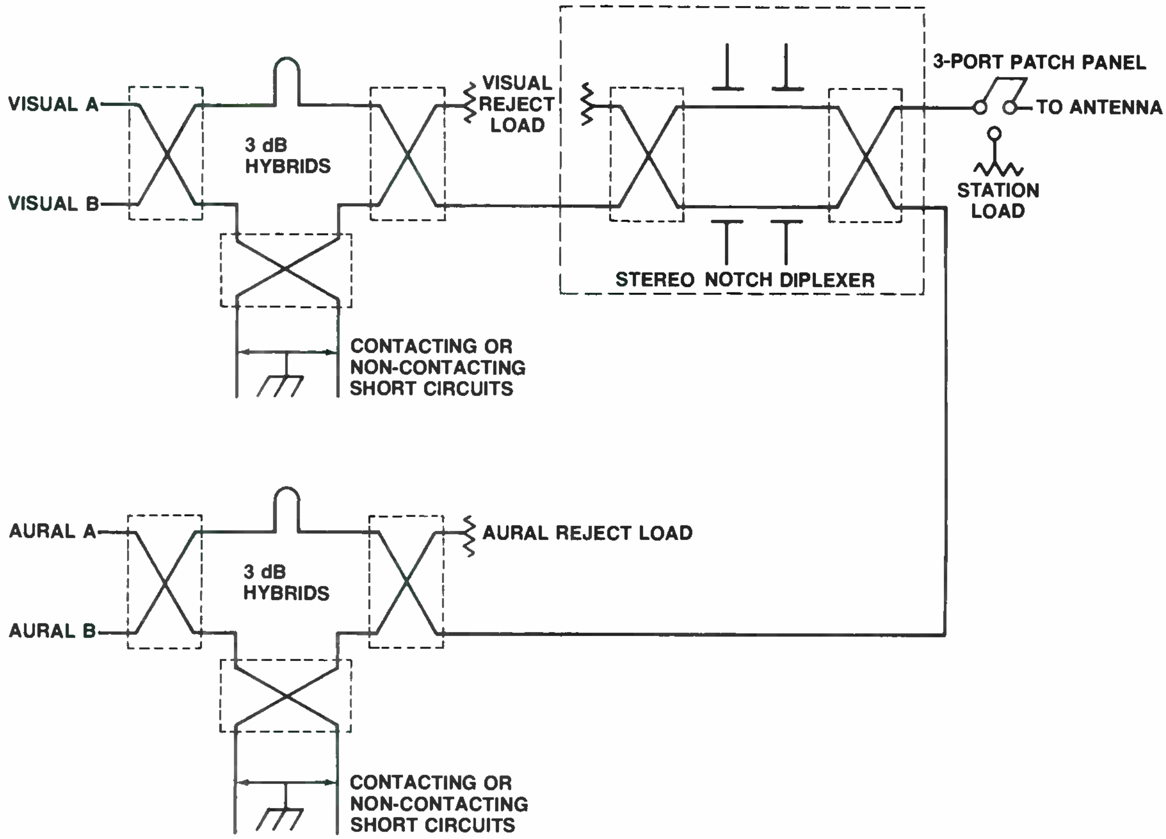
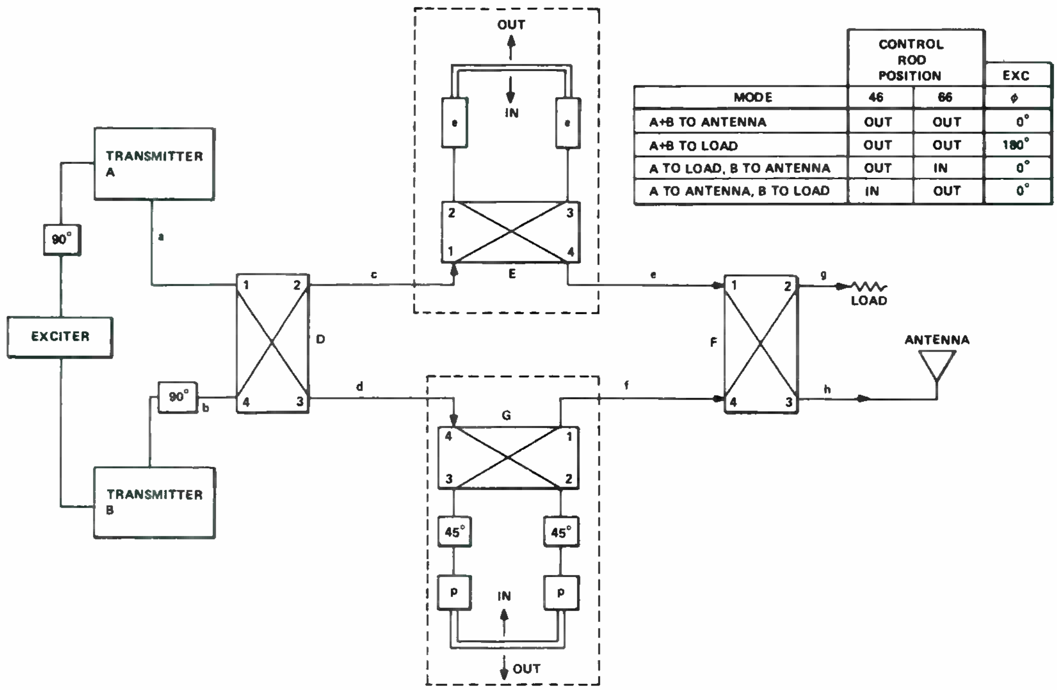


Fig. 33. RF flow diagram VHF "switchless" system with hybrid phase shifters.



MODE	CONTROL ROD POSITION 46	66	EXC φ
A+B TO ANTENNA	OUT	OUT	0°
A+B TO LOAD	OUT	OUT	180°
A TO LOAD, B TO ANTENNA	OUT	IN	0°
A TO ANTENNA, B TO LOAD	IN	OUT	0°

Fig. 34. Block diagram RCA OPTO-SX "switchless" system. (Courtesy RCA)

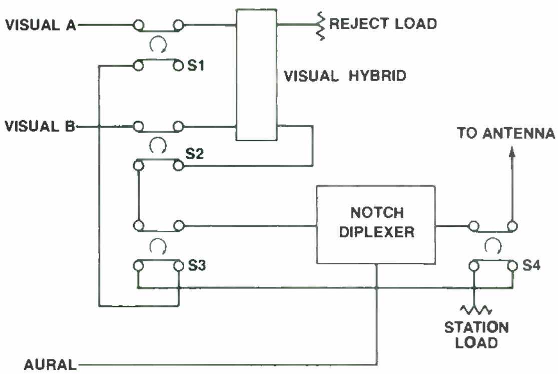


Fig. 35. RF flow diagram output switcher parallel visual amplifiers.

whether the transmitter signals will be routed through the diplexer, while S4 routes the output of the diplexer to the antenna or station load. The aural amplifier is routed directly to the diplexer. This system would have the four basic modes of operation:

1. Visual A & B combined to the antenna
2. Visual A & B combined to the station load
3. Visual A to the antenna and visual B to the station load
4. Visual B to the antenna and visual A to the station load

In addition, each of the modes could be operated either multiplexed or normal.

Recent developments in diplexers have simplified the switching systems. Aural notch detuners allow the multiplexed signals to pass through the notch diplexer, rather than being switched around it. The detuners will raise the aural notch cavities frequency so that it is above the aural carrier. This allows the multiplexed visual carrier to pass through the diplexer, just as the visual signal does normally.

Each RF output switching system is usually unique. Either the RF layout of the system will be slightly different, or the mechanical layout of the system needs to be changed to fit in the transmitter building. Since this is usually the case rather than the exception, most manufacturers are equipped to handle these situations. Fig. 36 shows a system utilizing coaxial patch panels and switches on the input, and a waveguide patch panel on the output of the diplexer.

UHF "Switchless" System (Waveguide)

One of the more recent developments in RF switching systems is the "switchless" phase-shifter systems. It is used to combine the outputs of higher power UHF amplifiers and can be used for either aural or visual service. This system consists of a 3 dB 90 degree hybrid, a dual phase shifter, a reject load, and a magic tee (180 degree hybrid) and is shown in Fig. 37. To better understand how the system operates, it is essential to understand the individual component operation.

The magic tee (180 degree hybrid) works similarly to the 90 degree hybrid. The difference is the amount of phase difference of the device. When it is used as a splitter, the outputs will either be in-phase or 180 degrees out-of-phase, depending which input is being driven. When used as a combiner, the magic tee will combine signals that are in-phase into the main output or into the coupled output if the signals are 180 degrees out-of-phase.

The phase shifters consist of a movable piece of dielectric material inside a section of waveguide. When the dielectric material is against the side wall of the waveguide, the phase shift will be at the minimum. As the dielectric material is moved toward the center of the waveguide, the phase shift of the signal going through the waveguide will increase. By choosing the type and amount of dielectric material, the relative phase shift can be adjusted to produce 90 degrees of phase shift. The amount of phase shift with the dielectric material against the side wall is not important in this instance. The critical point is that the phase shift through the two units are equal. Therefore, assume that there is no phase shift through the unit, when the dielectric material is against the side wall and 90 degrees when it is in the center of the waveguide.

If a signal is applied to the A input of the hybrid, it will be split into two signals of equal amplitude that are phased 90 degrees apart. The signal appearing at point C will be in-phase with the input signal (Point A), while the signal at point D will lag the input signal by 90 degrees. The converse is true for a signal being fed into the B input. The signal at point D will be in-phase, while the signal at point C will lag 90 degrees. If two signals that are in-phase are applied to inputs A and B, then each of a the outputs (points C and D) will have two signals, one in-phase with the inputs and one lagging by 90 degrees.

With the assumption that the phase shifters have no phase shift when set to the minimum position, the signals at the output of the input hybrid (points C and D) would be applied to the input of the magic tee (points E and F). There will be a signal present at both points E and F that are in-phase with the input signal. The signal at point E was produced by amplifier A, while the signal at point F was produced by amplifier B. Since these signals are equal amplitude and in-phase they will combine into the main output of the magic tee. At the same time, the other two signals at point E and F are equal in amplitude and in-phase, therefore, they will combine just

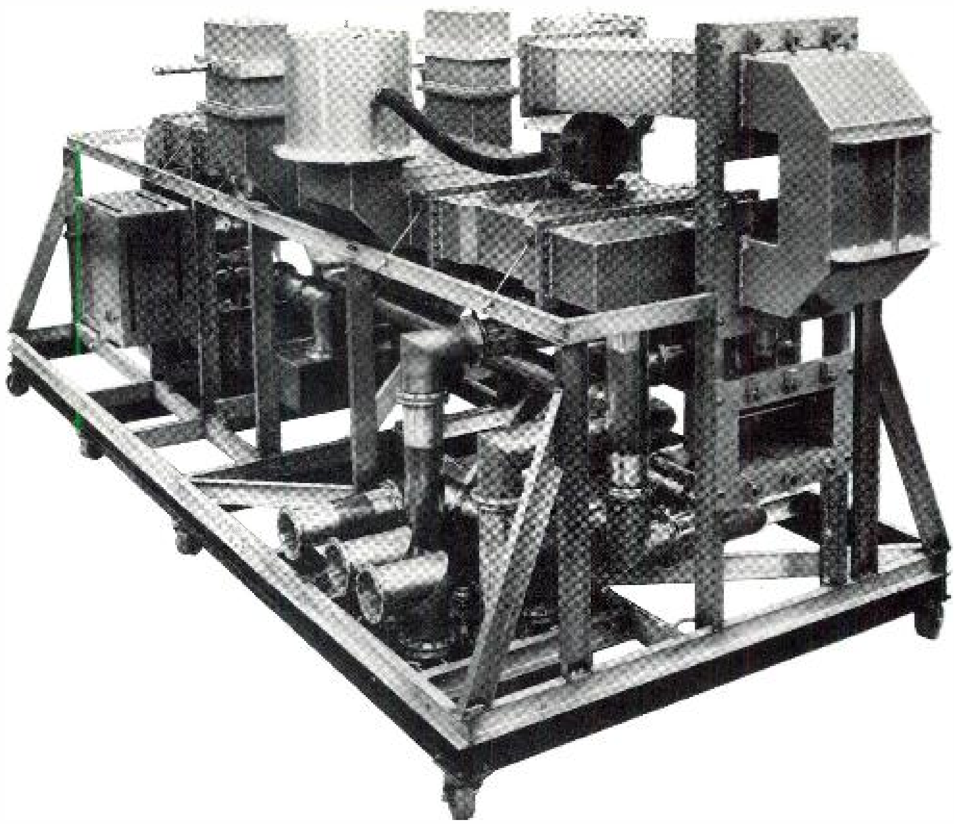


Fig. 36. UHF output switcher 110 kW TV transmitter.

MODE	PHASE SHIFTER #1	PHASE SHIFTER #2
A+B ANTENNA	0°	0°
A-ANTENNA B-LOAD	90°	0°
B-ANTENNA A-LOAD	0°	90°

INPUTS A + B ARE IN-PHASE

Fig. 37A. Phase chart magic tee "switching" system.

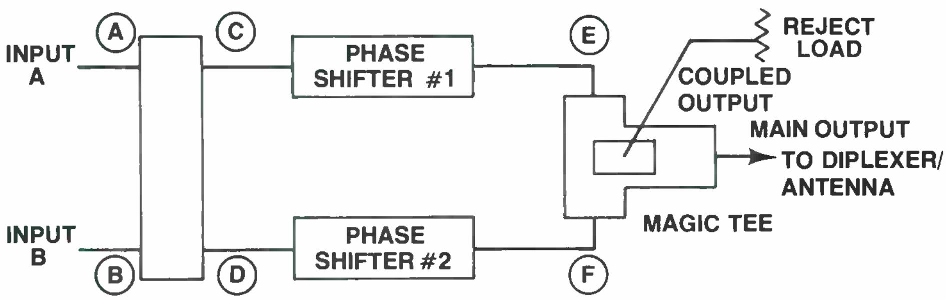


Fig. 37. RF flow diagram magic tee "switching" system.

as the other signals did. Since these signals are not in-phase at the output of the magic tee, the resultant signal will be the vector sum.

By inserting 90 degrees of phase shift in phase shifter #1, a new mode is created. The phases at the output of the hybrid (points C and D) will be the same as before. Since 90 degrees is added between points C and E, the phases at E will now be 90 degrees for signal from input A and 180 degrees for the one from input B. Therefore, on the inputs of the magic tee, the signals from input A are in-phase, while the signals from the B input are 180 degrees out-of-phase. The in-phase signals will add at the main output of the magic tee while the signals that are 180 degrees out-of-phase will add in the coupled output.

If phase shifter #1 is returned to the minimum position and phase shifter #2 is set for 90 degrees of phase shift, the signals from the B input will add in the main output, while the signals from the A input will add in the coupled output. By adding the phase shift in the #2 phase shifter, the signals at point F will be 90 degrees for the one from input B and 180 degrees for the one from input A. Thus the signals from input B will be in-phase at the inputs of the magic tee, while the ones from input A are 180 degrees out-of-phase.

Thus far three modes of operation have been accomplished within the "switchless" system. The fourth mode, both transmitters combined to the station load, can be done two ways. If the phase of the input signals are changed from in-phase to 180 degrees, the combining that takes place, will be applied to the coupled output (reject load) rather than the main output. The second method is to add a switch to the output of the system to allow the output to be connected to the antenna or the station load. The later seems to be the more common method at the present time.

The "switchless" phase shifter can be changed under power, since there are no contacts that are breaking and making. The only part that is moving is the piece of dielectric material in the phase shifter section. Since the full power of one transmitter can be applied to the reject load, it must be capable of handling that power.

In the past, switching systems used switches that changed the RF path by mechanically moving the parts of the switch. A typical switch will have around 60 dB of isolation between the paths of the switch. In the "switchless" system there is no mechanical isolation. The isolation is provided by the isolation of the hybrid and the magic tee within the system. Typically, this isolation will be on the order of 35 to 45 dB, which is sufficient for good performance. However, the operator must be aware that the isolation that he has been used to in a switch type system is not there in the "switchless" system. Therefore, when maintenance is being performed on the system or the transmitters, there may be a small amount of power present from the other transmitter.

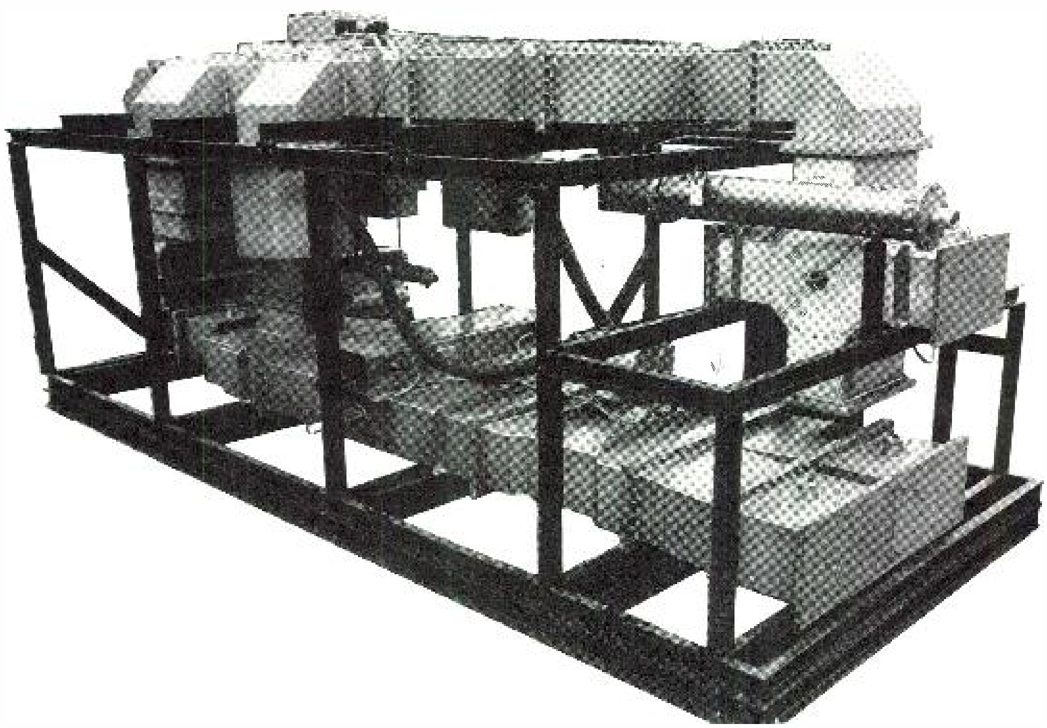


Fig. 38. UHF "Switchless" system with notch diplexer.

Multi-Transmitter Different Frequencies

Coax System

Within the FM band there is a growing demand for multiplexing systems that not only provide the capability of simply combining several stations but also provide a spare broadband port for emergency use should any module in the system fail and/or dual outputs with switching should either half of the antenna fail and extended monitoring capabilities.

The basic functions of a multiplexer module have been discussed as a category of filters earlier in this chapter. Here the peripheral features will be explored in an effort to examine additional benefits of a multiplexer system.

Whether the diplexer modules in the system are made of band pass or band stop cavities the system can be built with N modules or N-1 modules where N is the number of channels to be combined. Building the system with N-1 modules is the most economical way while N modules provide a spare broad band input. The spare input can be used as an emergency input if any of the modules fails for any reason. A switch or patch panel is needed both on the input side and output side of each module. See Fig. 39 and 40 for typical schematics of these systems. (Fig. 41 is a 9-station band stop system). The need for a patch panel on the input side is obvious. The patch panel is also necessary on the output so that the defective module can be by-passed. It would reject the frequency of the bypassed module at any input of the module due to symmetry.

The modules in the multiplexer also provide built-in isolation to any other frequency which might be transmitted from the same tower or another antenna. This is true only at the so called narrow band inputs. So the likelihood of generating inter-modulation products in transmitters tied to multiplexer is reduced in combination with sister stations in the multiplexer and also in combination with other local stations. However, this system does not necessarily preclude the, need for filters in "other" local stations transmitters.

If broadcasters on the system are committed to back up systems, they may also find it advantageous to split the output of the multiplexer into two transmission lines, one each feeding top and bottom half of the antenna. With proper combination of patch panels and a hybrid it is possible in emergency situations to operate at full or reduced power into either half of the antenna assuming lines and antenna have appropriate power capacity.

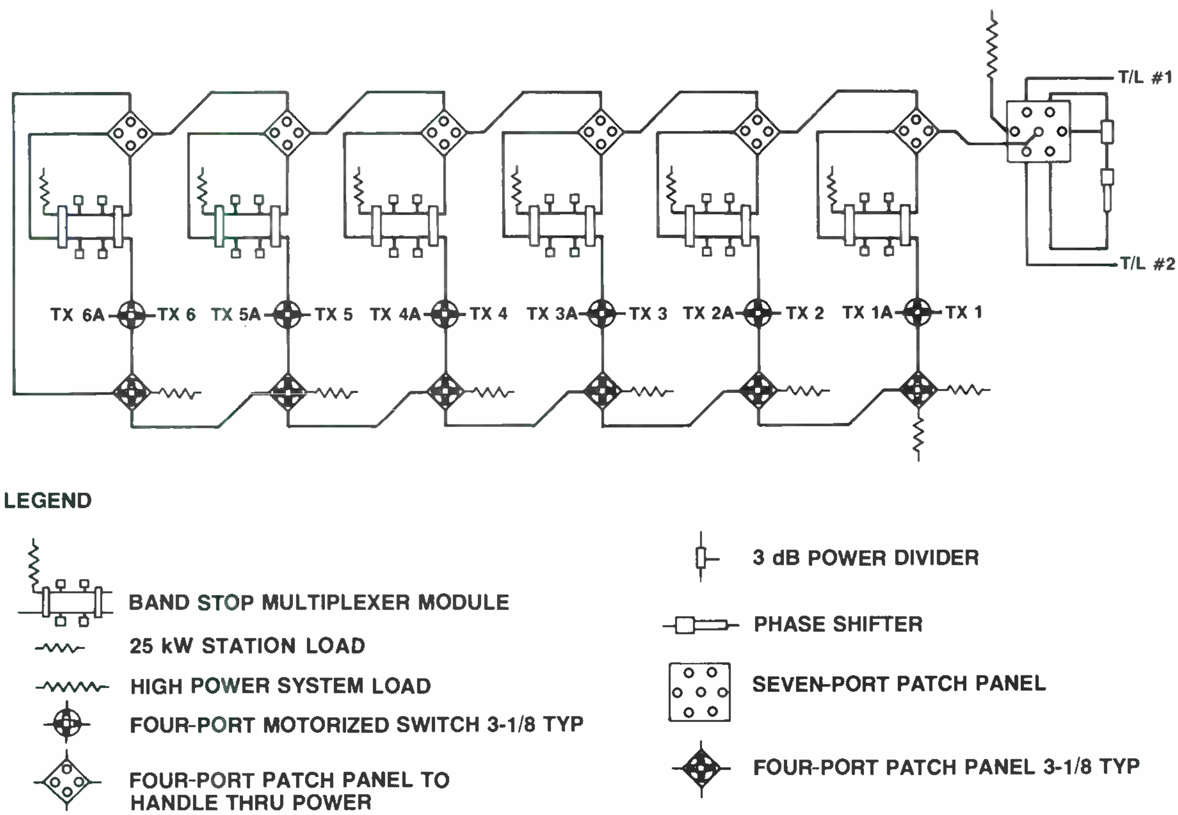


Fig. 39. Schematic of 6 module band stop multiplexer.

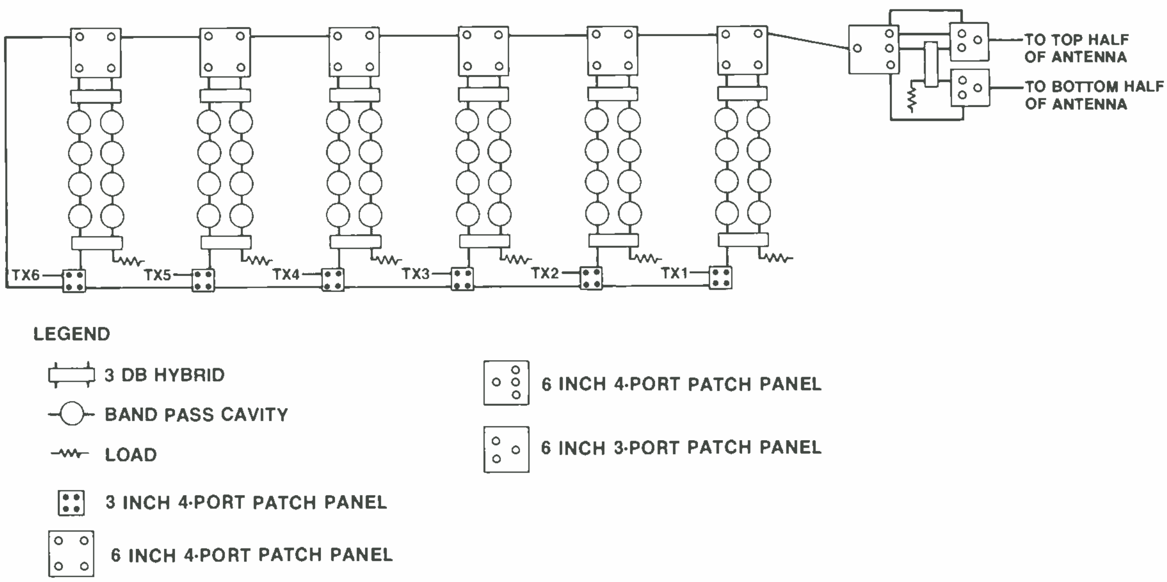


Fig. 40. Schematic of 6 module band pass multiplexer.

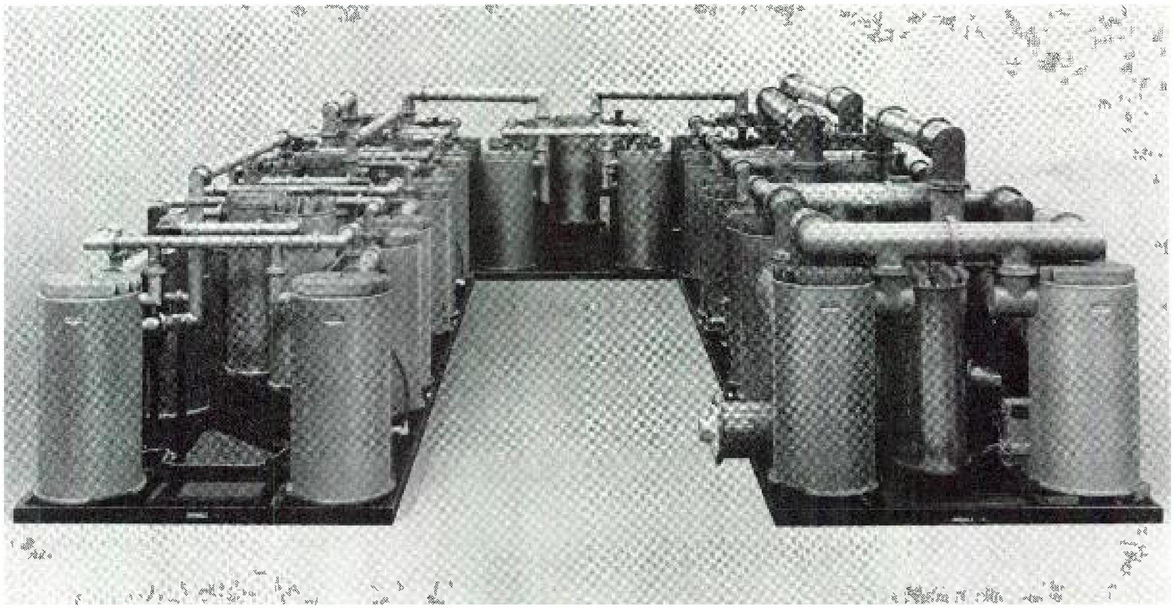


Fig. 41. 9 station band stop multiplexer at Senior Road Tower Group in Houston, Texas. Manufactured by Dielectric Communications.

The dividing of costs for a system among all participants often makes it possible to consider monitoring systems that any one participant might have considered too costly. At a minimum, each station must have individual fail safe power trip to trip the transmitter. Some broadcasters may consider a computer monitor system superimposed on the fail safe. The computer can monitor forward and reflected power. It can monitor status of interlocks and heat sensors. It can be programmed to transmit status hourly, daily or upon an unusual event through a modem to a responsible individual.

All of the features mentioned need to be addressed with the philosophy of the participants in mind. These systems are all custom made using components that have been standardized over years of use in the industry. Extensive discussions with manufacturers or suppliers are necessary to specify sizes, power capacity, VSWR, insertion loss, band width response, group delay, patch panels, switches, monitoring, interlocks, heat sensors, cooling and layout to meet individual requirements. When seeking bids it is prudent to specify all of the above so that all bidders are quoting the same system. These systems can be built with all the bells and whistles or stripped to a bare minimum.