TELEVISION ANTENNA INFORMATION

(UHF AND VHF)

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A NEW UHF TELEVISION ANTENNA TFU-24B

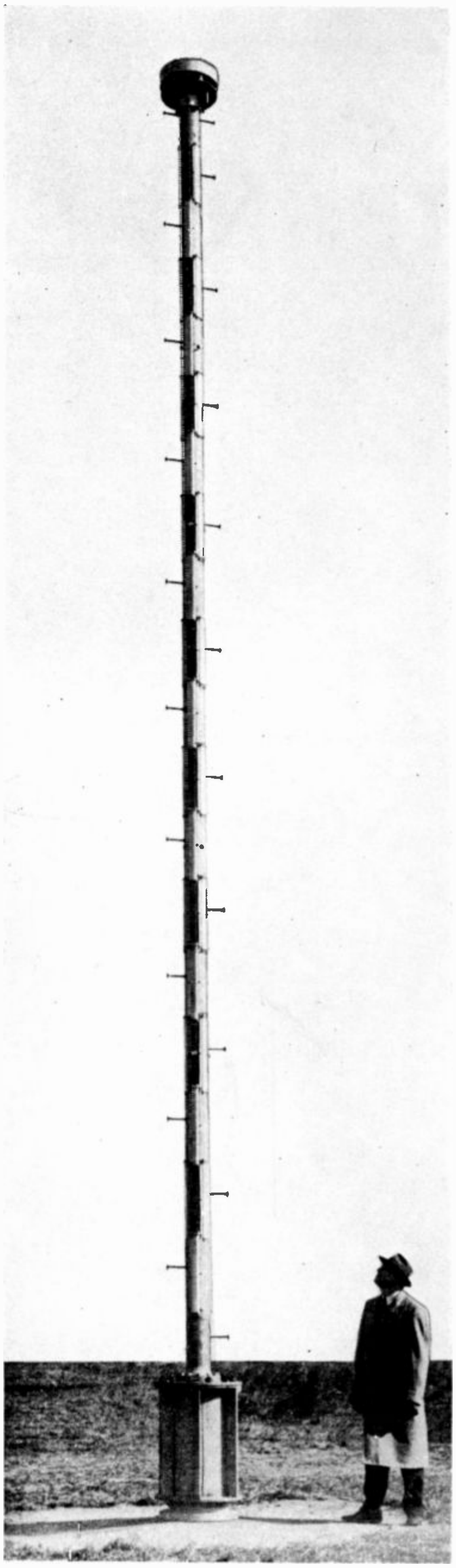

FIG. 1. TFU-24-BH Antenna Setup for Icing and Horizontal Pattern Tests.

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RCA Broadcast Engineering

RCA has pioneered in research and development of UHF transmitting equipment since World War II.[1,2,3,4,5,6,7] Much work has been done on UHF transmitting antennas[1,2,6] and two experimental television transmitting installations were made by RCA using slotted cylinder antennas.[2,6] This experience, combined with that obtained with the RCA 8-section Pylon FM broadcast antenna[8,9] having a power gain of about 12, has contributed to the design of the new RCA Type TFU-24-B commercial antenna.

The TFU-24-B antenna has the highest gain of any omni-directional antenna yet developed for high frequency transmission. The improvement in performance and simplicity of the TFU-24-B antenna is readily apparent when comparison is made with its prototype antenna installed at Bridgeport, Conn. during 1949[6], which has given continuous trouble-free operation for more than a two-year period.

The many features of the Bridgeport[6] model antenna which contributed to its excellent reliability have been included in the commercial TFU-24-B antenna. However many improvements which have been made are evident when the typical experimental performance data are considered.

The RCA TFU-24-B antenna is of slotted tubular steel construction as shown in Figs. 1, 2, 3, 4, 5 and 6. Each radiating layer consists of 1-inch wide slots approximately 1.3 wavelengths long parallel to the axis of the cylinder and equally spaced around the circumference of the cylinder. Adjacent layers of slots are staggered or rotated 60° to obtain maximum mechanical strength and a circular horizontal pattern. The energy is distributed to the 16 to 18 layers of slots by means of a single coaxial line feeder system within the self-supporting slotted cylinder radiat[illegible] The inside of the slotted steel radiator serves as the outer conductor of the coaxial line and a coaxial copper tube within the cylindrical radiator serves as the inner conductor. A coaxial line is installed within the inner conductor to obtain center feed with attendant benefits of adjustable vertical pattern tilt, symmetrical patterns for any frequency, and greater bandwidth than obtainable with an end-fed antenna.

The antenna incorporates many mechanical features and qualities not available in any other high frequency broadcast antenna. The slotted cylinder is constructed of hot-rolled open hearth structural steel, hot dip galvanized to obtain a structural life which is expected to exceed 50 years. The outer fiber stress for the highest wind loadings (50/30 lbs./sq. ft.) is less than half that permitted by most building and structural steel codes as shown in Fig. 7. Particular attention has been given to all parts of the antenna to assure maximum durability; all parts and materials are selected for high corrosion resistance and galvanic compatibility. Slot cover end caps are cast aluminum; small hardware and metal parts aluminum or stainless steel; pole steps hot dipped galvanized forged steel; mounting flange bolts stainless steel or hot dip galvanized high strength alloy steel; leveling plates hot dip galvanized steel; transmission line copper with brass or bronze parts and teflon insulators; coupling loop capacitors teflon; shorting plugs brass and bronze; beacon mounting and ventilator aluminum or hot dip galvanized steel; and slot covers polyethylene containing antioxidant and ultra-violet inhibiting dye.

The pole mounting flange is of special high strength alloy steei having high impact resistance at temperatures of −60°C. This is particularly important since ordinary carbon structural steel does not have

** Part of a Dissertation to be submitted to the Graduate School of the University of Pennsylvania as partial fulfillment of the requirements for a degree of Doctor of Philosophy in Electrical Engineering.*

FIG. 2. Top View of TFU-24-BH Antenna with Beacon Mount Removed Showing Spoke Type Shorting Plug and Transmission Line. Harness is moved by use of Ring for Electrical Pattern Tilt Adjustment.

very good impact resistance at low temperatures. The weld neck mounting flange is welded to the structural tube by an automatic machine and the weld is "gamma rayed" using a radium capsule within the tube and a photographic film around the outer circumference of the weld. The weld exceeds requirements of the American Welding Society. Each weld photograph is filed by the fabricator for a period of 10 years.

The slots are cut in the steel cylinder by an automatic oxyacetylene cutting torch. This process is fast, less expensive and produces tolerances and finish comparable to those of milled slots. The automatic cutter utilizes a photo-electric or magnetic follower following a master template or layout and has sufficient "intelligence and skill" to cut the semi-circular slot ends without the necessity of drilling holes at each end of the slot.

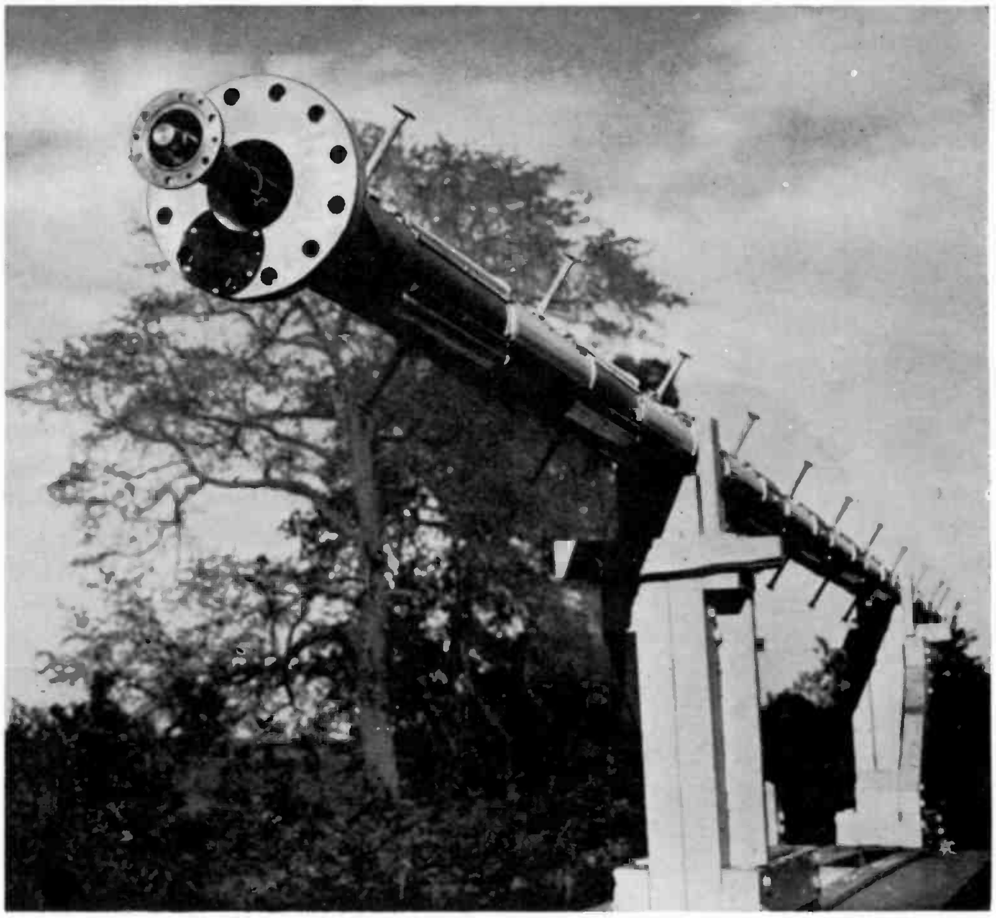
The entire antenna is a complete one-piece assembly which is shipped to the customer completely tested and adjusted. Experience has indicated that UHF antennas shipped "knocked-down" will require a large amount of adjustment and test after installation to obtain satisfactory performance for UHF television. The cost of such extensive field adjustment and test greatly exceeds the small additional shipping cost of an antenna completely assembled and tested. Because of the critical nature of UHF antenna equipment, it is recommended that an RCA Service Company Television Broadcast Engineer "check out" the antenna system on arrival and after installation to assure a minimum of installation trouble and expense. Experience has shown that many outages of television transmitting antennas are caused by lack of specialized installation experience and tests.

The TFU-24-B antenna (see Fig. 7) is inexpensive and easy to install and in most cases may be installed in one or two hours after the rigging is set up. Two wedge-shaped disk leveling plates are installed under the antenna mounting flange to provide a level base for the antenna mounting. The leveling plates may be adjusted prior to the antenna installation by using a sensitive machinist's level to obtain a very accurate adjustment. If desired, the antenna may be tilted mechanically using a level and feeler gauges to adjust the leveling plates to the required slope. Electrical tilt may be incorporated by shifting the harness a few inches during or after the initial installation. The simplicity of this adjustment permits determination of optimum tilt by field experiments after the antenna has been put into operation.[8] A combination of mechanical tilt and electrical beam tilt is desirable for many terrain conditions existing at suitable UHF television antenna sites.

Both types of beam tilt adjustment assure that the high gain of the TFU-24-B antenna will give the best possible coverage with presently available UHF transmitter powers. If the FCC should decide upon no limit, or a very high ERP limit for UHF-TV, a station will obtain maximum Class A service area when a combination of highest practical gain and highest available transmitter power are used.

Where economical operation is not an essential consideration and UHF transmitters of sufficiently high power are available, perhaps some UHF stations may consider the use of 500 to 1000 KW UHF transmitters and low gain antennas. Propagation

FIG. 3. Bottom View of TFU-24-BH Antenna Mounted on Turntable for Vertical Pattern Measurements, Showing Mounting Flange and Transmission Line Connection.



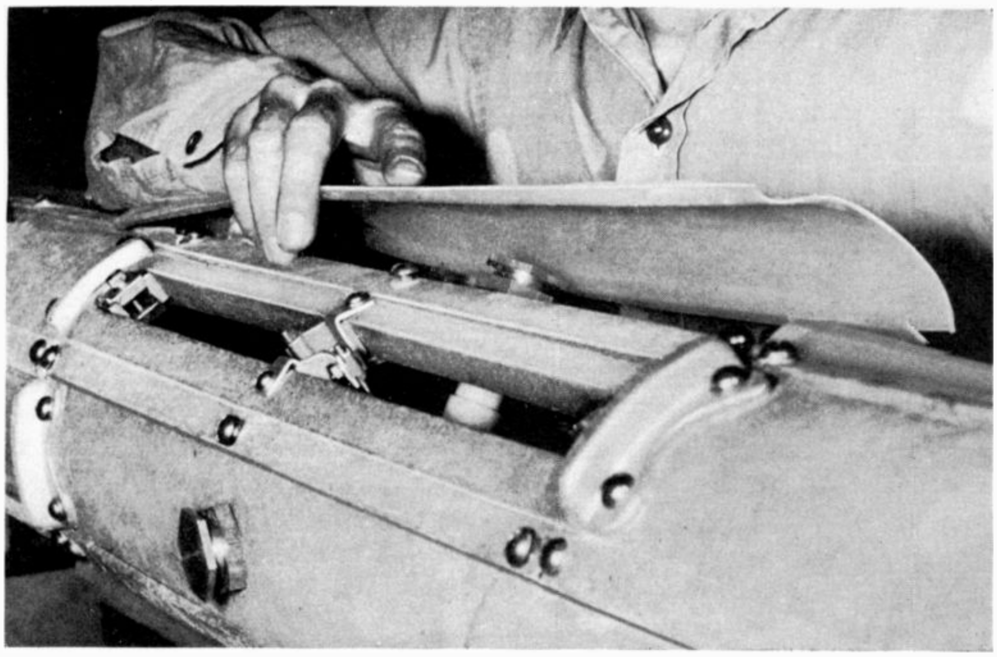


FIG. 4. Closeup of TFU-24-BH Antenna Showing Removal of Slot Cover.

measurements made at Princeton, N. J. on UHF signals transmitted from Bridgeport, Connecticut indicate that interfering signals beyond the useful service area of a UHF station can be greatly reduced by tilting the vertical pattern of a high-gain antenna down a suitable amount.[10]

A high-gain tilted beam antenna can give greater ERP within its service area than at the horizon. If ERP limitations by the FCC are based upon interference signals at and beyond the radio horizon and stated in terms of maximum permissible ERP directed at the horizon, stations with high-gain tilted beam antennas will have the advantage of greater signal strength within their service areas. Fig. 8 shows the relative advantage of a TFU-24-B antenna (Directivity gain 27.3) compared with a low gain horizontally polarized isotropic radiator (Directivity gain .61) which radiates equal signal in all directions. Fig. 8 considers both mounted on a 5000-foot tower and driven by a 10 KW transmitter. The advantage of higher signals within the service area is characteristic of the TFU-24-B antenna.

Recordings of field strength of Bridgeport UHF Station KC2XAK made on top of the RCA Building in New York City during 40 to 50 miles an hour winds at Bridgeport, Connecticut indicated received field strength variations of approximately ±10%.[3,4] The tower used in the Bridgeport installation is self-supporting and does not provide an antenna base stability nearly as great as that of most guyed towers supporting a similar antenna load.

This experience is particularly significant because width of the main beam and locations of first nulls are almost identical for the Bridgeport antenna and the new TFU-24-BH antennas. Greater field strength variations were observed at some close-in locations at Bridgeport during high winds. However, satisfactory reception was obtained at all locations since the signal variations were well within the control range of the receiver A.G.C. system. Experience indicates that A.G.C. is required on all UHF TV receivers to obtain satisfactory reception for many reasons. Consequently, signal variations caused by mechanical oscillations of a properly installed high gain transmitting antenna will not cause unsatisfactory reception during high winds which occur occasionally. Exceptionally strong storms may cause unfavorable reception in some locations.

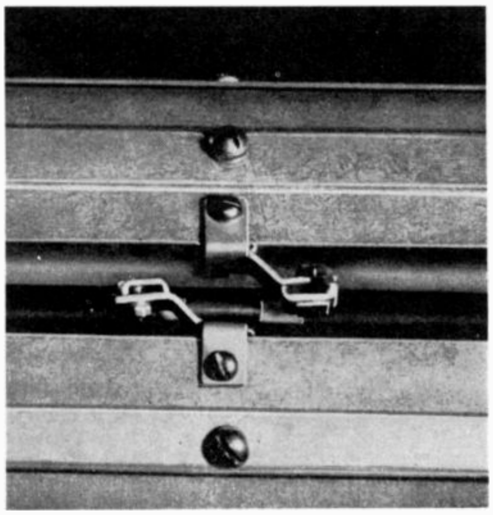
The effect of high winds on lead in and receiving antenna stability will have a more disastrous effect on the quality of reception than any possible transmitting antenna variation for a well designed transmitting antenna and support installation. The bending stresses in the TFU-24-B antenna at the highest wind velocities are quite conservative (about 9000 psi) in comparison with permissible structural stresses (about 20,000 psi) to minimize bending and deflection of the antenna structure during high winds.

Horizontal Pattern

The horizontal pattern in the principal plane of the TFU-24-B antenna may be calculated from assumed boundary conditions on the outside surface of a perfectly conducting slotted cylinder.[11,12,13] In the case of the TFU-24-B antenna, excellent agreement is obtained between calculated and measured results as shown in Figs. 9 and 10.

Assume an infinitely long perfectly conducting cylinder of radius, a, with three slots parallel to the axis equally spaced around the circumference. The slots are excited with equal in-phase voltages and the field is assumed to be uniformly distributed across the slot and polarized to produce only a circumferential component of electric intensity E_ϕ (in cylindrical coordinates). In the case of the principal plane pattern, E_ϕ through the center of the array normal to the axis of the cylinder, the amplitude and phase of the field along the slot does not affect the pattern. This is true for the TFU-24-B antenna whose horizontal pattern may be computed from an array of six equally spaced in-phase slots on the circumference of a cylin-

FIG. 5. Closeup of TFU-24-BH Antenna Slot Showing Tuned Coupling Loop.



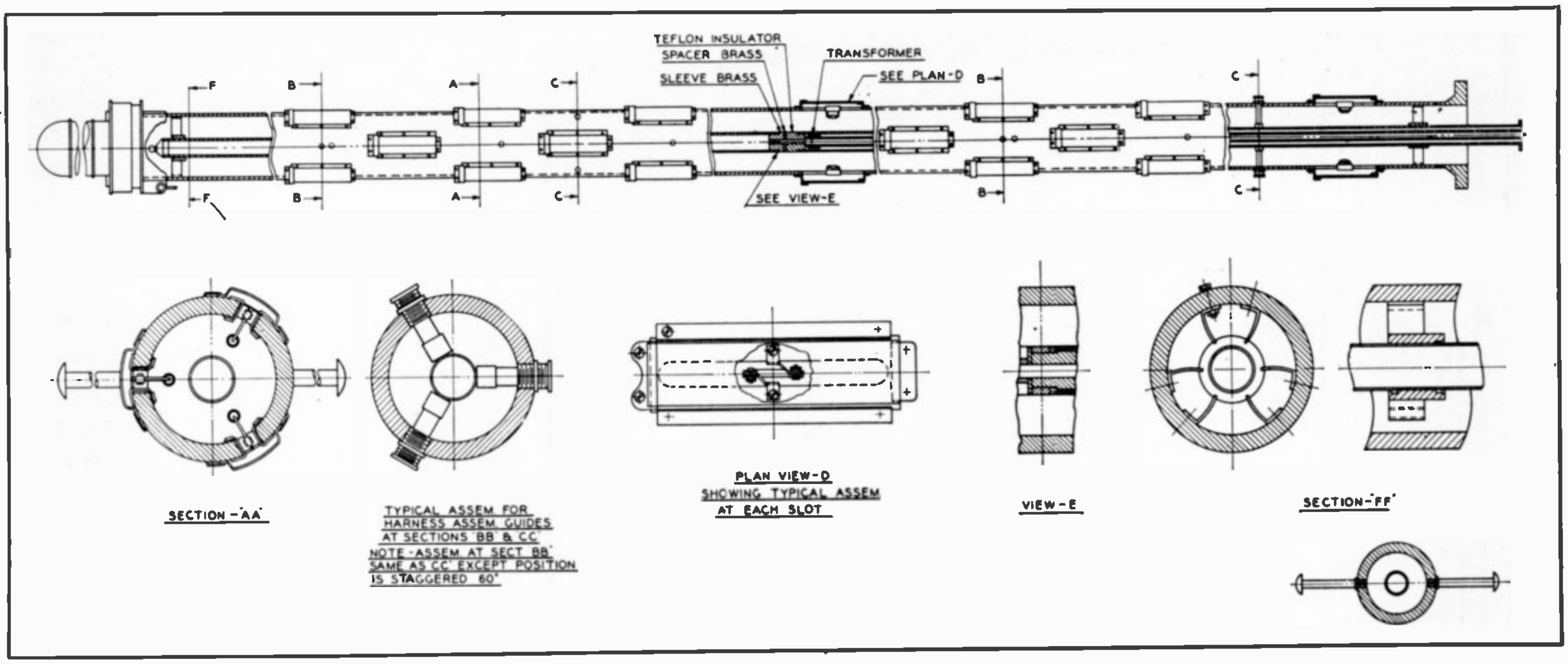


FIG. 6. Cross Section of TFU-24-BH Antenna Assembly.

der or by vector addition of two 3-slot patterns similar to Figs. 9 and 10 rotating one pattern 60° relative to the other.

For a 3-slot cylinder with slots equally spaced around the circumference and parallel to the Z axis, a is the radius of the cylinder and 2 δ is the angular width of the slots. The boundary conditions are:

$$E_\phi\Big|_{r=a} = E_o e^{j\omega t} \text{ for } \begin{cases} -\delta < \phi < \delta \\ -\delta < \left(\phi - \frac{2\pi}{3}\right) < \delta \\ -\delta < \left(\phi - \frac{4\pi}{3}\right) < \delta \end{cases} \qquad \text{Eq. 1}$$

$$E_\phi\Big|_{r=a} = 0 \qquad \text{for all other real } \phi$$

These boundary conditions may be expressed by a Fourier Series of the cylindrical field distribution on the surface of the conducting cylinder of the form:

$$E_\phi\Big|_{r=a} = \sum_{n=-\infty}^{\infty} C_n \left\{ e^{j[n\phi + \omega t]} + e^{j[n(\phi - \frac{2\pi}{3}) + \omega t]} + e^{j[n(\phi - \frac{4\pi}{3}) + \omega t]} \right\} \qquad \text{Eq. 2}$$

The coefficient C_n is:

$$C_n = \frac{E_o}{n\pi} \sin(n\delta) \qquad \text{Eq. 3}$$

The field at any radius r outside the cylinder may be represented by an infinite series of Hankel Functions.[11]

$$E_\phi = jk\mu\omega \sum_{n=-\infty}^{\infty} a_n H_n^{(2)'}(kr) \left\{ e^{j[n\phi + \omega t]} + e^{j[n(\phi - \frac{2\pi}{3}) + \omega t]} + e^{j[n(\phi - \frac{4\pi}{3}) + \omega t]} \right\} \qquad \text{Eq. 4}$$

where $H_n^{(2)}(Z)$ = Hankel Function of Second Kind

$$H_n^{(2)'}(Z) = \frac{d}{dZ} H_n^{(2)}$$

$$\left.\begin{array}{l} k = \frac{2\pi}{\lambda} \\ \lambda = \text{wavelength in space} = \frac{v}{f} \\ v = \text{velocity of light in space} \\ \mu = \text{permeability} \end{array}\right\} \text{in M.k.s. units}$$

When r = a, equation 4 must be equal to equation 2 and the coefficients of the exponentials are therefore equal.

$$\frac{E_o}{n\pi} \sin(n\delta) = jk\mu\omega\, a_n H_n^{(2)'}(ka)$$

$$a_n = \frac{E_o \sin n\delta}{jk\mu\omega n\pi H_n^{(2)'}(ka)} \qquad \text{Eq. 5}$$

The horizontal radiation pattern may then be determined at a large fixed radius r_a from the antenna.

For $r_a >> a$ and $r_a >> \lambda$ we may use the asymptotic expression for Hankel functions.

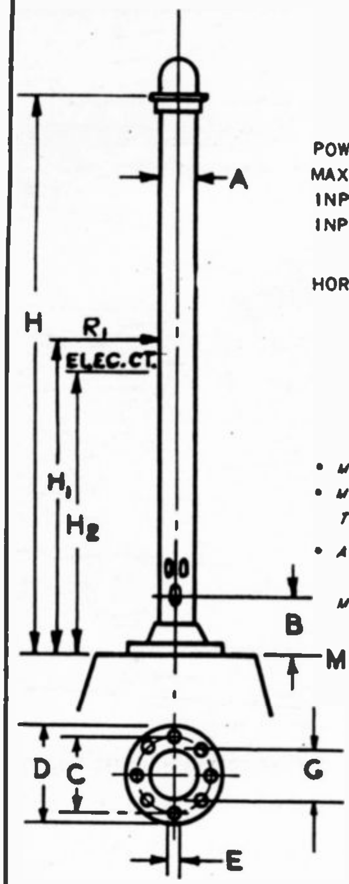
Also for narrow slots

$$\frac{\sin n\delta}{n} \cong \delta \text{ for } |n| \leqq n_o \qquad \text{Eq. 6}$$

where n_o is defined as the largest n for which the approximate equation 6 is true.

If the maximum number of terms n of the Hankel function series is such that $n \leqq n_o$ for good accuracy, then

PRELIMINARY ENGINEERING DATA
UHF SLOTTED TELEVISION ANTENNAS



ELECTRICAL SPECIFICATIONS

POWER HANDLING - 10 KW UP TO 5000'
MAXIMUM AMBIENT - 45C
INPUT IMPEDANCE - 50 OHMS V.S.W.R. LESS THAN 1.1
INPUT CONNECTION - SINGLE 3-1/8 U.H.F. FLANGED COAXIAL LINE.
HOR. PATTERN CIRCULARITY - ± 0.5 DB

MECHANICAL SPECIFICATIONS

DESIGN ASSUMPTIONS

- *Max. wind velocity (1/2" rad. ice) 95 mph.*
- *Max. wind velocity (no ice) 110 mph. (50/30 psf) Tensile stress - below 20,000 psi*
- *Actual wind velocity*

Max. Stress on Bolts 18,000 psi

CHANNEL	LOW	MEDIUM	HIGH
FREQ. BAND (APPROX.)	470-625 MC	625-750 MC	750-900 MC
TYPE NUMBER	TFU-24 BL	TFU-24 BM	TFU-24 BH
MI NUMBER			
W LBS.	2300	1900	1600
A IN. (DIA.)	10-3/4	8-5/8	6-5/8
B IN.	39-	32	25
C IN. (BOLT CIRCLE)	15-1/4	13	10-5/8
D IN. (DIA.)	17-1/2	15	12-1/2
E IN. (BOLT DIA.)	1-1/8	1	7/8
F NUMBER HOLES	16	12	12
H FT.	40	37	34
H_1 FT. & IN.	21-6	19-4	18
H_2 FT. & IN. (ELEC. CT.)	20	18-6	17
R_1 (50/30 psf) NO ICE	1200	960	630
M FT/LBS (MOMENT)	26000	18500	12000
TENTATIVE GAIN	24	26	28
G TOP CAP HOLE IN. (DIA.)	9-3/4	7-5/8	5-3/4

FIG. 7.

$$E_\phi\Big|_{r>>a} = \frac{A}{j2\pi}\sum_{n=-n_o}^{n_o}\frac{e^{j[n(\phi+\frac{\pi}{2})+\omega t]}+e^{j[n(\phi-\frac{\pi}{6})+\omega t]}+e^{j[n(\phi-\frac{5\pi}{6})+\omega t]}}{H_n^{(2)\prime}(ka)} \qquad \text{Eq. 7}$$

$$A = 2E_o\,\delta\sqrt{\frac{2}{\pi kr}}\;e^{-j(kr-\frac{\pi}{4})} \qquad \text{Eq. 8}$$

$$E_\phi\Big|_{r>>a} = \frac{A}{j\pi}\left[3a_o + \sum_{n=1}^{n_o} a_n\left\{\cos n\phi + \cos n(\phi-120^\circ) + \cos n(\phi-240^\circ)\right\}\right] \qquad \text{Eq. 9}$$

$$a_o = \frac{1}{2H_o^{(2)\prime}(ka)}$$

$$a_n = \frac{j^n}{H_n^{(2)\prime}(ka)}$$

$$ka = \frac{2\pi a}{\lambda}$$

a and λ are in the same units.

Inspection of equation (9) will show that the coefficients of a_n are $\equiv 0$ except for $n \equiv 3m$, where m is any positive integer. For the TFU-24-B antenna, the single layer pattern may be evaluated with good accuracy by using only a_0 and a_3. Substitution of the following numerical values in equation (9) will give the horizontal pattern shown in Fig. 9.

$f = 850$ Mc.

$\lambda'' = \frac{11800}{f_{mc}}$

$D = 2a = 6\frac{5}{8}''$

Slot Width $= 1''$.

The relative phase of the field given in Fig. 9 is shown in Fig. 10. Vector addition of the field pattern of Fig. 9 with a similar pattern rotated 60° will give the field pattern of 6 equally spaced slots on the $6\frac{5}{8}''$ diameter cylinder which is the horizontal pattern in the principal plane of the TFU-24-BH antenna at 850 Mc. for an even number of layers. Fig. 12 shows the measured and calculated horizontal pattern for the TFU-24-BH antenna in the principal plane for which the angle of elevation $= 0$.

For one layer of the TFU-24-B antenna, the horizontal pattern becomes from equation (9) for $\theta = 0°$.

$$E_\phi\Big|_{r>>a} = \frac{3A}{j\pi}\left\{\frac{1}{2H_o^{(2)\prime}(ka)} - j\frac{\cos 3\phi}{H_3^{(2)\prime}(ka)}\right\} \qquad \text{Eq. 10}$$

$\theta =$ angle of elevation.

The horizontal pattern of a TFU-24-B antenna with an even number of layers is, by vector addition of two patterns, given by equation (9) which are shifted relative to each other 60°.

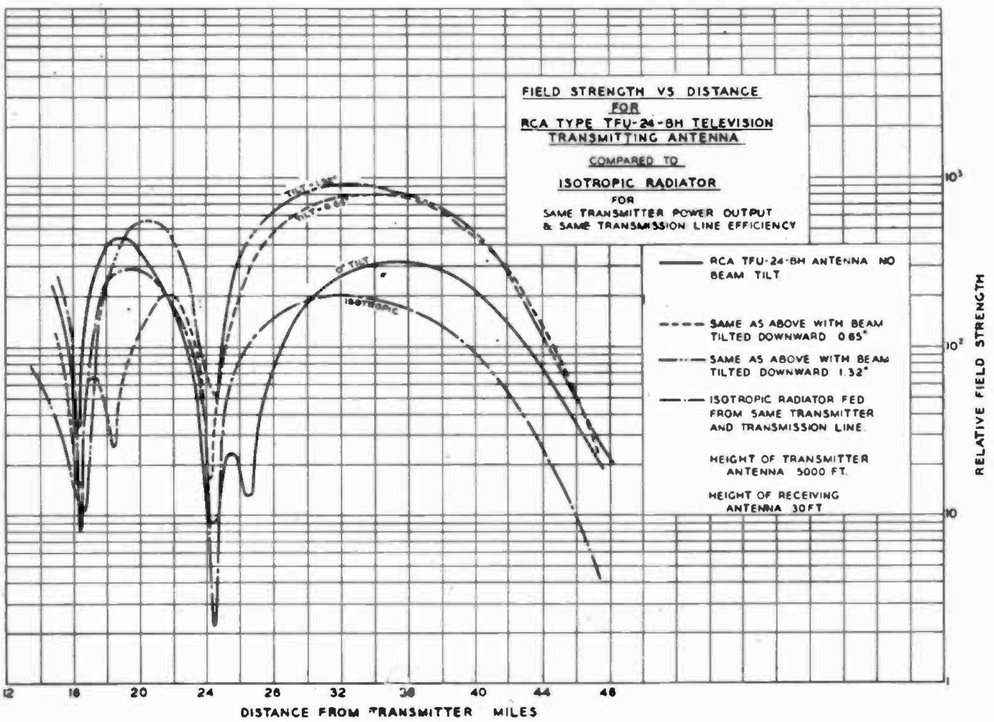


FIG. 8. Relative Field Strength Comparison for Low and High Gain Antennas with Same Power Input.

For $\theta = 0°$

$$E_\phi\Big|_{r>>a} = \frac{A}{j\pi}\left[6a_o + \sum_{n=1}^{n_o} a_n \left\{\cos n\,\phi^\circ + \cos n\,(\phi^\circ - 60^\circ) + \cos n\,(\phi^\circ - 120^\circ) + \cos n\,(\phi^\circ - 180^\circ) + \cos n\,(\phi^\circ - 240^\circ) + \cos n\,(\phi^\circ - 300^\circ)\right\}\right] \qquad \text{Eq. 11}$$

Inspection of coefficients of a_n in equation (11) reveals the coefficients of a_n are $\equiv 0$ except for $n = 6m$, where m is any positive integer; therefore, considering only a_o and a_6 we obtain the horizontal pattern of the TFU-24-B antenna with an even number of layers:

for $\theta = 0°$

$$E_\phi\Big|_{r>>a} = \frac{6A}{j\pi}\left[\frac{1}{2H_o^{(2)\prime}(ka)} - \frac{\cos 6\phi}{H_6^{(2)\prime}(ka)}\right] \qquad \text{Eq. 12}$$

From equation 12, it is apparent that the phase of the field does not vary with ϕ. If a_6 were neglected, the horizontal pattern would be a perfect circle. For the TFU-24-BH antenna at 850 Mc. a_6 is .232 percent of a_o. Consequently, the horizontal pattern is theoretically a perfect circle within ±.232%. Fig. 12 confirms this within the accuracy of measurement for $\theta = 0°$. If each layer of the TFU-24-B antenna had six slots instead of three slots, the horizontal patterns shown in Fig. 12 for other values of θ would approach a perfect circle as closely as the measured pattern for $\theta = 0°$. The calculation of Figs. 9 and 10 was done by H. B. Yin.

Directional horizontal patterns may be obtained using TFU-24-B antenna components to suit special applications. Fig. 13 illustrates a horizontal pattern obtained by using 1 set of colinear slots in a TFU-24-BM antenna cylinder. Directional UHF antennas would be custom designed for a particular application and the RCA Broadcast Transmitter Engineering Department should be consulted regarding directional UHF antennas.

Vertical Pattern

The measured vertical pattern of the TFU-24-B antenna closely resembles the

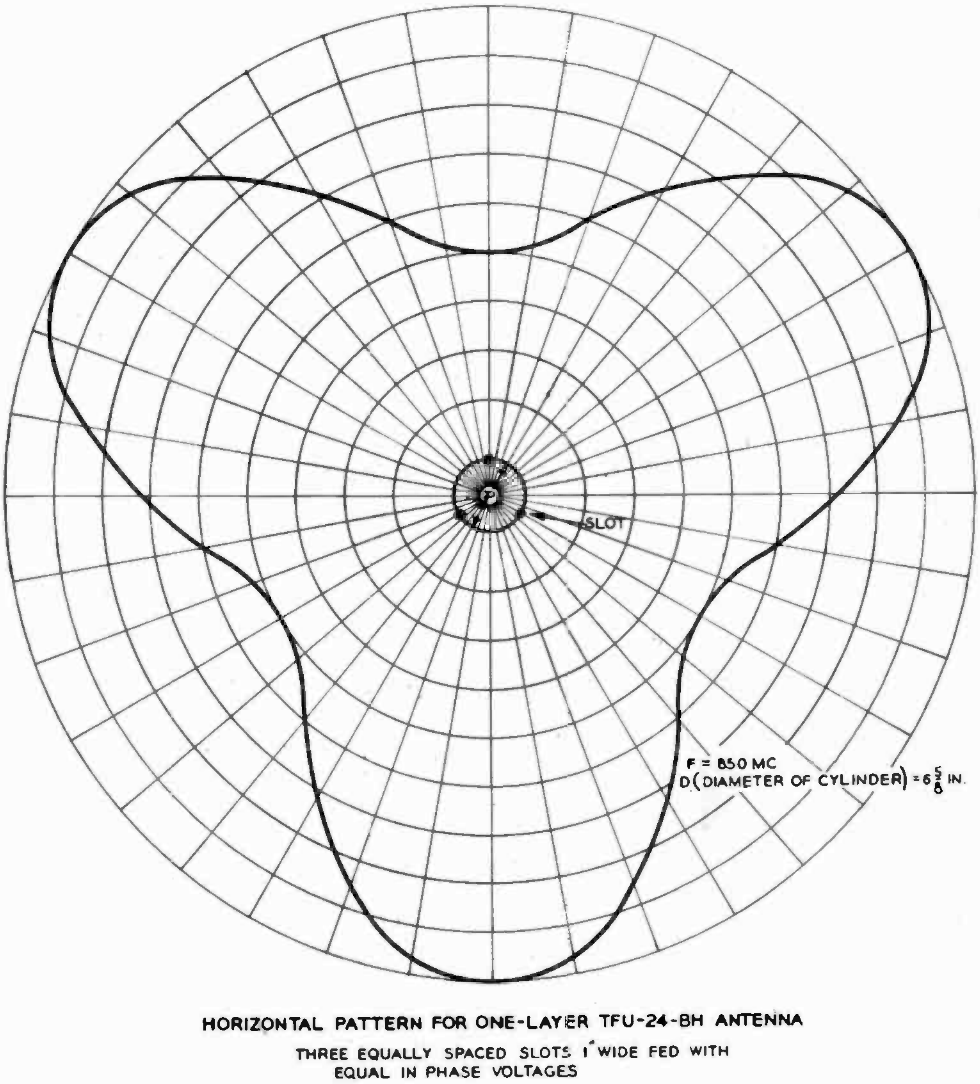


FIG. 9. Horizontal Pattern of One-Layer of TFU-24-BH Antenna at 850 Mc.

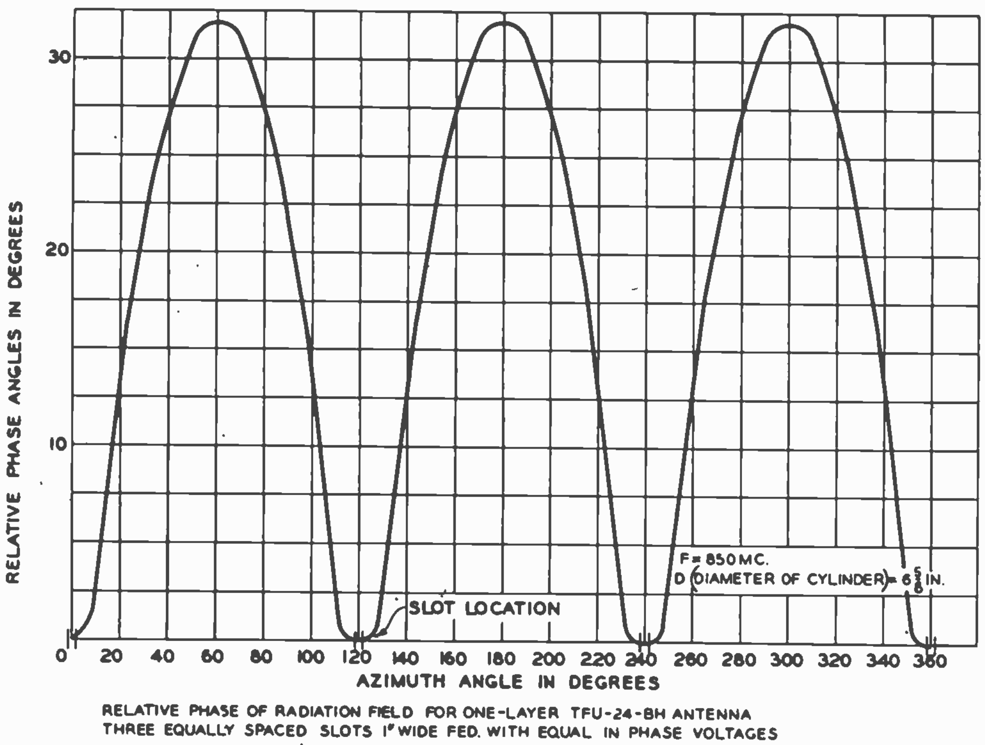


FIG. 10. Relative Phase of Radiation Field for One-Layer of TFU-24-BH Antenna at 850 Mc.

calculated pattern obtained by the product of an array factor for a colinear broadside array and a suitable element pattern.[13]

For the 18-layer TFU-24-BH antenna, the vertical pattern for the horizontally polarized component of electric field, E_ϕ, is given by the equation:

$$E_{\phi 18}(\theta) = \frac{\sin\left[\frac{9(1080°)}{2}\cos\theta\right]}{9\sin\left[\frac{1080°\cos\theta}{2}\right]} E_{\phi 2}(\theta) \qquad \text{Eq. 13}$$

where $E_\phi(\theta)$ = the relative field intensity, E_ϕ, of the array at a fixed radius, r, as a function of θ, maximum $E_\phi(\theta) = 1$.

$E_{\phi 2}(\theta)$ = the vertical field pattern of the radiating element, maximum $E_{\phi 2}(\theta) = 1$, at a fixed radius r. To obtain symmetry in the TFU-24-B case $E_{\phi 2}(\theta)$ is the field pattern of two layers of a slotted cylinder spaced 1.5 λ between centers. A typical $E_{\phi 2}(\theta)$ is shown in Fig. 14.

θ = angle from Zenith, in the spherical coordinate system shown in Fig. 17.

For a 16-layer TFU-24-BL and TFU-24-BM antenna, the theoretical vertical pattern is given by the equation:

$$E_{\phi 16}(\theta) = \frac{\sin\left[\frac{8\,(1080°)\cos\theta}{2}\right]}{8\sin\left[\frac{1080°\cos\theta}{2}\right]} E_{\phi 2}(\theta) \qquad \text{Eq. 14}$$

The TFU-24-B antenna may be considered approximately as an array of infinitesimally spaced circular current loop antennas whose diameter is the same as the TFU-24-B antenna. The total aperture is equal to the TFU-24-B antenna. Each loop has a uniform in-phase circumferential current.

Such an idealized array of uniform current loop antennas would radiate only a horizontally polarized component of electric field, E_ϕ.[18] Actual measurements of E_ϕ and E_θ on a TFU-24-BH antenna show the cross or vertically polarized component of electric field, E_θ, to be very small, as shown in Fig. 14. The power radiated by the E_θ component shown in Fig. 14 is about .3% of the total power radiated and hence causes a .3% reduction in measured gain. It is quite possible that the measured E_θ component is greater than that actually radiated due to non-ideal conditions in the measuring site, which cause conversion of some of the E_ϕ component of polarization. This polarization conversion could be caused by irregular terrain, trees, weeds and brush, fences, wires, etc.[18,14] In any case, the E_θ component of field in the TFU-24-B antenna is negligible for broadcast applications. However, it should not be concluded that all omni-directional antennas intended to radiate only an E_ϕ or E_θ component of field have negligible radiation in the undesired plane of polarization. Antennas whose radiating elements yield elliptic polarization may depend on interfering fields in adjacent elements to cancel undesired polarization in the principal plane. Such cancellation in the principal plane can still leave large amounts of cross polarized energy at other elevation angles. A measurement made on an antenna construction using the polarization interference principle indicated the gain was reduced approximately 25% by the undesired E_θ component of electric field. Some omni-directional VHF television broadcasting antennas radiating predominantly horizontal polarization have been shown theoretically and experimentally to have a gain reduction of 5 to 15% due to radiation of the E_θ component of field. It has been commonly accepted practice in the past to measure only the polarized component for which the antenna was intended to radiate and ignore the cross polarized undesired component. This was often justified by theory and measurements which showed the undesired cross polarized field to be zero or negligible in the principal horizontal plane. However, a later, more detailed study has shown the power radiated at other angles may represent 5 to 15% of

[13] Ibid. page 431.

[18] Ibid. page 163.

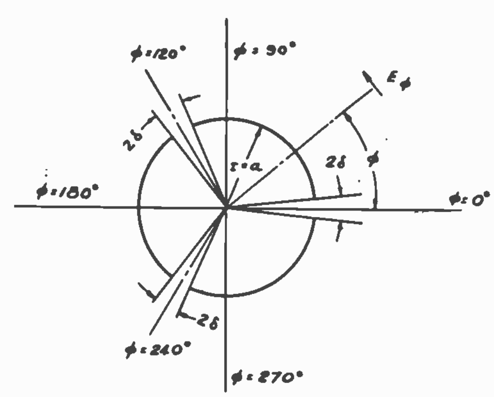


FIG. 11. Cylindrical Coordinate System Used for Three Slots in a Circular Cylinder.

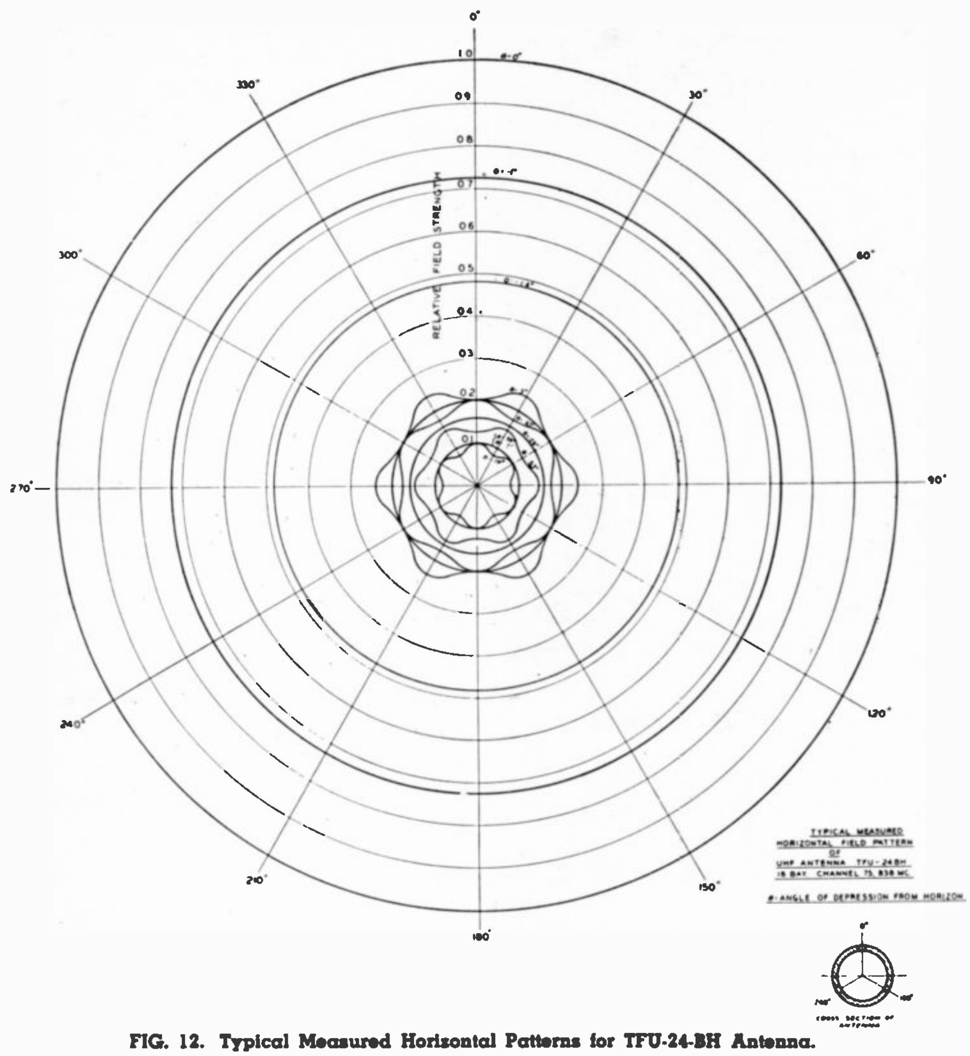


FIG. 12. Typical Measured Horizontal Patterns for TFU-24-BH Antenna.

the total power. The practical effect of 15% reduction of ERP on the coverage is negligible, and such an error should be acceptable; but as the state of the art developed and more accurate measuring techniques were used, an attitude approaching perfectionism has appeared. For this reason and because some more recent antennas have undesired cross polarized radiation which is not negligible, it is very desirable in pattern and gain measurements to account completely for both the E_ϕ and E_θ components of electric field.

Power gain and patterns are measured in a setup where the antenna whose pattern is to be measured is set on a rotating spindle with its center of radiation over the axis of the spindle as shown in Figs. 1 and 3. The plane of the antenna in which it is desired to measure the pattern is placed parallel to the ground.

The antenna whose pattern is to be measured is used as a receiving antenna which drives a recording voltmeter. The recorder chart is driven by a gear and servo system connected to the antenna spindle. A transmitting antenna which provides the received signal of the desired frequency is located at a point sufficiently distant to obtain nearly the lowest possible relative field strength in the nulls of the vertical pattern. In the case of the setup shown in Fig. 3, the transmitting antenna is about 2400 feet from the turntable and results in a waveform phase error of less than 15.7 electrical degrees at the extremities of the antenna aperture. Both components of electric field E_ϕ and E_θ are measured for each antenna position. The polarization of the distant fixed transmitting antenna may be changed from the pattern recording position by means of a remote controlled motor drive which rotates the dipole in the parabolic disk from horizontal to vertical as desired. Remote control of the dipole motor is obtained by use of a telephone dial selector system. Many other functions are controlled remotely such as frequency, transmitter power output and 60 cycle power by the same dial system. The remote control system and an automatic computer is being developed which will integrate the radial component of Poynting vector to obtain the relative power radiated while the antenna is rotated.

Although the TFU-24-B antenna is omni-directional and it might be assumed that the total radiated power could be evaluated by the single integral of one vertical pattern,[9] assuming rotational symmetry of the vertical pattern, such an approach can produce errors for patterns in certain meridians as great as 10% in power gain due to the slight variation from rotational symmetry shown in Fig. 12. The power gain should be computed from a sufficient number of vertical patterns for both components of polarization E_θ and E_ϕ to produce the desired accuracy. The magnitude of the vertical pattern field should be normalized to agree with the corresponding relative field intensity in the principal plane horizontal pattern, Fig. 12, for the corresponding meridian angle ϕ. In the case of the TFU-24-B antennas, the vertical patterns in the plane of any line of slots are all the same and the vertical pat-

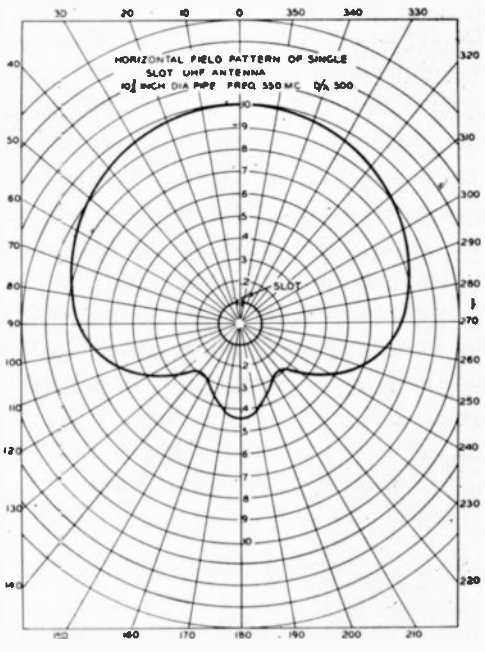


FIG. 13. Horizontal Pattern at 550 Mc. for a Pipe the Same Size Used for the TFU-24-BM Antenna Except for Slots in One Side Only.

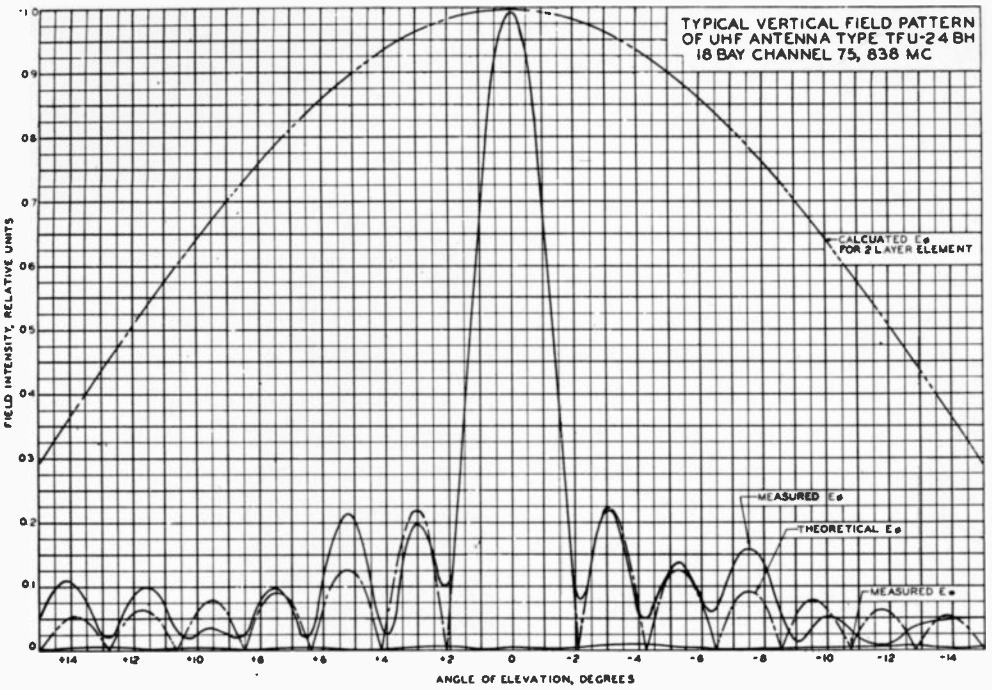


FIG. 14. Typical Calculated and Measured Vertical Patterns for TFU-24-BH Antenna.

terns in a plane half way between slots are the same. The variation with ϕ of the field between the two vertical patterns at any particular angle from Zenith, θ, is approximately sinusoidal, as shown in Fig. 12. Consequently, the average of the two vertical patterns mentioned above may be used in a single integral to evaluate the gain of the TFU-24-B antennas.

Referring to Fig. 17, the power radiated may be integrated over the surface of a sphere whose radius is sufficiently great. For purposes of this derivation, the radial component of power flow at the surface of the sphere may be assumed to be dissipated (or radiated) in the intrinsic impedance of free space which is approximately 120π or 377 ohms per square. If the tangential components of electric field, E_θ and E_ϕ, at a particular point on the surface of the sphere are measured the power dissipated in the intrinsic impedance (or radiated) at the particular point is simply

$$\frac{E^2}{R_s} = E^2 G_s \text{ watts per square meter.}$$

$$R_s = \frac{1}{G_s} \text{ Intrinsic impedance of space}$$

accounting for both E_θ and E_ϕ then the total power dissipated (or radiated) in the particular square meter on the surface of the sphere is

$$\frac{E_\phi^2 + E_\theta^2}{377} = P \text{ watts/sq. meter}$$

where E_ϕ and E_θ are in volts per meter.

The total power radiated is obtained by integrating the power density at the surface of the sphere over the entire surface as shown in Fig. 17.[13]

[13] Ibid. pages 540-543.

$$P_{radiated} = \frac{r^2}{377} \int_0^{2\pi} \int_0^{\pi} \left\{ E_\phi^2 (\theta, \phi) + E_\phi^2 (\theta, \phi) \right\} \sin\theta d\theta d\phi \qquad \text{Eq. 15}$$

where r is in meters.

It is usually convenient for purposes of gain calculation to normalize the maximum value of $(E_\phi^2(\theta, \phi) + E_o^2(\theta, \phi))$ to unity.

The directivity gain, D, relative to an isotropic radiator is the ratio of powers required to produce unit field strength at a fixed radius r in the direction of maximum field.

$$D = \frac{P_{radiated\ isotrope}}{P_{radiated\ TFU\text{-}24\text{-}B}} \qquad \text{Eq. 16}$$

The power radiated by a horizontally polarized isotrope is

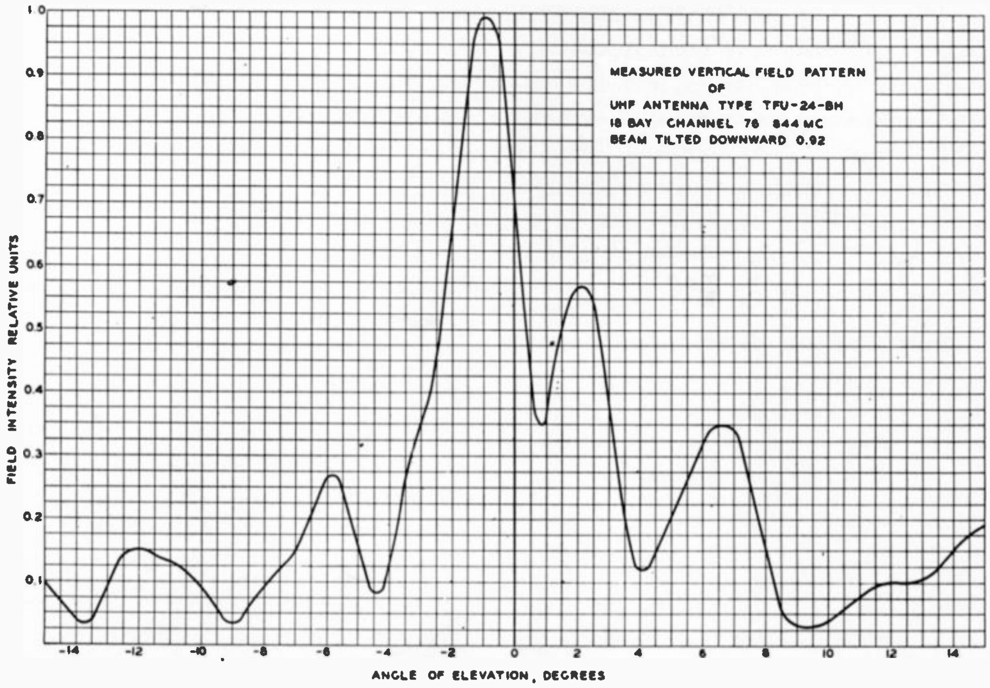
$$P_{isotrope} = \frac{r^2}{377} \int_0^{2\pi} \int_0^{\pi} E_\phi^2 \sin\theta d\theta d\phi$$

$$P_{isotrope} = \frac{4\pi r^2}{377} \qquad \text{Eq. 17}$$

Since E_ϕ^2 is normalized to unity and is constant for an isotropic radiator.

Substituting equations 17 and 15 in equation 16, we obtain the gain relative to an isotropic radiator, D

FIG. 15. Typical Measured Vertical Pattern of TFU-24-BH Antenna with Phasing Adjusted for .92° Pattern Tilt.



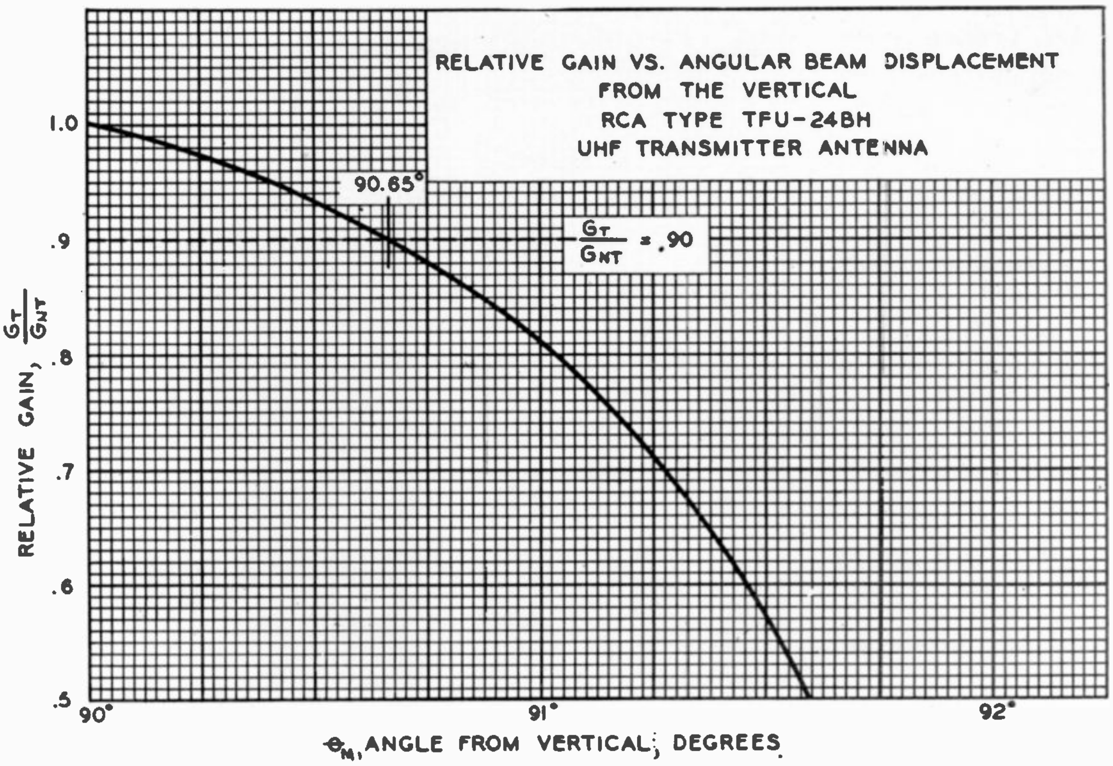


FIG. 16. Typical Relative Gain vs. Pattern Tilt for TFU-24-B Antennas.

$$D = \frac{4\pi}{\int_0^{2\pi}\int_0^{\pi}\left\{E_\theta^2(\theta,\phi) + E_\phi^2(\theta,\phi)\right\}\sin\theta d\theta d\phi} \qquad \text{Eq. 18}$$

Now, the directivity gain of a half wave dipole $D_{\lambda/2}$ is:[9]

$$D_{\lambda/2} = \frac{4\pi}{2\pi\int_0^{\pi}\frac{\cos^2\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}d\theta} = 1.641 \qquad \text{Eq. 19}$$

The gain, G, of any antenna relative to a half wave dipole, using equations 18 and 19 is then given by:

$$G = \frac{4\pi}{1.641}\,\frac{1}{\int_0^{2\pi}\int_0^{\pi}\left\{E_\theta^2(\theta,\phi) + E_\phi^2(\theta,\phi)\right\}\sin\theta d\theta d\phi} \qquad \text{Eq. 20}$$

Consider the integral of equation 20 for a particular angle from Zenith

$$\left.\int_0^{2\pi}\left\{E_\theta^2(\theta,\phi) + E_\phi^2(\theta,\phi)\right\}d\phi\right|_{\theta=b} \qquad \text{Eq. 21}$$

Now $\left.E_\phi^2(\theta,\phi)\right|_{\theta=b}$

is a scalloped circular pattern for a particular value of θ as shown in Fig. 12. The magnitude of the scallop is quite small in comparison with the magnitude of E_ϕ, par-

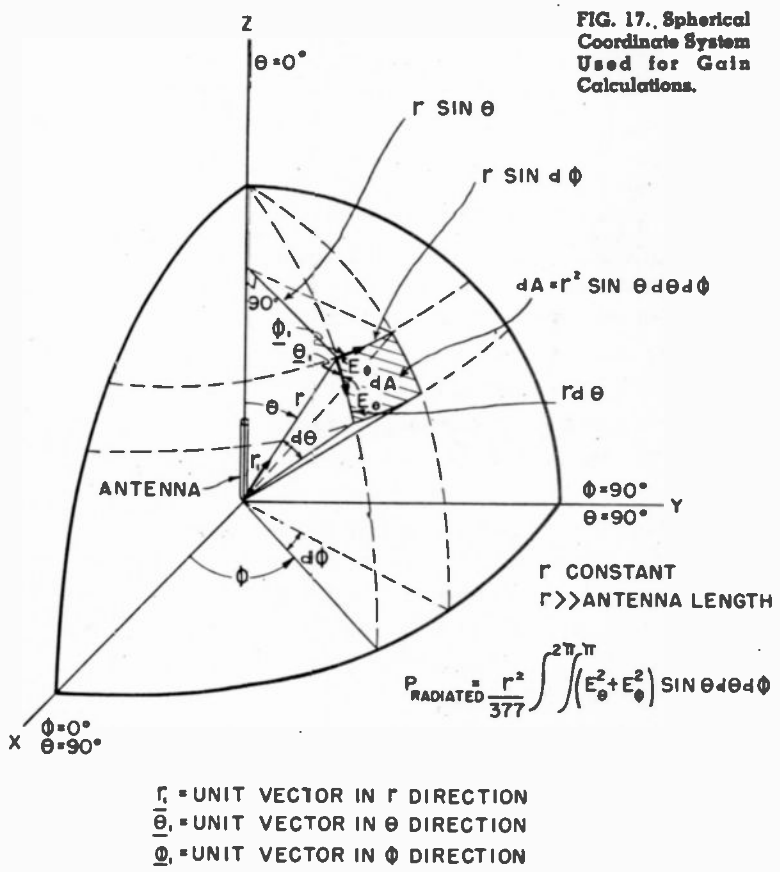


FIG. 17. Spherical Coordinate System Used for Gain Calculations.

ticularly when E_ϕ is large and contributes appreciably to the total radiated power. By inspection of the measurements shown in Fig. 12, we can express any horizontal pattern by the equation

$$E_\phi(\phi)\Big|_{\theta=b} = A + B\cos 6\phi$$

where B and A are functions of θ only and $B/A << 1$

$$E_\phi^2(\phi)\Big|_{\theta=b} = [A + B\cos 6\phi]^2 = A^2 + 2AB\cos 6\phi + B^2\cos^2 6\phi$$

$$E_\phi^2(\phi)\Big|_{\theta=b} = A^2 + 2AB\cos 6\phi + B^2\left(\frac{1+\cos 12\phi}{2}\right) \qquad \text{Eq. 22}$$

A similar expression results from measurements of $E_\theta(\phi)$

$$E_\theta^2(\phi)\Big|_{\theta=b} = C^2 + 2\,CD\cos 6 + D^2\left(\frac{1+\cos 12\phi}{2}\right)$$

where $D/C << 1$ Eq. 23

C and D are functions of θ only.

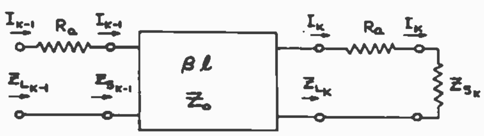


FIG. 18. Equivalent Circuit of One Section of Antenna Feeder System Used for Gain Calculations.

Substituting equations 22 and 23 in equation 21.

$$\int_0^{2\pi}\{E_\theta^2(\theta,\phi) + E_\phi^2(\theta,\phi)\}\,d\phi\Big|_{\theta=b} =$$

$$\int_0^{2\pi}\left\{A^2 + C^2 + 2\,(AB+CD)\cos 6\phi + (B^2+D^2)\left(\frac{1+\cos 12\phi}{2}\right)\right\}d\phi$$

$$= 2\pi\left\{A^2 + C^2 + \frac{B^2+D^2}{2}\right\}\Big|_{\theta=b}$$

since $\int_0^{2\pi}\cos n\phi\,d\phi = \frac{\sin n\phi}{n}\Big|_0^{2\pi} = 0$

where n is any integer

Eq. 24

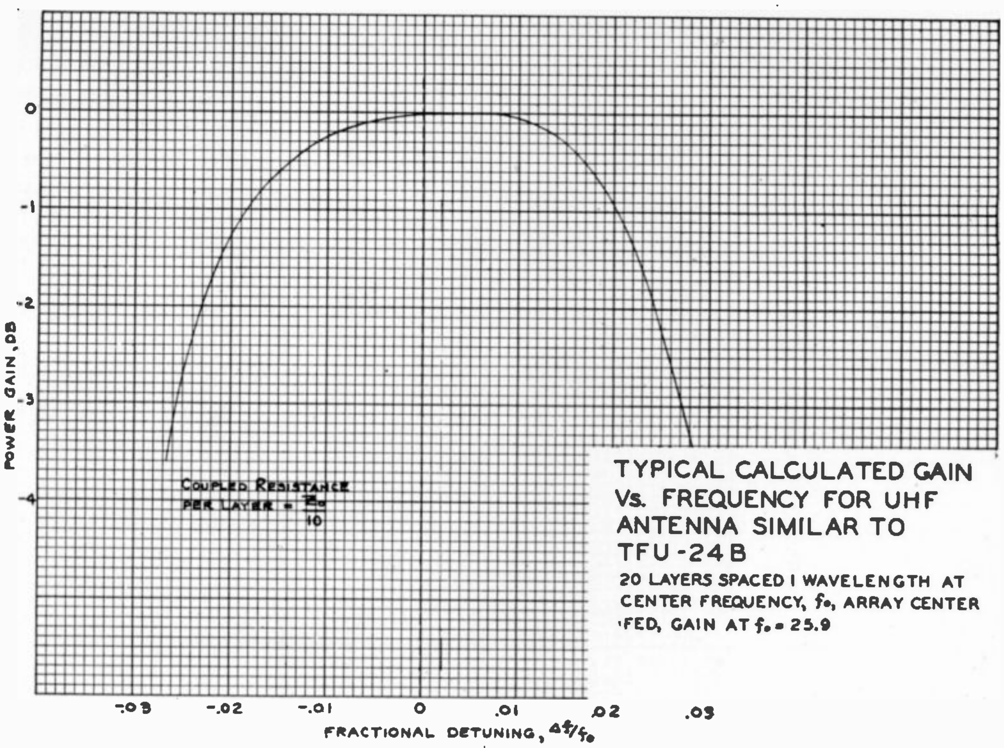


FIG. 19. Calculated Gain vs. Frequency for Early UHF Antenna.

Since $B << A$ and $D << C$ we may neglect the second order terms containing B and D in equation 24.

$$\int_0^{2\pi}\left\{E_\theta^2(\theta,\phi) + E_\phi^2(\theta,\phi)\right\}d\phi\Big|_{\theta=b} = 2\pi\left\{A^2 + C^2\right\} \qquad \text{Eq. 25}$$

where

$$A = \frac{E_{\phi\,max}(\theta,\phi) + E_{\phi\,min}(\theta,\phi)}{2}\Big|_{\theta=b}$$

and

$$C = \frac{E_{\theta\,max}(\theta,\phi) + E_{\theta\,min}(\theta,\phi)}{2}\Big|_{\theta=b}$$

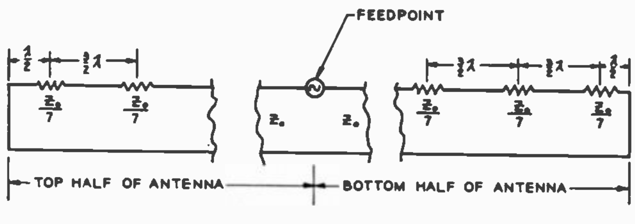
$$\int_0^{2\pi}\left\{E_\theta^2(\theta,\phi) + E_\phi^2(\theta,\phi)\right\}\Big|_{\theta=b} = 2\pi\left\{\left(\frac{E_{\phi\,max}(\theta,\phi) + E_{\phi\,min}(\theta,\phi)}{2}\right)^2 + \left(\frac{E_{\theta\,max}(\theta,\phi) + E_{\theta\,min}(\theta,\phi)}{2}\right)^2\right\}\Big|_{\theta=b} \qquad \text{Eq. 26}$$

Consequently for the TFU-24-B antenna we may take the average of 2 vertical patterns A (θ) and C (θ), one taken in the plane of the slots and one half way between slots and evaluate the gain by a single integration of the average E_θ and E_ϕ fields. Substituting equation 25 in equation 20 we obtain a simplified equation which can be used to accurately evaluate the gain, referred to a half wave dipole, G_o.

$$G = \frac{2}{1.641}\;\frac{1}{\int_0^{\pi}\{A^2(\theta) + C^2(\theta)\}\sin\theta\,d\theta} \qquad \text{Eq. 27}$$

The indicated integration is readily performed on a rectangular coordinate plot

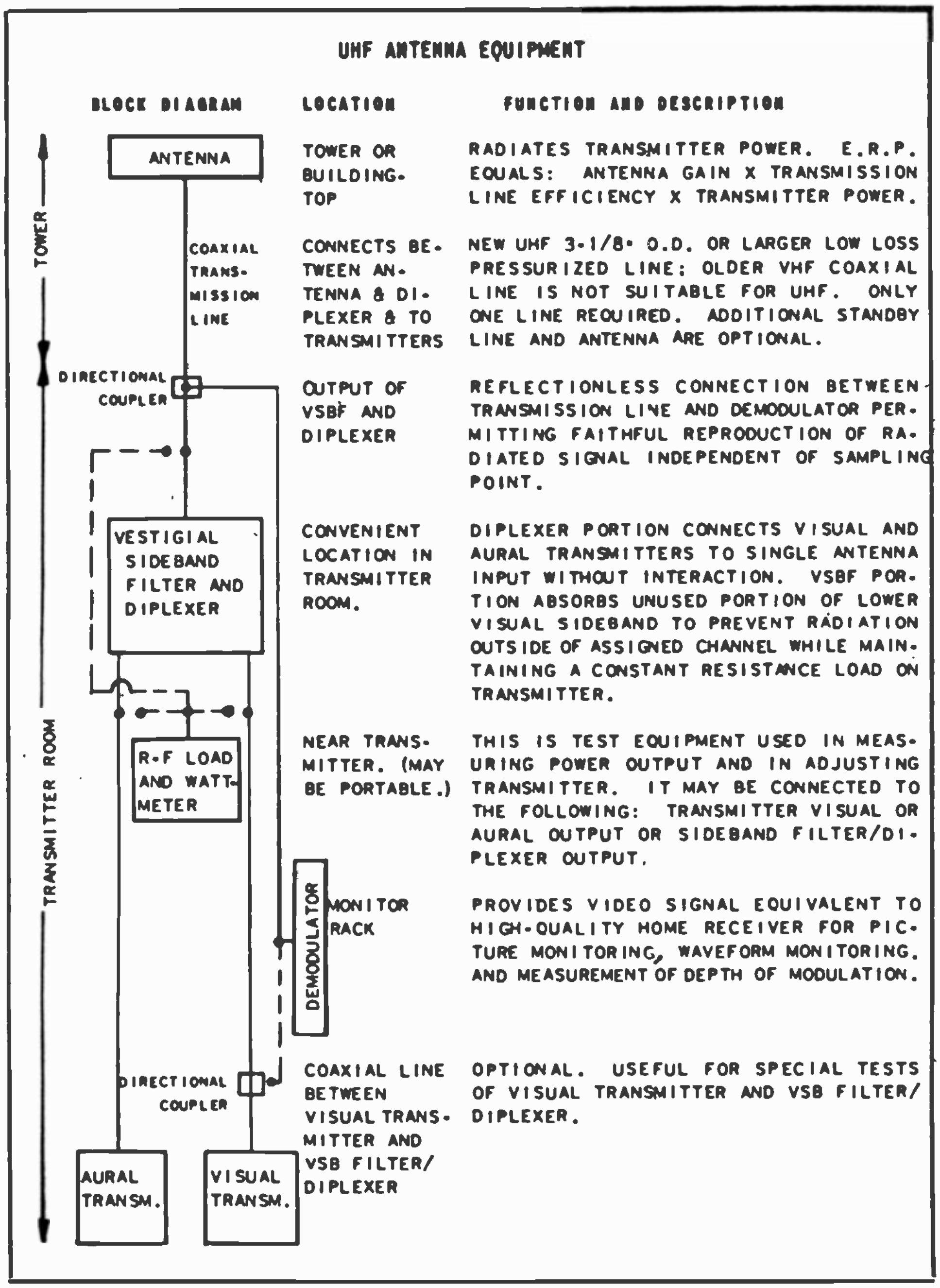
FIG. 20. Simplified Schematic Diagram of 14-Layer Center Fed Antenna Similar to the TFU-24-B Antenna.



using a planimeter.[9] In the case of the TFU-24-BH antenna considered here, the gain calculated from measured patterns was about 1.3% below theoretical, .3% of this is accounted for by the cross polarized field component E_θ and 1% is due to filling of the nulls in the measured vertical pattern.

The filling of the nulls in the vertical pattern may be caused by slight departures from uniform, in-phase, current distribution assumed for the theoretical pattern calculations. In a practical antenna using an iterated feed system for the radiating system, shown in Figs. 6, 20 and 24, small dimensional errors and variations in impedance of different layers due to different mutual impedances will produce the null filling shown in Fig. 14, which helps to assure adequate field strength at all locations within the service area. It is probable, however, that even without null fill-in a high gain antenna will produce greater field strength in its low signal areas than a low gain antenna with the same power input; because ground reflections and scattering help to distribute the signal from a highly directive source. With a low gain antenna which radiates signals of comparable magnitude at all angles of elevation, low signal areas are produced by interfering reflections. Fig. 8 shows a field strength radial comparing the TFU-24-B antenna with a low gain antenna having the same power input and height. A null fill-in of 2% of the maximum field was assumed for the high gain antenna. The actual null is approximately 10% of the maximum field for the antenna null at greatest distance from the high gain transmitting antenna, consequently, the field strength in this null may be expected to be about 5 times greater than shown in Fig. 8. This is clearly much better than obtained with a low gain antenna using the same transmitter, tower and locations. In general, a high gain antenna (gain 20 to 30) will produce field strengths 4 to 7 times greater than a low gain antenna (gain approx. 1 or 2), with the same power input over most of the service area.

FIG. 21. Block Diagram of RCA UHF Antenna System.



Electrical Vertical Pattern Tilt

By shifting the feed point from the center of the array, the phases of the top half and the bottom half of the array are shifted relative to each other, causing the vertical pattern to tilt up or down as desired. This is mechanically accomplished by loosening the clamp on the hub of the lower shorting bar which holds the harness in position, as shown in Fig. 6, and shifting the harness longitudinally as required. This may be easily accomplished in the field to assure optimum coverage as was described for the 8 section Pylon,[8] or it may be preset to a calculated position.

In the case of the TFU-24-B antenna the spacing between the radiating centers, d, of the upper and lower half of the array is 12 to 14 wavelengths, consequently the mutual impedance between the two halves of the array is very small in comparison with the self impedance of each half and the driving point impedance is therefore equal to the self impedance and practically independent of the relative phase of the current of the upper and lower half of the antenna. Since the input impedance of each half stays constant for any phase adjustment, δ, the current and power distribution on each half is independent of the adjustment.

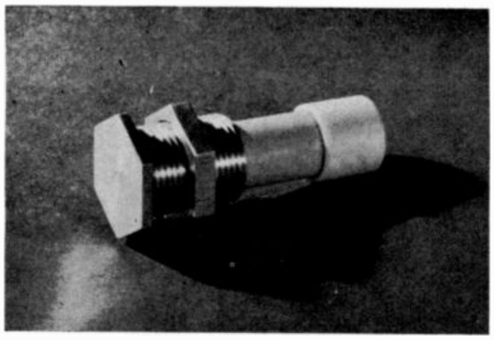


FIG. 22. Antenna Transmission Line Centering Insulator Showing Teflon Bearing Cap.

For the TFU-24-B antenna, the relative gain for various phase adjustments depends only upon the value of δ or beam tilt angle $\theta_{maximum}$ required for the particular antenna.[13]

The ratio of the gain tilted, G_T, to the gain without tilt, G_{NT}, is

$$\frac{G_T}{G_{NT}} = \left\{F_{1/2}(\theta_{max}) \cos\left[\frac{\beta d}{2}\cos\theta_{max} + \delta\right]\right\}^2 \qquad \text{Eq. 28}$$

where θ = angle from Zenith or the axis of the array; 2δ = relative phase of current or voltage driving each half of the array; $F_{1/2}(\theta)$ = vertical field pattern of the upper or lower half of the TFU-24-B array; $F_{1/2}(\theta_{max})$ = value of field intensity (normalized to $F_{1/2}(\theta=90^\circ) = 1$) at the angle θ_{max}, measured from the Zenith, for which the total field produced by the entire antenna is a maximum when the two halves are driven 2δ out of phase. βd is the spacing between the centers of the upper and lower arrays of the antenna.

The expression $\cos\left[\frac{\beta d}{2}\cos\theta + \delta\right]$ in equation 28 is the array factor for 2 radiators separated βd electrical degrees and driven with a phase difference of 2δ electrical degrees.

To find the value of θ_{max} at which the total field $F(\theta)$ becomes a maximum one would set $\frac{d}{d\theta}F(\theta) = 0$; neglecting constants:

$$\left.\frac{d}{d\theta}\left\{F_{1/2}(\theta)\cos\left[\frac{\beta d}{2}\cos\theta + \delta\right]\right\}\right|_{\theta=\theta_{max}} = 0 \qquad \text{Eq. 29}$$

Equation 29 may be solved for θ max. using Newton's method, or successive approximations, for various values of δ. Fig. 16 is a typical solution, obtained by use of equations 28 and 29. Fig. 15 shows a measured vertical pattern for the TFU-24-BH antenna with .92° of pattern tilt.

Theoretical Impedance and Gain vs. Frequency Calculations

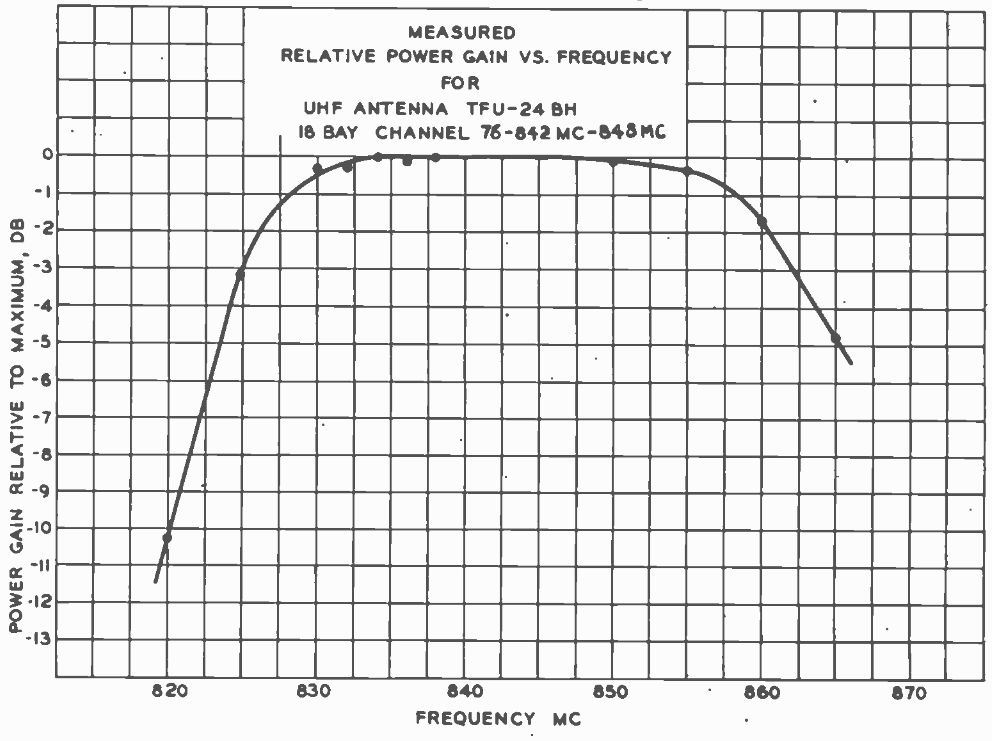
As early as September 1949, performance characteristics of antennas with feed systems similar to the TFU-24-B antenna had been calculated by use of simple transmission line theory and Smith Charts.

Calculations were based on a simplified schematic similar to Fig. 20 except for 20 layers center fed. Fig. 25 illustrates the method of using the Smith Chart for impedance calculations. A similar chart calculation is used for each value of fractional detuning. In the case shown, the center frequency, f_o, is the frequency for which the spacing between layers is exactly one wavelength in the transmission line. Fig. 26 shows a voltage standing wave ratio vs. frequency characteristic calculated by use of the Smith Chart using constant coupled resistances per layer of $\frac{Z_o}{10}$ and $\frac{Z_o}{5}$. It is apparent from Fig. 26 that a coupled impedance per layer which produces a minimum ratio of stored energy to energy dissipated in the feeder system should produce the maximum impedance bandwidth. The use of a pure resistance coupled impedance is a reasonably accurate assumption for long arrays similar to the TFU-24-B since the bandwidth is largely determined by the Q of the feeder system. Later impedance calculations for the TFU-24-B were made using measured image parameters for a symmetrical section; each section being 1.5 wavelengths long at f_o and having a complex iterative impedance and propagation constant. The use of charts[15] of complex hyperbolic functions, facilitated the calculation of the required input impedance for 8 or 9 sections or layers.

By making some simplifying assumptions which are fairly accurate for antennas similar to the TFU-24-B antenna, we may calculate the relative gain vs. frequency characteristic of the antenna system using data obtained from Smith Chart calculations similar to Fig. 25. The assumptions are:

The loss in the transmission line feeder is negligible and all dissipation occurs in the coupled radiation resistance of each layer of the antenna. Mutual impedance between layers is small and can be neglected in comparison with the resistance component of self impedance. The coupled

FIG. 23. Typical Measured Power Gain vs. Frequency for TFU-24-BH Antenna.



[13] Ibid. pages 292-295.

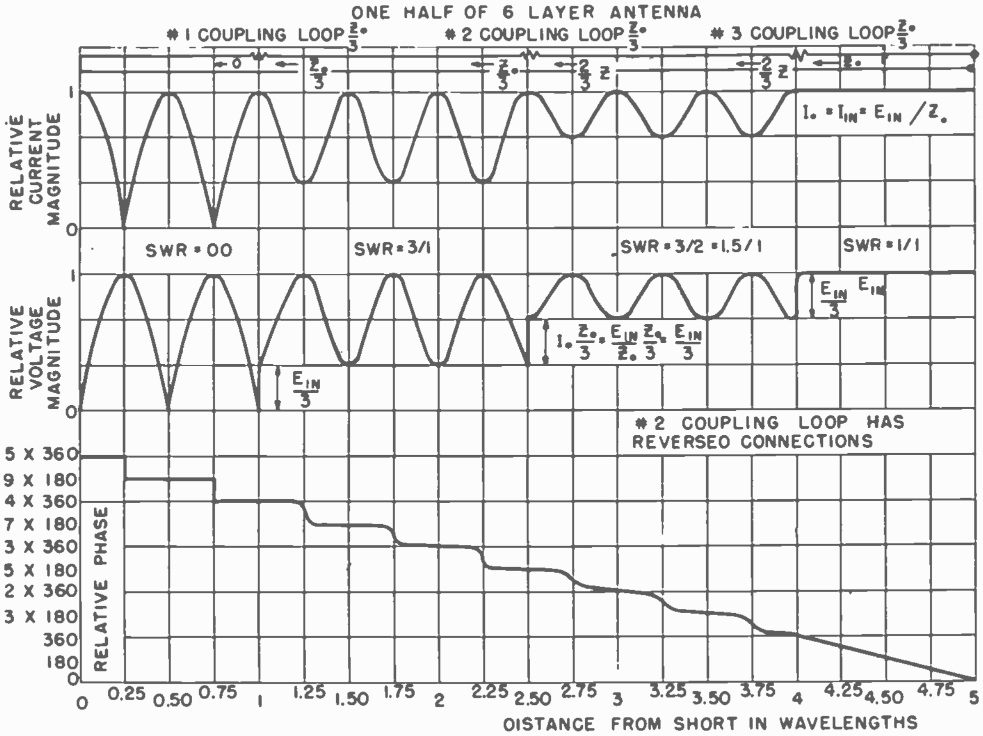


FIG. 24. Simplified Illustration of Current and Voltage Distribution Principle Used in the TFU-24-B Antenna Feed System.

impedance per layer is constant and equal to a pure resistance. The coupled resistance is lumped at a discrete point on the feeder.

Since the coupled resistance is lumped, the currents I_k in and out of the coupled resistance R_a must be equal. (Fig. 18).

$$I_{k\,in} = I_{k\,out} = I_k$$

The power in and out of the transmission line connecting two adjacent coupled resistances is equal

$$I_k^2 R_k = I_{(k-1)}^2 R_{k-1}$$

$$R_k = \mathrm{Re}\,(Z_{L_k});\quad R_{k-1} = \mathrm{Re}\,(Z_{S_{k-1}}) \qquad \text{Eq. 30}$$

$$R_k = \mathrm{Re}\,(R_a + Z_{S_k})$$

The current ratio, m, between adjacent antenna layers is

$$m = \left|\frac{I_{k-1}}{I_k}\right| = \sqrt{\frac{R_k}{R_{k-1}}}$$

For a zero loss transmission line

$$\frac{I_s}{I_L} = \cos\beta l + j\frac{Z_L}{Z_o}\sin\beta l$$

$$\frac{I_s}{I_L} = m\angle\theta = \frac{I_{k-1}}{I_k}$$

$$m\angle\theta = \cos\beta l + j\left(\frac{R}{Z_o} + j\frac{X}{Z_o}\right)\sin\beta l$$

$$m\angle\theta = \cos\beta l - \frac{X}{Z_o}\sin\beta l + j\frac{R}{Z_o}\sin\beta l$$

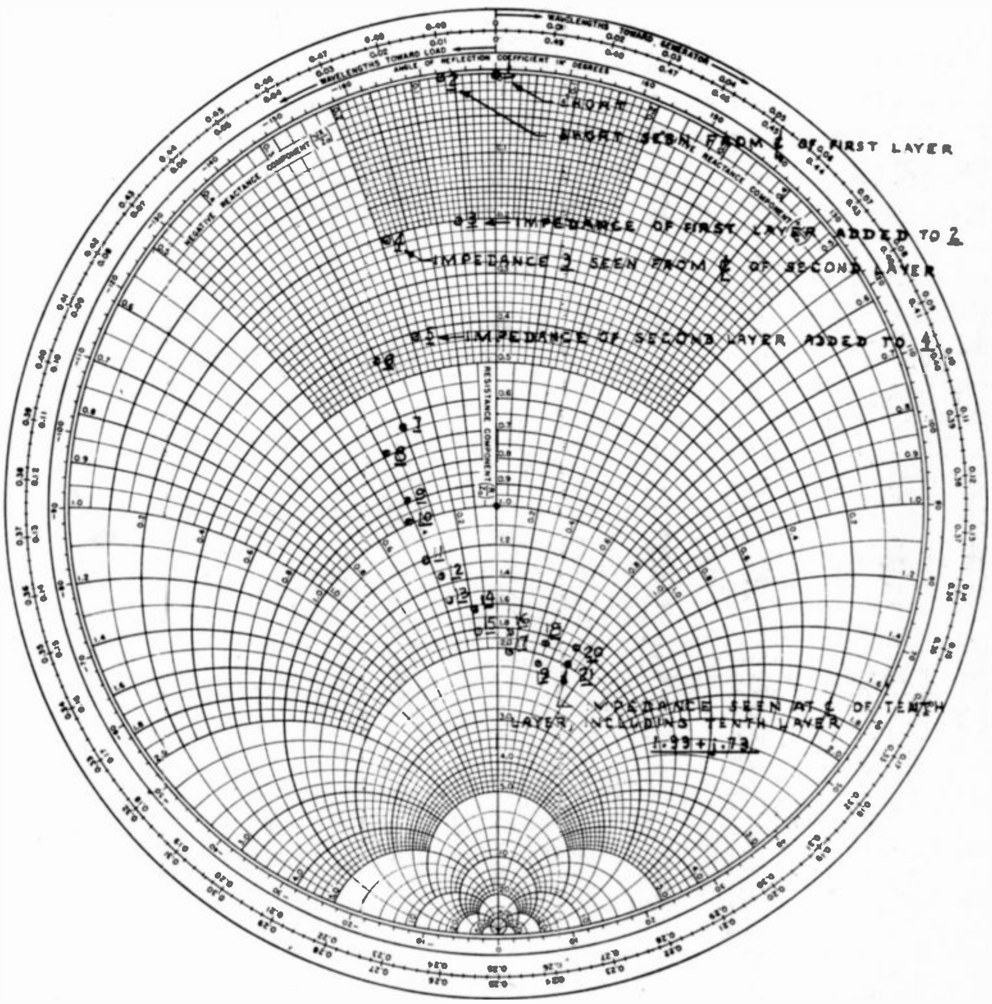
$$\sin\theta = \frac{\frac{R_k}{Z_o}\sin\beta l}{m}$$

where θ is the phase angle of the current in the k−1 section relative to the kth section.

Power gain at f_o

$$G_o = \frac{N\left|\sum_{n=1}^{k} I_{nf_o}\right|^2}{W_T}$$

where W_T is the total power input at any frequency f and N is a constant.



TYPICAL IMPEDANCE CALCULATION FOR UHF ANTENNA SIMILIAR TO TFU-24B

20 LAYERS SPACED 1 WAVELENGTH AT CENTER FREQUENCY f_o. COUPLED RESISTANCE PER LAYER $\frac{Z_o}{3}$; DISTANCE FROM SHORT TO FIRST LAYER $\frac{1}{2}$ WAVELENGTH AT f_o. IMPEDANCE CALCULATED FOR $f = .98 f_o$ WHERE DISTANCE BETWEEN LAYERS BECOMES .98 λ. $\left(\frac{\Delta f}{f_o} = -.02\right)$

FIG. 25. Example of Method Using Smith Chart to Calculate Input Impedance of TFU-24-B Type of Feeder Systems.

Power gain at any frequency f

$$G_f = \frac{N \left| \sum_{n=1}^{k} I_{nf} \right|^2}{W_T}$$

If there are K layers in an equivalent circuit similar to Fig. 20 between the feed point and the shorting plug, the gain ratio is

$$\frac{G_f}{G_{f_0}} = \frac{\left| \sum_{n=1}^{k} I_{nf} \right|^2}{\left| \sum_{n=1}^{k} I_{nf_0} \right|^2} \qquad \text{Eq. 31}$$

Now the power input must be maintained constant if power gain at f is compared with power gain at f_0.

For equal power input:

$$I^2_{1f_0} \; R_{1f_0} = I^2_{1f} \; R_{1f} \qquad \text{Eq. 32}$$

Where the R_1 and I_1 are respectively the input resistance and currents to the array at the feed point which is shown at the center of Fig. 20.

If ΣI_{nf} is written as

$$I_{1f} \left\{ \Sigma 1 + \frac{I_{2f}}{I_{1f}} + \ldots \right\}$$

and ΣI_{nf_0} is written

$$I_{1f_0} \left\{ \Sigma 1 + \frac{I_{2f_0}}{I_{1f_0}} + \ldots \right\}$$

then equation 31 becomes

$$\frac{G_f}{G_{f_0}} = \frac{I^2_{1f} \left| \sum_{n=1}^{k} I'_{nf} \right|^2}{I^2_{1f_0} \left| \sum_{n=1}^{k} I'_{nf_0} \right|^2} \qquad \text{Eq. 33}$$

where $I'_{nf} = \frac{I_{nf}}{I_{1f}}$ and $I'_{nf_0} = \frac{I_{nf_0}}{I_{1f_0}}$

Combining equations 32 and 33, the gain ratio becomes

$$\frac{G_f}{G_{f_0}} = \frac{R_{1f_0} \left| \sum_{n=1}^{k} I'_{nf} \right|^2}{R_{1f} \left| \sum_{n=1}^{k} I'_{n_0} \right|^2} \cdot \frac{f}{f_0} \qquad \text{Eq. 34}$$

The ratio $\frac{f}{f_0}$ is introduced to correct for the constant physical length of aperture which would make the gain directly proportional to frequency if properly illuminated.

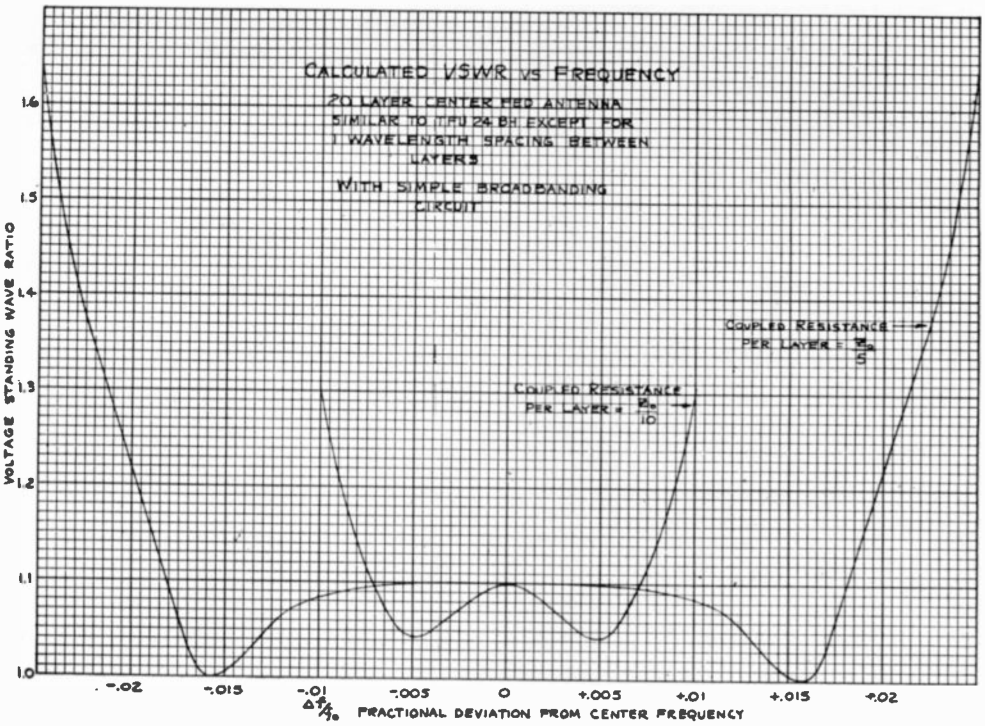
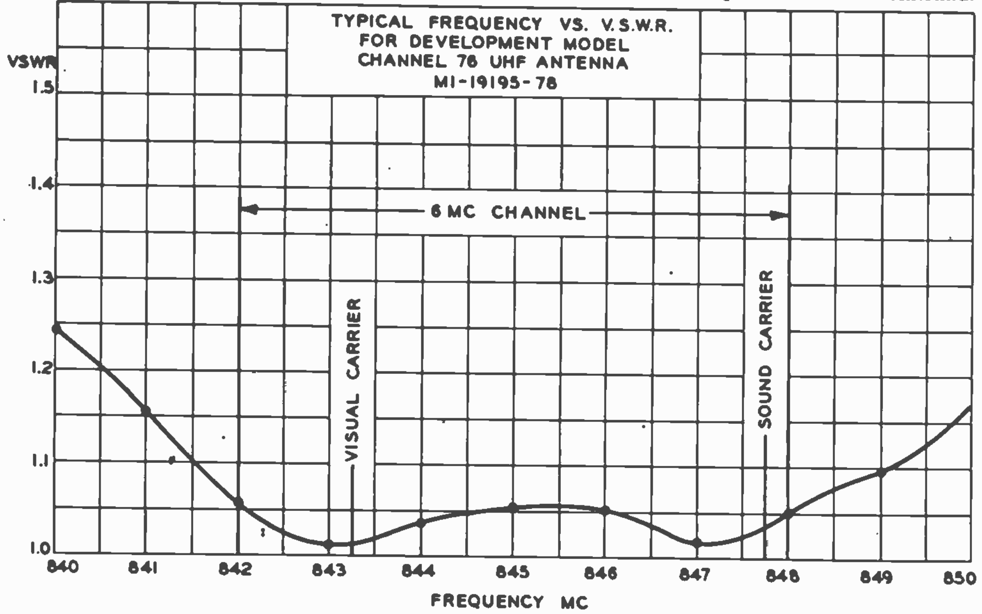


FIG. 26. Calculated Voltage Standing Wave Ratio vs. Frequency for an Antenna Using a Feeder System Similar to the TFU-24-B Antenna.

FIG. 27. Typical Measured Voltage Standing Wave Ratio vs. Frequency for TFU-24-BH Antenna.



Mechanical Features of Antenna Harness

The harness may be removed from the antenna by loosening the same clamp which was loosened for the beam tilt adjustment. Low loss ceramic pin centering insulators similar to those shown in Figs. 6 and 22 support the transmission line harness in the center of the antenna cylinder. A teflon cap on the end of the ceramic pin prevents abrasion of the transmission line during removal or installation, and when the antenna is swaying in the wind. This same type of support insulator was used in the Bridgeport antenna which has given trouble-free operation for a period greater than two years. The teflon end cap has a hard waxy feel with a very low coefficient of friction which permits easy adjustment, removal, or installation of the transmission line within the antenna, without disturbing the centering insulator adjustment.

Icing

Voltage standing wave ratio measurements were made on the antenna at Bridgeport during a severe ice storm and the change in voltage standing wave ratio was found to be small. The antenna system and transmitter were able to operate with the antenna in an iced condition without difficulty, and the transmitted picture was of normal quality. Because of the improved performance characteristics, it is believed the TFU-24-B antenna may not require de-icing. However, if further tests indicate de-icing is desirable in locations where icing is very frequent and severe, de-icing equipment will be available as an accessory. Fig. 1 shows the TFU-24-B antenna setup at Camden, N. J. A sprinkler is included—at the top for icing tests. These tests will be made as weather permits.

* * *

The data presented here on the TFU-24-B antenna is representative of the general characteristics and principles. Since the development and design of this antenna is intensively continuing, improvements and minor changes may be incorporated in the first production units delivered. At the present time, engineering work is being done on a large number of engineering model antennas to obtain statistical data for production. Two TFU-24-B UHF TV transmitting antennas will be shipped to experimental UHF transmitting stations about April 1952.

Acknowledgment

The TFU-24-B antenna is a result of contributions of many engineers in the Broadcast Antenna Engineering Section of RCA. Particular credit is due to Charles Polk who did much of the electrical development, E. H. Shively who was responsible for the field pattern work, and A. Mathern who accomplished the mechanical design.

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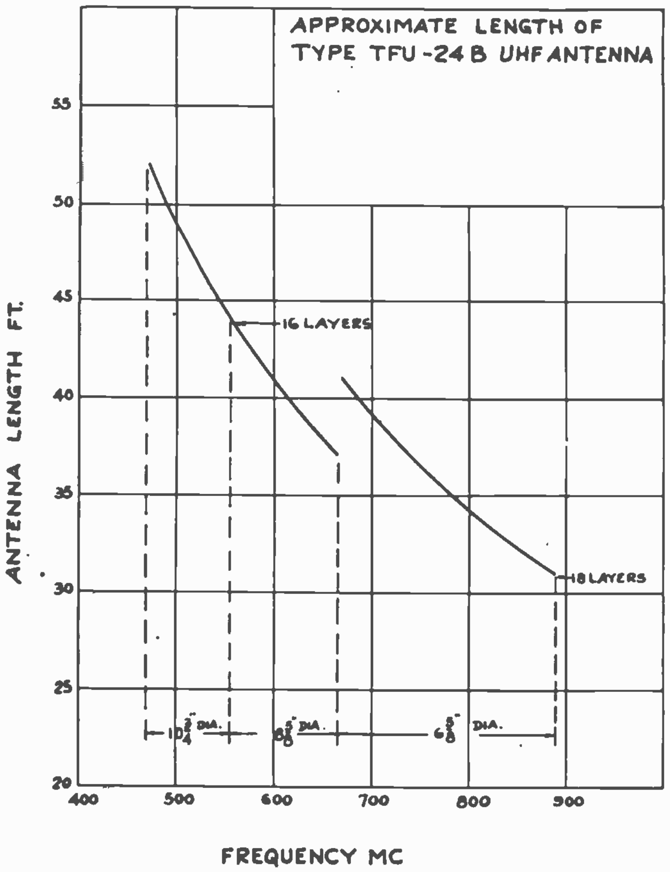


FIG. 28. Approximate TFU-24-B Antenna Length vs. Frequency.

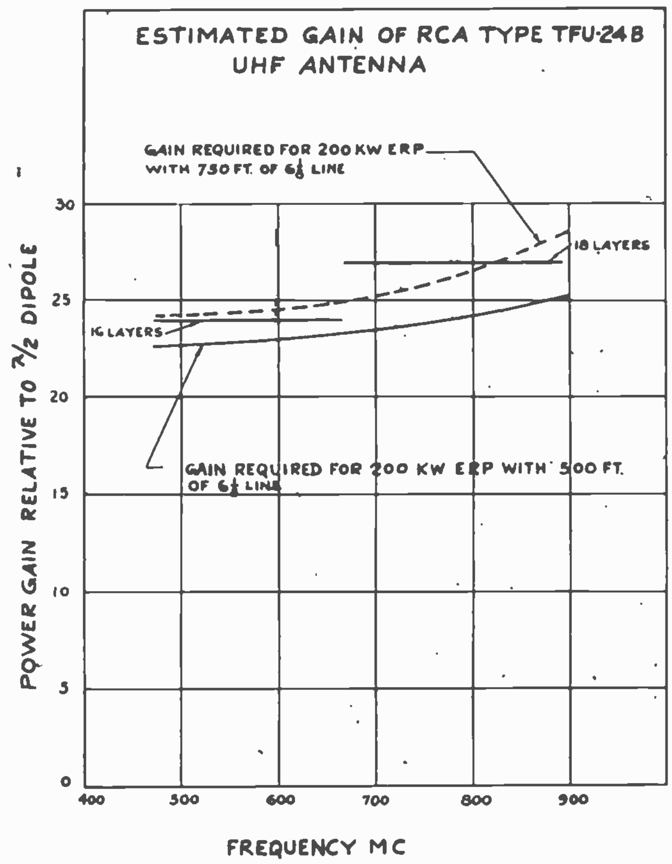


FIG. 29. Approximate TFU-24-B Antenna Gain vs. Frequency.

PATTERN-TESTING THE TFU-24B UHF ANTENNA

By E. H. SHIVELY
RCA Broadcast Engineering

In September of 1951, the first TFU-24-BH antenna, designed for channel 76, was completed at Camden, and after preliminary impedance tests and adjustments there, was taken to the Medford site for pattern tests. The following material outlines the principles involved and describes the test procedure, including data.

The pattern testing of a television broadcast antenna leads to two important results: (1) The radiation field intensity as a function of direction (radiation pattern) is measured and recorded; (2) The ratio of total radiated power from a dipole required to produce a given field intensity at a specified distance to the power radiated by the antenna when yielding equal maximum field at equal distance is measured. This is the directivity gain of the antenna.

The Basic Principle

Consider the antenna to be placed at the center of a sphere of radius large compared to the dimensions of the antenna, Fig. 1. All of the radiated power will flow through the surface of the sphere, and the surface integral of the radiated power density on the sphere will yield this total power.[1] That is

$$W = \iint P \cdot ds$$

where P is the Poynting vector and ds is an increment of surface.

If then, a half-wave dipole be placed in the center of the sphere and the total radiated power adjusted so that the field intensity at the maximum point on the sphere is equal to the maximum field obtained with the unknown antenna, the gain of this unknown compared to the dipole will be:

$$\text{Power Gain} = \frac{\text{W of dipole}}{\text{W of unknown}} = \frac{\iint P_d \cdot ds}{\iint P_u \cdot ds}$$

The total radiated power of each antenna is obtained by integrating the power density over the surface of a sphere. In the case of the dipole, this can be calculated by analytic methods. The total radiated power of the unknown must be determined graphically, since it is related to the recorded pattern which is not readily expressible as an analytic function.

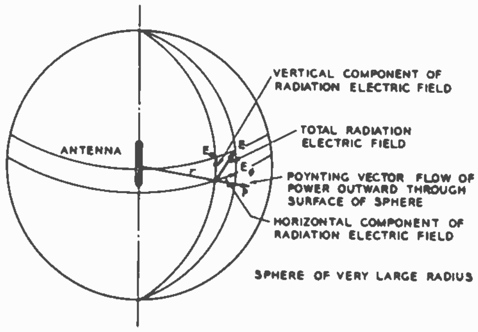


FIG. 1. Antenna in Imaginary Sphere.

The spherical coordinate system is shown in Fig. 2. The incremental power radiated is that flowing through the area dA. In this system $dA = r^2 \sin\theta \, d\theta \, d\phi$, and the total power is

$$W = \int_0^{2\pi}\int_0^{\pi} P(\theta,\phi)\, r^2 \sin\theta \, d\theta \, d\phi$$

Since $P = E \times H$, the normal component of $P = \frac{E_T^2}{n} = \frac{E_T^2}{377}$

where E_T is the rms tangential component of the electric field on the surface of the sphere and n is the intrinsic impedance of free space, 377 ohms. Thus

$$W = \frac{r^2}{n}\int_0^{2\pi}\int_0^{\pi} E_T^2 \sin\theta \, d\theta \, d\phi.$$

The total tangential electric field $E_T(\theta,\phi)$ is ordinarily determined by its components $E_\theta(\theta,\phi)$ and $E_\phi(\theta,\phi)$, which, by reference to Fig. 1, are the vertically and horizontally polarized components, respectively, so that

$$W = \frac{r^2}{n}\int_0^{2\pi}\int_0^{\pi} (E_\theta^2 + E_\phi^2) \sin\theta \, d\theta \, d\phi$$

For practical measurements, it is necessary to be able to express the definite integral of θ as a function of ϕ. In the TFU-24-B antenna, where the horizontal pattern is perfectly circular in the horizontal plane and the scallops are not appreciable at

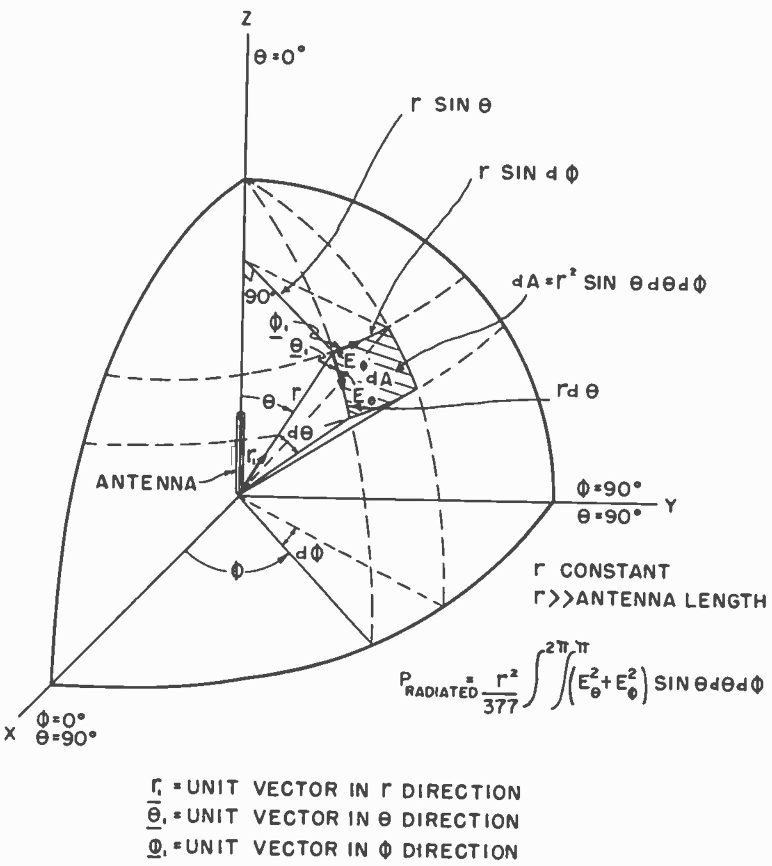


FIG. 2. Spherical Coordinate System.

[1] "Antennas," by J. D. Kraus, McGraw-Hill Book Company, 1950, pp. 11-40.

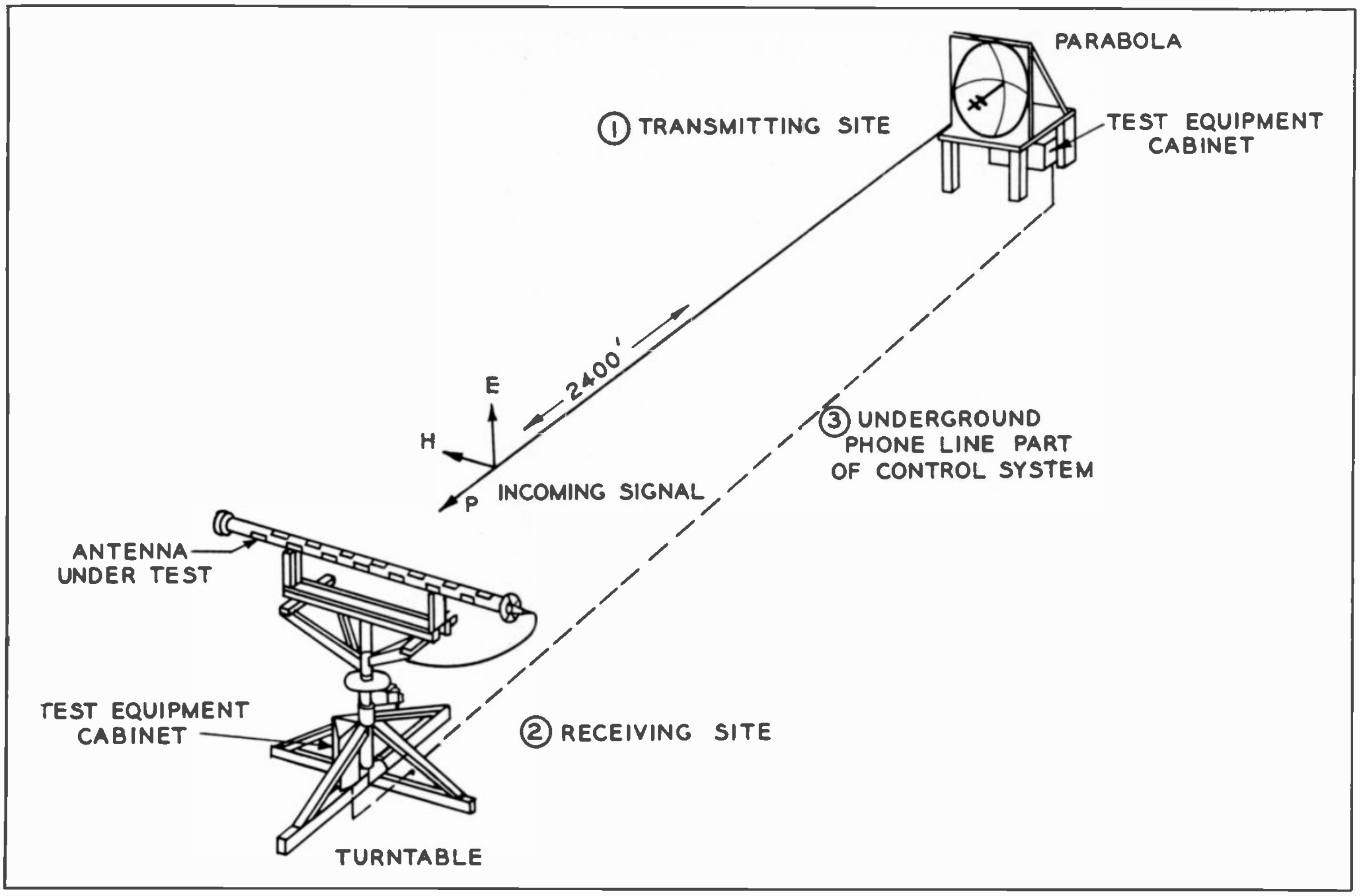


FIG. 3. Pictorial View of Antenna Test Ground.

higher angles, it has been shown that it is sufficient to measure a vertical pattern in the plane of the peak of a scallop and in the valley and average the readings point by point during the plotting process.[2]

The Practical Considerations

The radiated field intensity as a function of θ, the latitude angle, for any fixed ϕ, the longitude angle (Fig. 1), may be found by mounting the antenna horizontally on a turntable and rotating it while the radiated signal is received at a remote point. Due to the principle of reciprocity,[3] the antenna may just as well be tested in receiving, and this is usually preferred, since the major quantity of test equipment is at the receiving location.

In order for the pattern to be accurately recorded, the chart of the recorder must be driven in synchronism with the antenna turntable. This is done at present by a selsyn link driven from a ring gear on the turntable shaft.

The antenna test ground thus comprises (Fig. 3):

1. A transmitting site, from which the signal is beamed.
2. A receiving site at a distance, where the antenna under test is located, together with the turntable and associated test equipment.
3. A control system to link the transmitting and receiving sites so that operations may be carried on from one point.

The receiving site, shown in Fig. 4, comprises a wooden framework turntable carrying the antenna in a horizontal position and provided with anti-friction bearings so that the entire upper half may be very easily rotated. A gin pole (extending out of the picture to the right) may be raised to a vertical position and guyed to permit placing antennas on the turntable by chain hoist. A light framework is provided so that a tent may be set up in inclement weather.

A closer look at the turntable base, Fig. 5, reveals the test equipment. The signal from the antenna is received on the UHF converter (lower left corner), where it is transformed into a VHF signal and enters the RCA type WX-1A field intensity meter (lower center). The DC output current from this instrument drives the recorder pen (center). The chart is driven by the receiving selsyn according to information from the selsyn transmitter geared to the turntable spindle (upper right center). The angular position of the antenna thus automatically positions the chart. This position may also be read directly on the compass rose (behind recorder) which is provided with a vernier to permit angular readings to be taken to within ±0.10°. In setting the compass, the antenna is "aimed" at the transmitting site by mounting a pair of sights, similar to rifle "peep sights" on the pipe. With the axis of the antenna thus pointing at the distant site, a clamp is loosened and zero on the rose set to zero on the vernier.

A heterodyne frequency meter is provided to check oscillator frequency. The cable is

[2] "A New UHF Television Antenna, TFU-24-B," by O. O. Fiet, BROADCAST NEWS, Vol. 68, March-April, 1952, pp. 8-23.

[3] "A Generalization of the Reciprocal Theorem," by J. R. Carson, Bell System Technical Journal, 3, July, 1924, pp. 393-399.

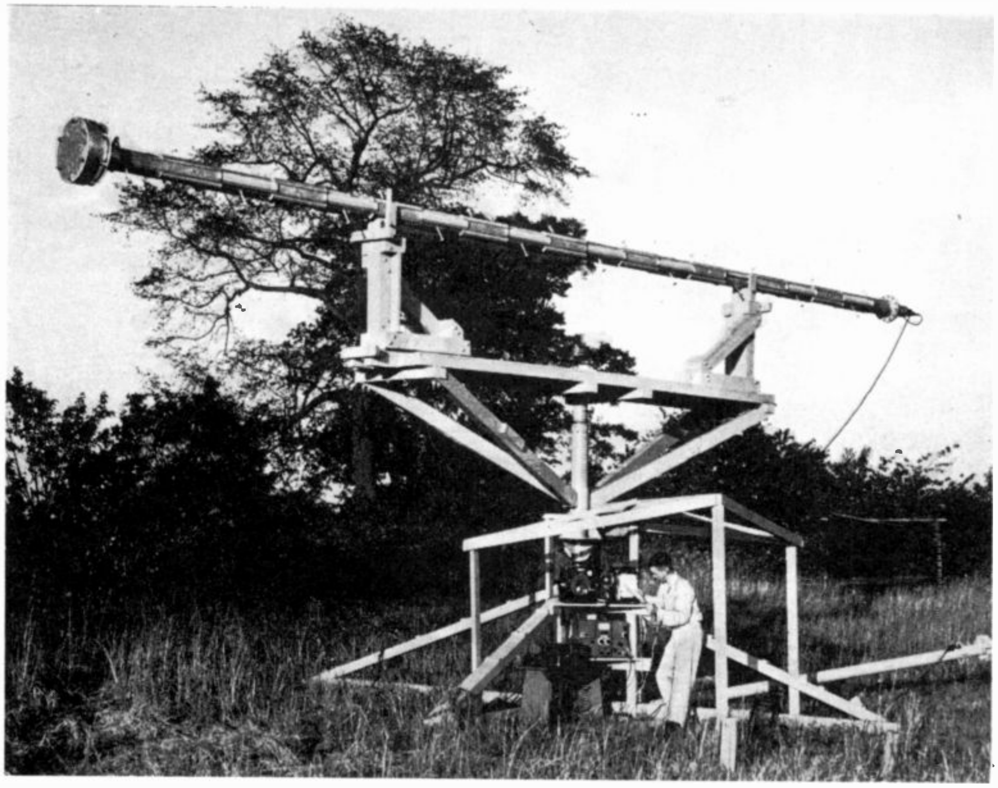


FIG. 4. The Receiving Site with UHF Antenna.

removed from the UHF converter, the antenna signal is applied directly to the frequency meter, and the oscillator frequency at the transmitting site is adjusted through the dial system.

At the transmitting site, Fig. 6, is located a high gain parabolic antenna supplied by a signal generator housed in a cabinet under the platform. This enclosure is shown in Fig. 7 and contains, beside the oscillator, the telephone stepping equipment, the motors for oscillator control, a sound powered telephone handset, and a constant voltage transformer. The phone permits contact with the receiving site when it is occasionally necessary to do so.

The knobs were removed from the oscillator and small geared motors of high ratio were coupled to the shafts through friction clutches. In this way, the motors could drive the shafts to the limit of travel without damage to either. A similar motor rotates the dipole assembly in the parabola in order to change the plane of polarization of the transmitted signal remotely.

The switching equipment (contained in the steel case with lid raised) is shown in schematic in Fig. 8. The system comprises a standard stepping switch (upper left in both schematic and in case) together with the necessary power and auxiliary relays. Ten operations may be performed independently by dialing the appropriate number at the receiving site. Two separate AC power circuits and three motors may be controlled.

As currently connected the phone book reads:

#1—AC outlet #1 on
#2—AC outlet #1 off
#3—AC outlet #2 on
#4—AC outlet #2 off

After each of these operations the step switch is automatically returned to its home position. In positions 5-9 the stepper remains on the contact until "O" is dialed and it is released.

These operations are:

#5—raise frequency
#6—lower frequency
#7—increase signal output
#8—decrease signal output
#9—rotate dipole assembly

Once any of these are started the operation will continue until "O" is dialed.

All relays in this cabinet operate from 110 volts AC and there are no power supplies or rectifiers to cause a continual current drain. The metallic rectifiers shown in the schematic are used for time delay operations only. The only exception is the stepper, which is supplied by the DC pulses from the dial and its power supply. The overall schematic is shown in Fig. 9. The talking-dialing isolation, though not perfect, is sufficiently good that phone conversations may be continued while dialing is in progress. The only failure of the switching equipment in one year of service consisted of an "open" appearing in the step relay coil, in contrast to contact troubles, which might be expected.

Null Fill-In

Since all pattern calculations are made on the basis of parallel rays from the various elements of the antenna, the transmitting site should be at infinite distance from the receiving site. Obviously, the best compromise is to separate the sites as far as possible and then make allowances for discrepancies in the pattern due to the departure from a plane wave front as the wave arrives at the antenna. These discrepancies are caused by the currents at the various layers differing slightly in phase along the aperture.

This is shown in Fig. 10, wherein the wave front from the transmitting site is assumed to be spherical. In this case, the separation distance is r, the antenna aperture is a, and the distance from antenna center to any point A is l. The phase error, or time delay distance δ, at A is for $l << r$

FIG. 5. Test Equipment at the Receiving Site.

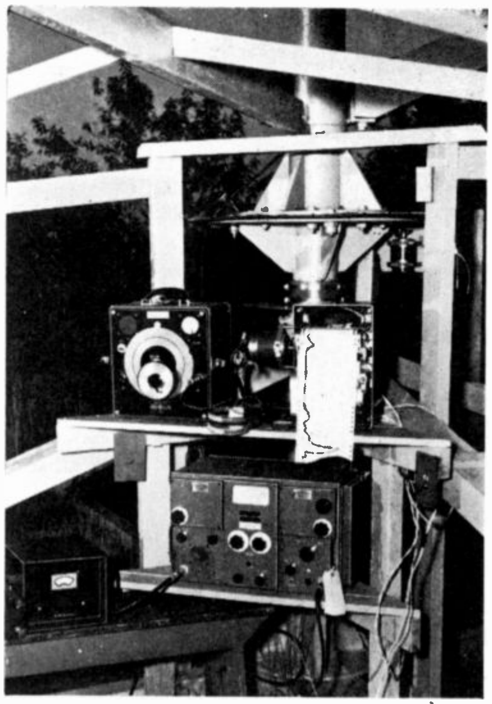


FIG. 6. The Transmitting Site at Marlton-Medford Airport.

$$\delta = \frac{l^2}{2r} \text{ in units of length.}$$

$$= \frac{360\, l^2}{2\, r\, \lambda} \text{ in elec. degrees.}$$

Thus, the phase variation along the array due to finite separation may be calculated, and this variation used to predict the amount of null fill-in to be expected.

Using the concept of the Fourier series representation of the antenna pattern, the far field at any angle θ from the axis of an array of in-phase sources whose amplitudes are distributed symmetrically about the center of the antenna (Fig. 11) may be represented by the series:[4]

$$E = 2 \sum_{K=0}^{N} A_K \cos K\psi$$

where $N = \frac{n-1}{2}$

n = Number of sources (here assumed to be odd)
$\psi = d \cos\theta$
d = distance between sources in elec. deg.
A_K = Amplitude of K^{th} source.

All sources are in phase, and the nulls in the pattern are clean, that is, are theoretically zero.

If the sources also have differing phase angles the Fourier series representation may be considered as the sum of two series:

[4] "Antennas," by J. D. Kraus, McGraw-Hill Book Company, 1950, p. 99.

$$E = 2 \left[\sum_{K=0}^{N} A_K \cos K\psi + j \sum_{K=0}^{N} B_K \cos K\psi \right]$$

where the first series is due to the "in-phase" components of the sources and the second, the "quadrature" components.

For phase angles due to finite separation, the B's vary as the square of the distance from the array center, so that

$$E = j\,2 \left[0 + \left(\frac{1}{4}\right)^2 B \cos\psi + \left(\frac{1}{2}\right)^2 B \cos 2\psi + \left(\frac{3}{4}\right)^2 B \cos 3\psi + B \cos 4\psi \right]$$

where B = Amplitude of end source
$= A \tan\delta$

However, since the distribution of the B's is in general different from that of the A's, the nulls in the two series will not occur at the same θ, and, therefore, the far field will have a phase angle and the nulls will be filled in generally.

Since the main field (due to A components) is zero at a null position, it is merely necessary to calculate the field due to the B components at this position and this yields the theoretical null fill-in.

$$E = j\,2 \sum_{K=0}^{N} B_k \cos K\psi$$

The eighteen layer TFU-24-BH antenna is equivalent electrically to nine sources spaced 3 λ and arranged symmetrically about the center source, so that the quadrature field is:

$$E = j\,2 \left[B_0 + B_1 \cos\psi + B_2 \cos 2\psi + B_3 \cos 3\psi + B_4 \cos 4\psi \right]$$

For example:

The first null of the TFU-24-BH 844 Mc. antenna occurs at $\theta = 88°$. How much null fill-in is expected for the Medford site?

$$r = 2060\,\lambda \qquad l = \frac{a}{2} = 12\,\lambda$$

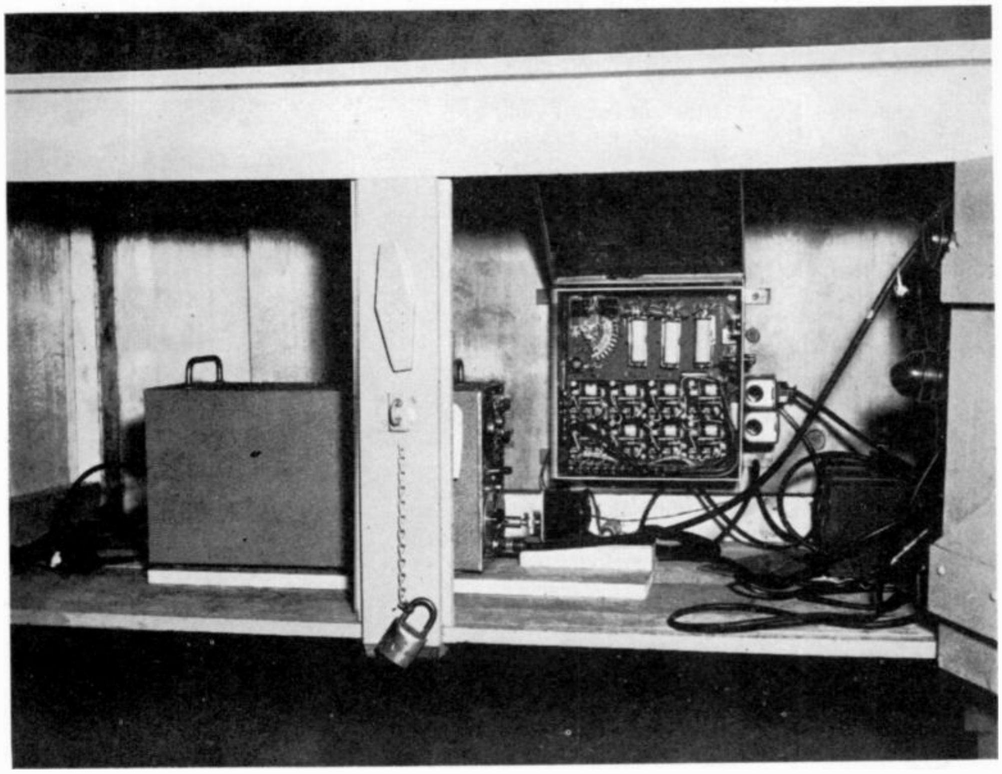
$$\delta = \frac{360\, l^2}{2\,\lambda\, r} = \frac{360\,(12\,\lambda)^2}{2\,\lambda\,(2060\,\lambda)} = 12.6°$$

$$B = A \tan\delta$$

$$= \frac{1}{9} \tan 12.6° = 0.0248$$

$$\psi = d\cos\theta$$
$$= 1080 \cos 88°$$
$$= 37.7°$$

FIG. 7. The Test Equipment Cabinet at the Transmitting Site.



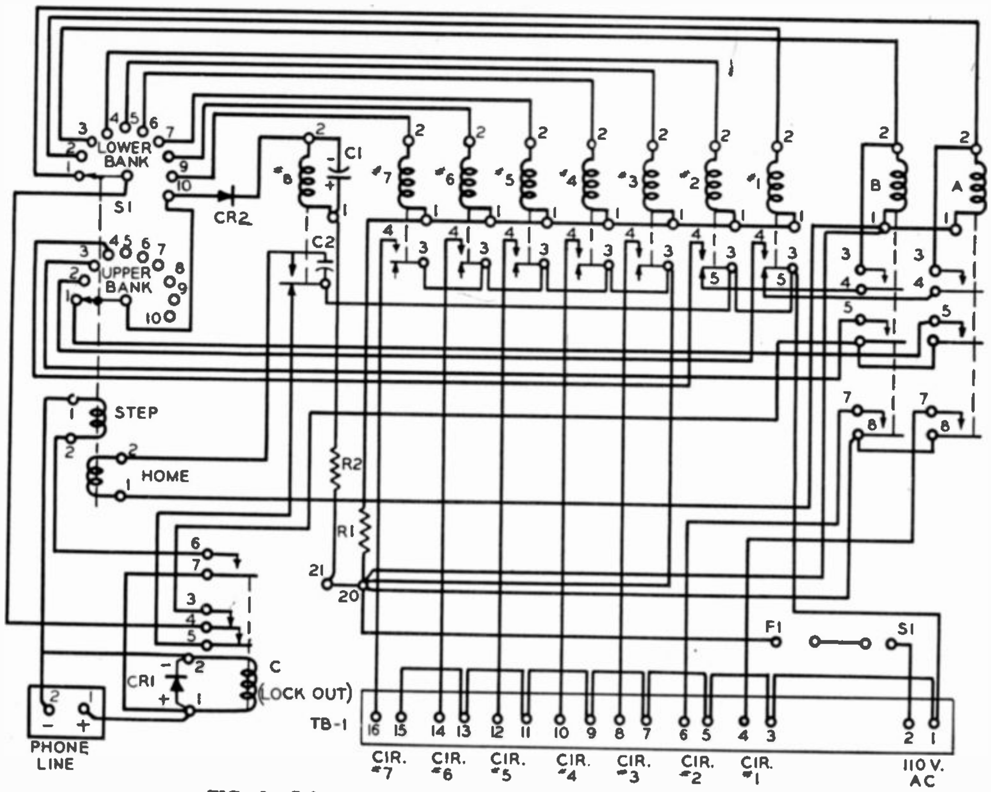


FIG. 8. Schematic Diagram of Telephone Step Equipment.

$$E = j\,2\left[\frac{1}{16}\,B\cos 37.7^\circ + \frac{1}{4}\,B\cos 75.4^\circ + \frac{9}{16}\,B\cos 113.1^\circ + B\cos 150.8^\circ\right]$$

$$= -j\,1.96\,B = .049\ \angle\text{-}90^\circ$$

This, then, shows a theoretical null fill-in of 4.9% due to finite separation between transmitting and receiving sites, at 844 Mc.

Reference to Fig. 10 will show that since the path length error is a fixed distance for any given aperture, the phase error is a function of frequency, being much less at lower frequencies.

As shown in Fig. 12, the measured null fill-in is about 10%, and consideration of this result will reveal that the actual null at this point will have a fill-in of from 5 to 15%, depending on the phase of the far field of the array relative to that of the site.

Greater fill-in than that shown in Fig. 12 may be provided by several methods, such as operating the antenna above design frequency, Fig. 13, beam tilting, Fig. 14, and by minor design changes. However, experience at the Bridgeport, Connecticut transmitter KC2XAK with the prototype of the present antenna has shown adequate signal uniformity in that region covered by the side lobes and nulls.[5]

[5] "Experimental Ultra-High Frequency Television Station in the Bridgeport, Connecticut Area," R. F. Guy, J. L. Seibert, and F. W. Smith, RCA Review, March 1950.

In general, the signal received at any point will be the vector sum of the direct and ground-reflected waves. The geometric relations are as shown in Fig. 20, in which a plane smooth earth is assumed. Since, for a horizontally polarized wave, the electric field reverses direction on ground reflection, there will be cancellation of the fields at the receiving antenna for path length differences of integral multiples of a wavelength.

As a receiving point is moved outward at constant height, the path length difference of the two waves will continually decrease, and there will be cancellations and reinforcements as this occurs. The cancellations are ordinarily not complete since the ground absorbs part of the signal and the direct wave is always stronger at the receiver.

With an isotrope or low gain antenna, the wave at the angle a is equal to that at angle b for D large compared to the antenna height h_1.

Near a cancellation point, the vectors are as shown in Case I and since E_r and E_o are almost equal, the resultant field will be very small.

With a high gain antenna, the waves at angles a and b will, in general, differ in magnitude so that, as in Case II, the cancellation is less complete and a greater field results. If, for example, the wave at either a or b comes from a null there will be no cancellation and the resultant field strength at the receiver will be greater than in either of the previous cases.

Fig. 23 shows a radial calculated for a transmitting height of 500 feet and receiving height of 30 feet over plane earth of common characteristics

$$(\sigma = 5.10^{-14}\ \text{e.m.u.}, E = 15),$$

wherein the less severe effects of ground reflection interference can be seen and in which the effect of antenna nulls is subordinate to that of reflection. These curves are for equal effective radiated powers. For equal transmitter powers, the isotropic curve must be lowered by the gain of the antenna relative to an isotrope, i.e., by approximately 16 DB. Calculations must, of

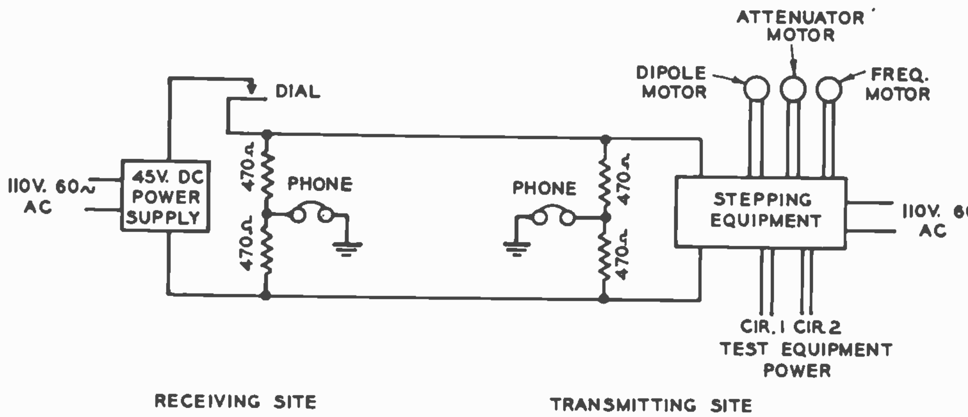


FIG. 9. The Control System.

course, be made on the basis of an earth surface of simple geometry, such as plane or spherical, but the same theory holds for other earth surface shapes, except that the interference positions may not occur at the same distances from the transmitter.

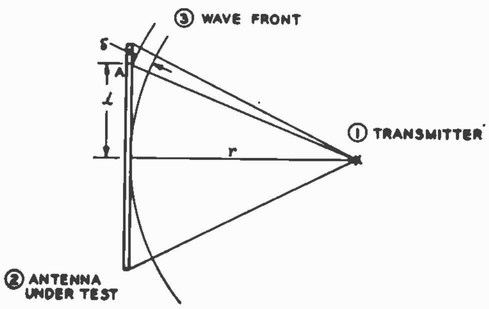


FIG. 10. Geometry of Path-Length Difference.

Recording System Accuracy

With high gain antennas having half-power beam widths in the order of 2 degrees, the recording accuracy requirements become quite critical, especially when it is

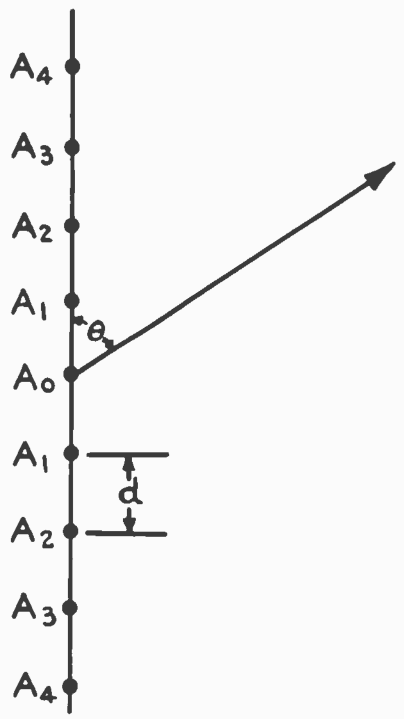


FIG. 11. Array of Point-Sources.

necessary to measure beam tilts. In this particular application, it is necessary to be able to record to within ±0.1°.

With the recording of narrow beams, it is necessary to "spread out" the chart, i.e., make each degree of turntable rotation equal to a considerable space on the chart. In the test here described, one degree equalled ¾ inch of chart. At these low gear ratios between selsyn and recorder, the input frictional torque supplied by the selsyn is considerable and the machine will drop behind its theoretical angular position until it develops sufficient torque to pick up the load.

A gear train of appropriate type must be interposed between selsyn and recorder to prevent the angular error in the selsyn from causing the recorder to fall back too far. These considerations are shown in Fig. 15.

Notation:

$$\text{All gear ratios} = \frac{\text{Driver teeth}}{\text{Driven teeth}}$$

N_1 = Ratio turntable to selsyn transmitter.

N_2 = Ratio selsyn receiver to recorder.

$$K_T = \text{Selsyn torque constant} = \frac{\text{Degree of rotational lag}}{\text{Inch-Oz.}}$$

$$K_R = \text{Recorder constant} = \frac{\text{Unit of chart}}{\text{Degrees of drum rotation}}$$

δ = Angular error of recorder, in chart units.

δ' = Angular error of receiver selsyn, in degrees.

T = Frictional torque required to drive drum, oz.-in.

θ = Degrees of rotational movement of turntable.

Torque seen by receiver selsyn (neglecting acceleration) is N_2T.

A perfect gear system is here assumed.

The receiver selsyn will drop behind the transmitter until sufficient torque is developed to carry load.

$$\delta' = N_2\,T\,K_T$$

This angular error appears at the recorder drum multiplied by N_2—

$$\delta = N_2^2\ TK_T \text{ (in degrees of drum rotation)}$$

$$= N_2^2\ TK_TK_R \text{ (in chart units)}$$

However, it is convenient to refer this error to θ, that is, express it in degrees of turntable rotation—

$$\delta = \frac{\text{Angular error of recorder drum}}{\text{Gear ratio, turntable to recorder drum}}$$

$$= \frac{N_2^2TK_T}{N_1N_2}$$

$$= \frac{N_2}{N_1}TK_T \text{ (in degrees of turntable rotation)}$$

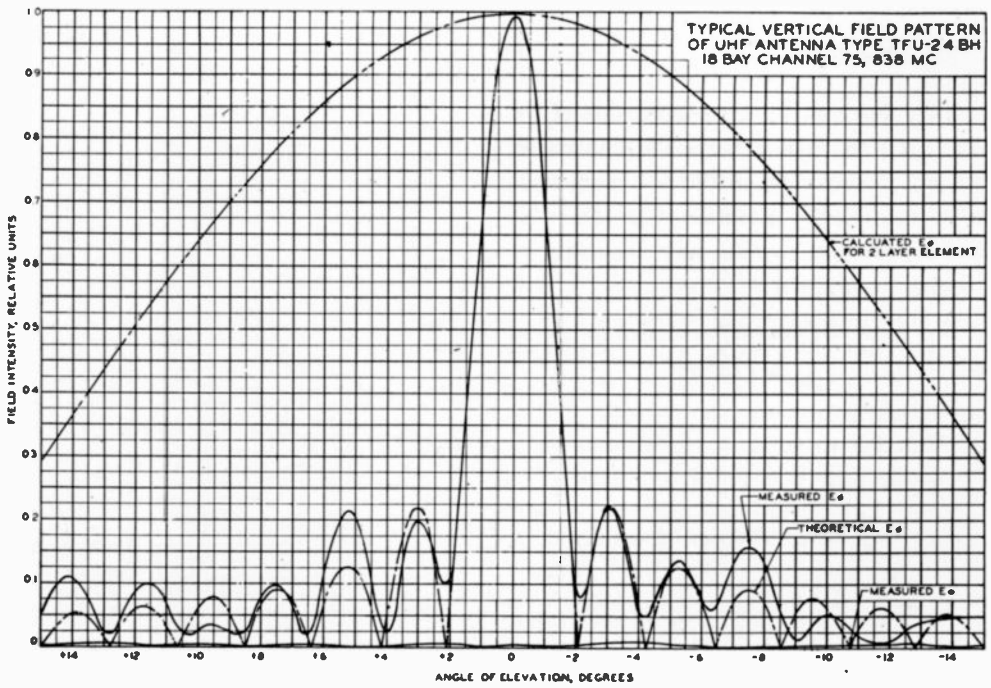


FIG. 12. Vertical Pattern of TFU-24BH.

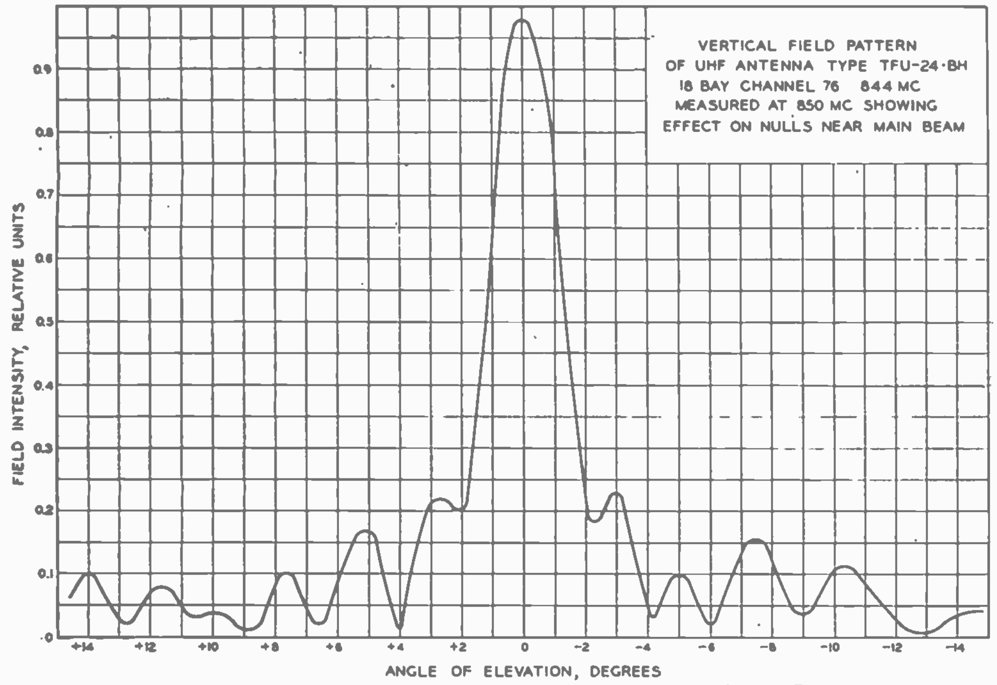


FIG. 13. Vertical Pattern of TFU-24BH Operated 6 Mc. above Center Frequency.

Usually, that ratio $\frac{N_2}{N_1}$ is to be determined which will allow recording to a specified accuracy. In this case:

$$(1)\quad \frac{N_2}{N_1} = \frac{\delta}{TK_T}$$

However, the overall ratio is determined by the degrees per unit of chart.

$$(2)\quad N_1 N_2 = \frac{1}{K_R}$$

If N_2 in (2) is substituted in (1):

$$(3)\quad N_1 = \sqrt{\frac{TK_T}{\delta K_R}}$$

This allows a direct determination of the gear ratio required to drive the transmitter selsyn. The second half of the overall train is determined by equation (2). Thus N_1 and N_2 are specified for any allowable recording accuracy.

For example, for the recorder in use at Medford during this period,

$K_T = 2.84°/\text{oz.-in.}$

$T = 3.5$ in.-oz.

$\delta = 0.1°$

$K_R = \frac{1}{60}$ chart division/drum degree

$$N_1 = \sqrt{\frac{3.5\,(2.84)}{0.1\,\frac{(1)}{60}}} = 77.5$$

$$N_2 = \frac{1}{N_1 K_R} = \frac{60}{77.5} = 0.775$$

In the actual Medford installation, the nearest lower combination for N_2 was 2/3. This dictated $N_1 = 90$, and is the ratio now in use.

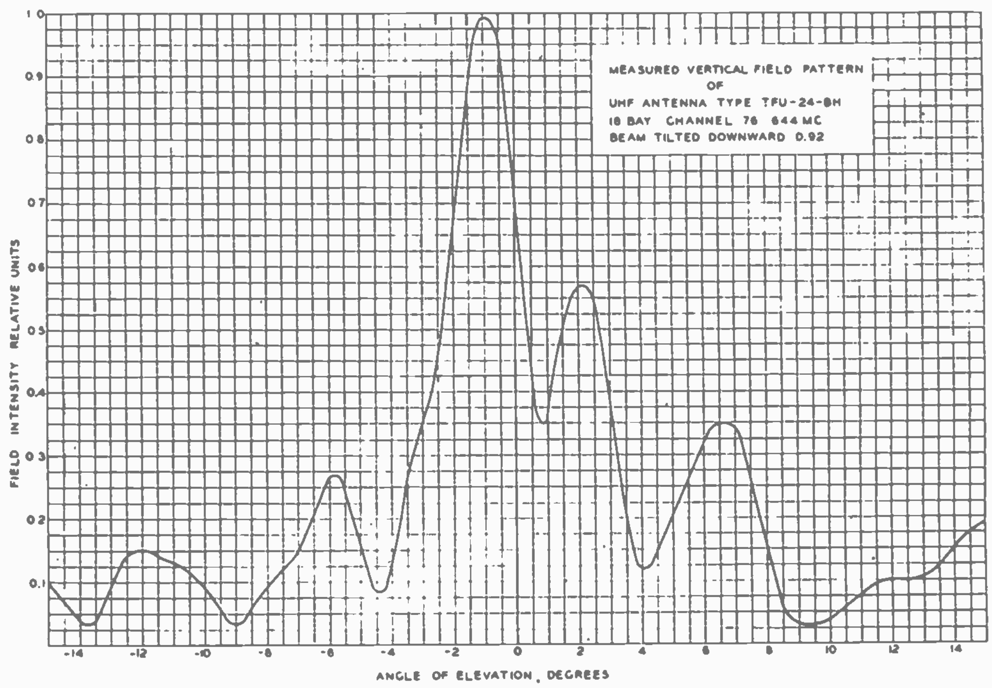
Many quantities not ordinarily considered assume prime importance. For example, some elastic angular deflection of the turntable and shaft will appear between antenna and bearings due to the bearing frictional torque, since the turntable is rotated by torque applied to the top of the rotating members. Because the selsyn must be mounted on a fixed support, its position is necessarily at the top bearing, and it will read the position of the shaft at that point with respect to the bearing.

The actual position of the antenna deviates from this due to the elastic angular deflection, and thus the antenna and its pattern (which appears at the pen) are ahead of the chart; consequently, a recording error results.

This effect is complicated by the fact that the bearing (on which the selsyn is mounted) itself is constrained by the elasticity of the mounting timbers, so that as force is applied to the top of the turntable and the antenna begins to rotate, first the lower bearing then the shaft and timbers at the top twist until the static bearing friction is exceeded, thus putting the antenna further ahead of the chart.

The effects are exaggerated in this description, being in the order of 3 to 5 minutes of arc; nevertheless, they do affect the results. The deflection of the bearing mounts has been measured by mounting a mirror on the bearing and sighting a transit on a distant object. Torque is applied until the turntable is on the verge of rotation,

FIG. 14. Tilted Vertical Pattern.



and the movement of the object measured in minutes of arc. If the transit shows θ minutes, the bearing rotates $\frac{\theta}{2}$ minutes.

An overall test of the system was made during this period. A transit was set up on the turntable beside the center of the antenna, Fig. 16, and a push button arranged in a circuit to apply a voltage pulse

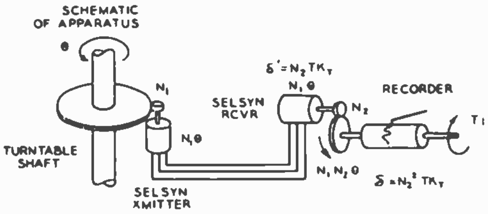


FIG. 15. The Recorder Drive System.

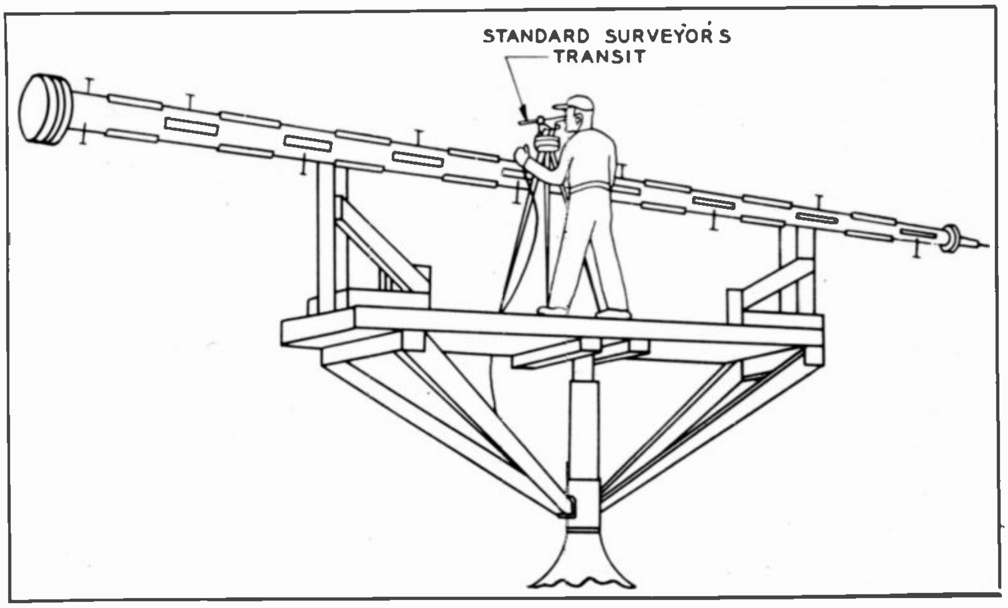


FIG. 16. Transit Test on Overall Recording Accuracy.

to the recorder. The transit was first sighted on the center of the transmitting parabola, 2400 feet away, and the recorder set on a main chart division. Then, as the turntable was slowly rotated, an observer set the transit ahead by ten degrees, locked it down, and waited for the cross-hairs to reach the center of the parabola. As they crossed, the button was pushed and a pulse appeared on the recorder. Enough readings were taken to average out the human errors, and from one of the charts shown in Fig. 17, it can be seen that the pulses do not lag the main divisions by more than 0.1°.

The Test Procedure

In taking a pattern, the antenna is turned approximately broadside to the incoming signal and the cable connected to the heterodyne frequency meter. The oscillator frequency is then measured and set to the desired value by dialing the appropriate numbers.

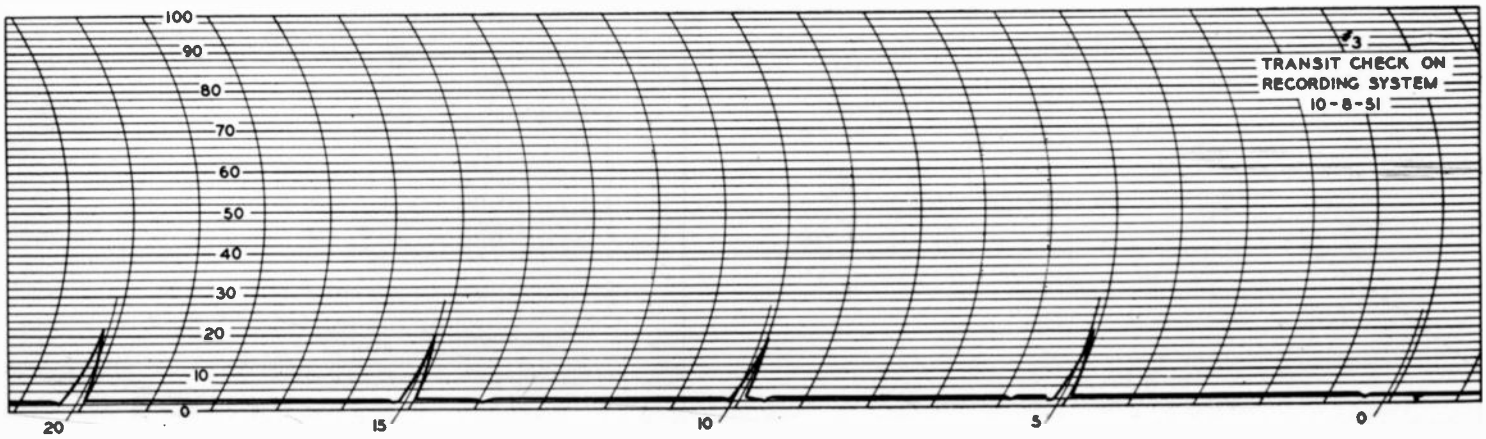
With the cable connected to the field intensity equipment and the antenna rotated until maximum signal is obtained, the correct gain and zero adjustments are made on the equipment.

The antenna is returned to zero (axis pointing at the transmitter) by means of the large compass rose and vernier. After exciting the selsyns and setting the recorder chart so the pen is on a main division, the run is begun. At this time, any aircraft in the vicinity of the airport invariably decide to land. Since the transmitted beam crosses the runway, an anomalous pulse is applied to the pattern which is marked and discounted later. The same effect which started radar development operates here also.

It is always desirable to check the power wasted in crosspolarized radiation in a new antenna. For this test, a small dipole, isolated from the re-radiated field of the main antenna by a metal reflecting sheet, is set up on the turntable and oriented parallel to the main antenna's normal radiation. The received field strength is read in relative units to give E_ϕ.

The transmitting dipole is then rotated by the dial system until a null occurs, at which time the incoming signal is a plane

FIG. 17. Transit Test Recorder Chart.



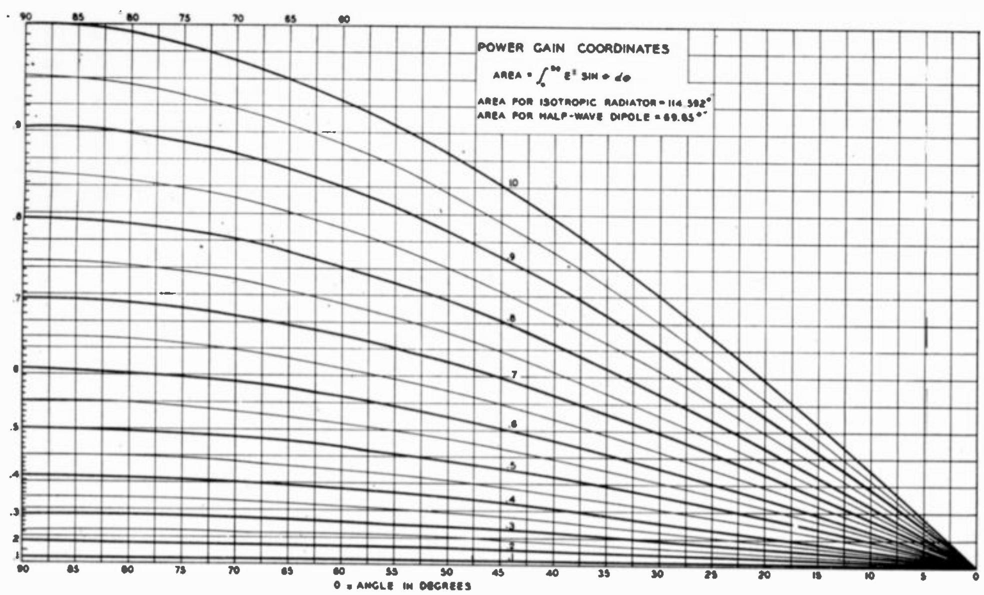
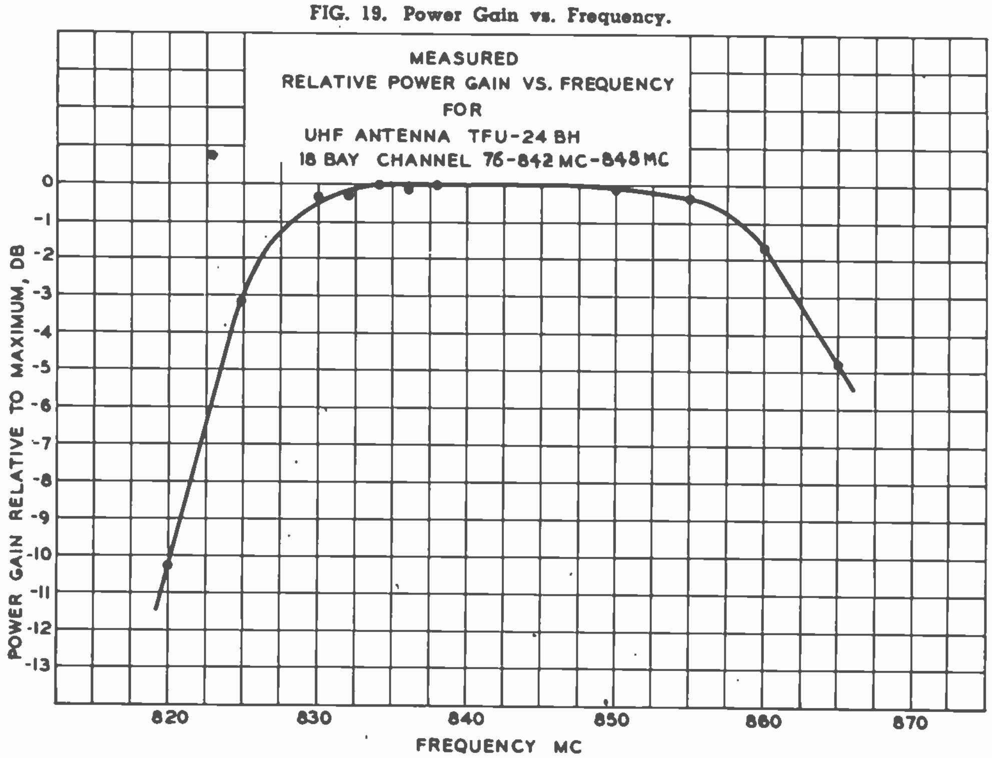


FIG. 18. Power Gain Coordinates.

FIG. 19. Power Gain vs. Frequency.



wave with electric field perpendicular to the receiving dipole axis. Then, the receiving dipole is positioned for maximum signal and this read in relative units to give E_θ.

In general E_θ will differ from E_ϕ because the reflection coefficient of the ground varies with polarization. However, the gain of the field intensity meter may be varied to give $E_\theta = E_\phi$.

A pattern is taken in this condition, though with antennas having very low cross-polarized radiation such as the TFU-24-B series, the attenuator on the field intensity meter must be decreased 20 db. to allow a readable chart to be recorded.

Patterns are taken in this way in both "vertical" planes (which are actually horizontal because the antenna axis is horizontal) through a line of slots ($\phi = 0°$) and halfway between a line of slots, ($\phi = 30°$). These two patterns are each repeated six times in going around the antenna in a plane normal to its axis.

A typical vertical field pattern of the TFU-24-BH is shown in Fig. 12, where the very low crosspolarized radiation can be seen.

In computing gain, the average of field values in the two planes vs. θ is plotted on power coordinate paper, Fig. 18, in which the ordinates are squared and multiplied by sin θ, so that it is merely necessary to plot the normalized field values vs. θ on this paper and integrate the result by planimeter. The area under the

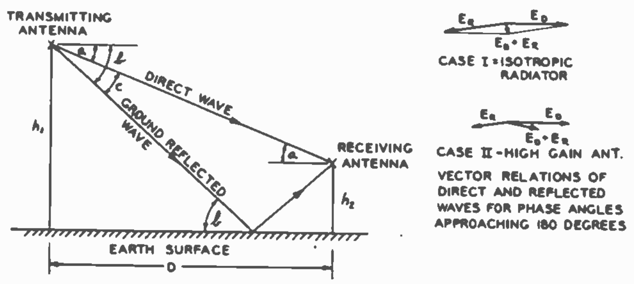
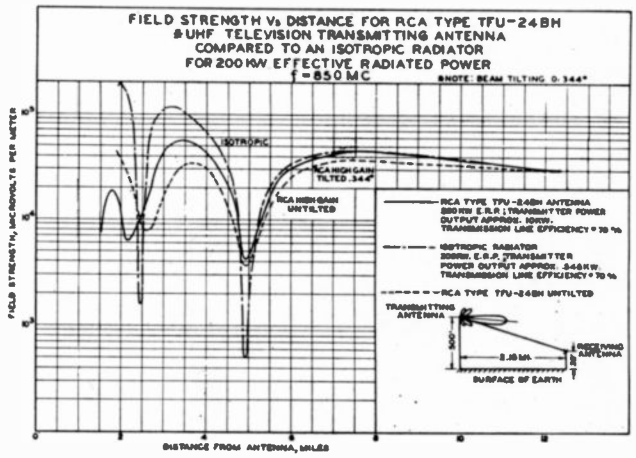


FIG. 20. Vector Diagram for Field Strength Relations in Ground Reflected Waves.

FIG. 21.



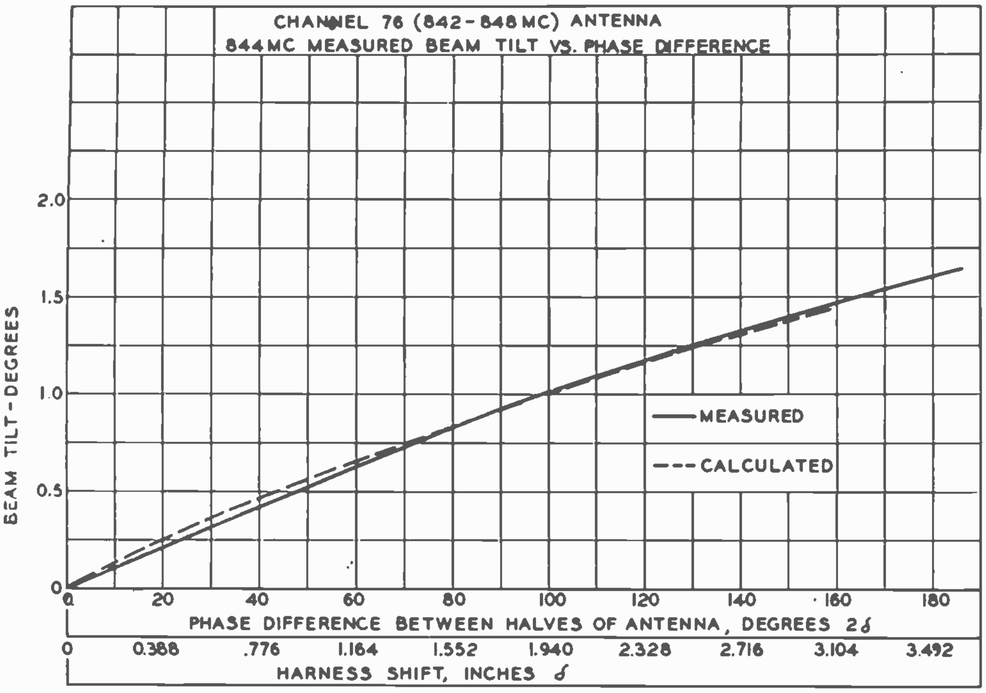


FIG. 22. Curve of Beam Tilt vs. Harness Shift.

A number of patterns are taken for various harness positions at the center frequency of the antenna. The position of the maximum of the main beam is measured and the gain evaluated for each position. Curves of beam-tilt vs. harness shift, Fig. 22, and of gain vs. beam-tilt, Fig. 23, result.

The process of antenna pattern measurements is continually undergoing changes in the direction of higher accuracy and greater speed; and this naturally points the way to greater mechanization. Effort, at the present time, is being directed along these lines in order to yield better patterns faster.

curve is proportional to the power radiated, and so the gain is:

$$G = \frac{K}{\int_0^{\pi} E_n^2 \sin(\theta) \sin\theta d\theta} = \frac{K}{\text{area}}$$

Where E_n is the normalized field pattern, average of patterns in the two principle planes, θ is the angle from vertical, and K is a constant determined by the paper dimensions, the gain of the reference antenna, etc.

As was mentioned previously, as long as the solid pattern is a figure of revolution, or at least has cyclic variation of small magnitude, so that the average of the field patterns in two vertical planes may be used, vertical patterns in those planes of the E_ϕ and E_θ components describe the total field and thus the total power radiated. This does not apply to some other types of antennas in which the vertical pattern varies greatly around the axis, or is not cyclic.

Accordingly, a plot is made of each on power coordinate paper and the resulting areas added in order to get the total gain:

$$\int_0^{\pi} (E_\theta^2 + E_\phi^2) \sin\theta d\theta = \int_0^{\pi} E_\theta^2 \sin\theta d\theta + \int_0^{\pi} E_\phi^2 \sin\theta d\theta$$

This procedure is followed for a number of different frequencies and the curve of power gain vs. frequency, Fig. 19, is obtained.

Acknowledgment

Appreciation is expressed to those members of the Broadcast Antenna Engineering Section who were connected with the pattern testing, especially to O. O. Fiet for many helpful suggestions both in the tests and in the preparation of this material, and to D. C. Stock and A. Feller for calculations and processing of test data.

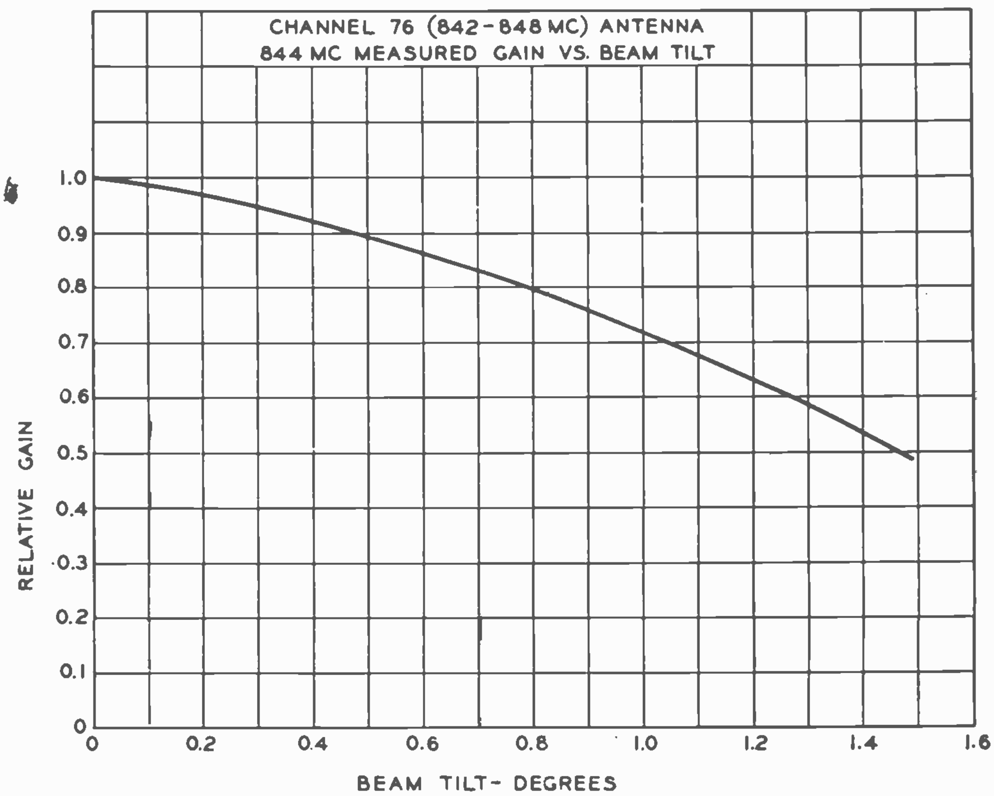


FIG. 23. Curve of Gain vs. Beam Tilt.


KLEENEX

THE EMPIRE STATE TELEVISION ANTENNA SYSTEM

By
H. E. GIHRING
Manager, Broadcast Antennas
Engineering Products, RCA

The Empire State Building has dominated the New York skyline since 1929. In 1930 television broadcast frequencies were shifted from the 2 Mc. region to the then new and relatively unknown ultra high frequency region now known as the VHF band. Since the behavior of these frequencies approached that of light, the importance of "line of sight" transmission from relatively high locations was recognized. In line with this thinking, some preliminary tests were made with low power oscillators by the RCA Victor Division on various New York buildings, including the Empire State Building, which confirmed this conclusion. Accordingly, the National Broadcasting Co. installed equipment on the Empire State Building and began television broadcasting in 1931, using a 1 KW transmitter.

When television broadcasting emerged as a major industry after the war, the superiority of the Empire State Building as a transmitting site became even more apparent not only because of its absolute height but also because it is the tallest structure in the area, thus minimizing the possibility of "ghosts" or secondary images reflecting from lower buildings. The reflected field from the lower buildings is low in amplitude compared to the field from the higher antenna. When the situation is reversed, however, the reflected field from a higher building, compared to the direct field from a lower antenna, can become comparable so that "ghosts" appear in the picture.

Meanwhile, as television broadcasting spread to other cities, a number of cases resulted where transmitting antennas were installed fairly close to each other. One of these was on the Civic Opera Building in Chicago in which the National and the American Broadcasting Company antennas were only 150 feet apart. On the top of Mt. Wilson near Los Angeles, quite a number of stations operated in close proximity to each other with no difficulty.

Hence, when the opportunity presented itself for the multiple use of the Empire State Building as a television center, several facts had become established.

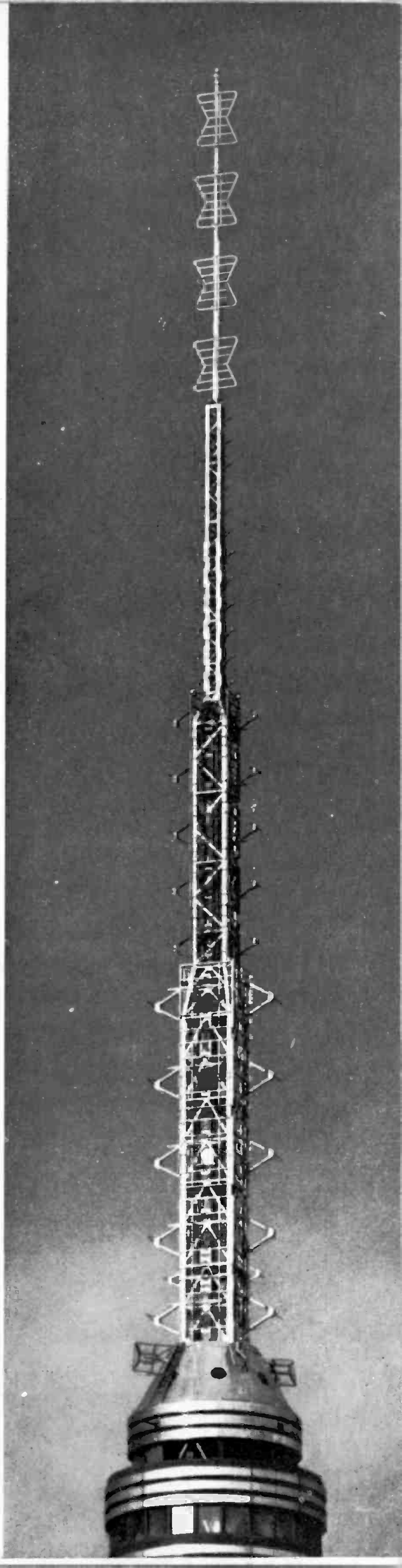
1. The desirability of the Empire State Building as a transmitting site.
2. The fact that multiple operation seemed feasible based on previous experience.

Once the decision had been made to use the Empire State Building for a multiple antenna site, many factors had to be considered, including administrative, legal, etc., as well as technical factors. A Primary Committee was established consisting of F. G. Kear representing Empire State, Inc. and all other licensees, and O. B. Hanson representing the National Broadcasting Company as the original licensee. Robert L. Kennedy was designated as alternate for F. G. Kear and Raymond F. Guy as alternate for O. B. Hanson. This committee was assigned the task of formulating the plans and conducting tests and generally controlling the work. The technical factors included both mechanical as well as electrical considerations. The architects, Shreve, Lamb and Harmon; the consulting structural engineers, Edwards & Hjorth; and the general contractors, Starrett Brothers and Eken; all of whom had been associated with the building when it was first built, were called into consultation by the Primary Committee to consider the height of a tower that could be placed on the building.

RCA Victor Division antenna engineers were consulted on the electrical factors, including the number of antennas and the coupling between them.

After preliminary investigations indicated that the project appeared feasible, a contract was entered into between the Primary Committee and the RCA Victor Division, and work was started.

◀ **(LEFT). High over Manhattan, three workmen perch on the WNBT array, as a fourth climbs the remaining portion of WPIX below.**



▶ **(RIGHT). Shown in full height, the Empire State Television Antenna.**

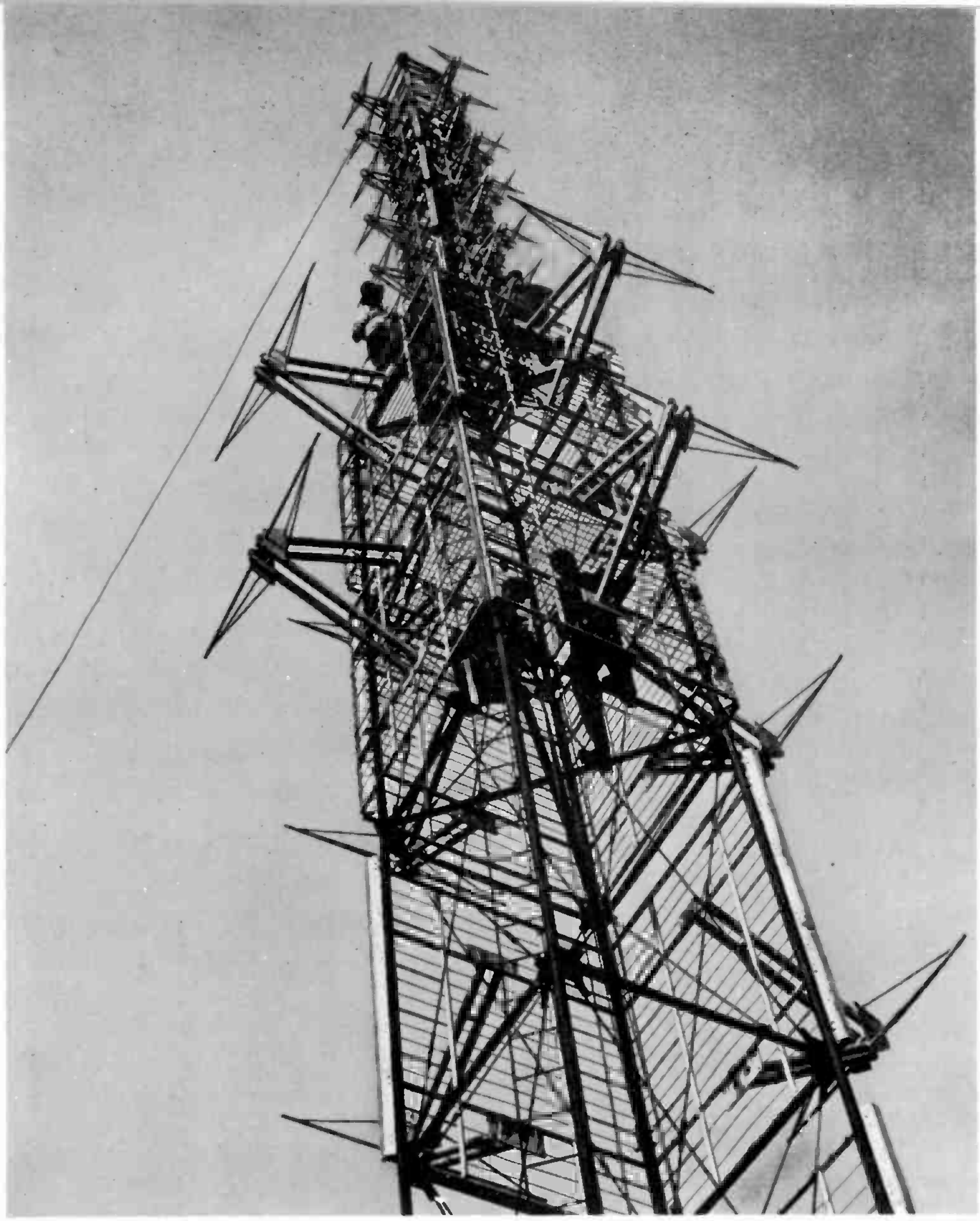


FIG. 1. View of Supergain Structure showing the Channel 5-7 Test Tower.

building proper would lower the height above terrain and result in a more complex antenna. The question was satisfactorily resolved by stacking all five TV antennas involved on the tower and allotting equal gain to each, with the exception of Channels 7 and 11 in the upper VHF band where the gain was 20% higher. The three FM services were to be obtained by other means such as interleaving, diplexing or triplexing.

The actual gain obtainable was contingent upon coupling between antennas since the closer the spacing between antennas, the greater the gain.

All aspects of the problem were studied in detail and target specifications were evolved as follows:

1. Coupling: —26 db. or less between any two antennas.
2. Input Voltage Standing Wave Ratio: 1.1:1 over the visual band; 1.5:1 over the aural band.
3. Gain: Directive gain of 4 relative to a thin one-half wavelength dipole for Channels 2, 4 and 5 antennas, and a gain of 5 for Channels 7 and 11 antennas.
4. Circularity: ±2 db.
5. Power Handling: Possibility of transmitting 100 KW ERP.

The choice of these specifications, the method of test and the results are described below.

General Requirements

In designing the Empire State television antenna system, special consideration was given to the following factors:

1. Provision for five television and three FM services.
2. Coupling effects between the eight antennas involved.
3. Bandwidth sufficient for television transmission.
4. Maximum gain in the aperture available.
5. Horizontal pattern suitable for area to be covered.
6. Power handling capability to permit 100 KW effective radiated power for the television services.

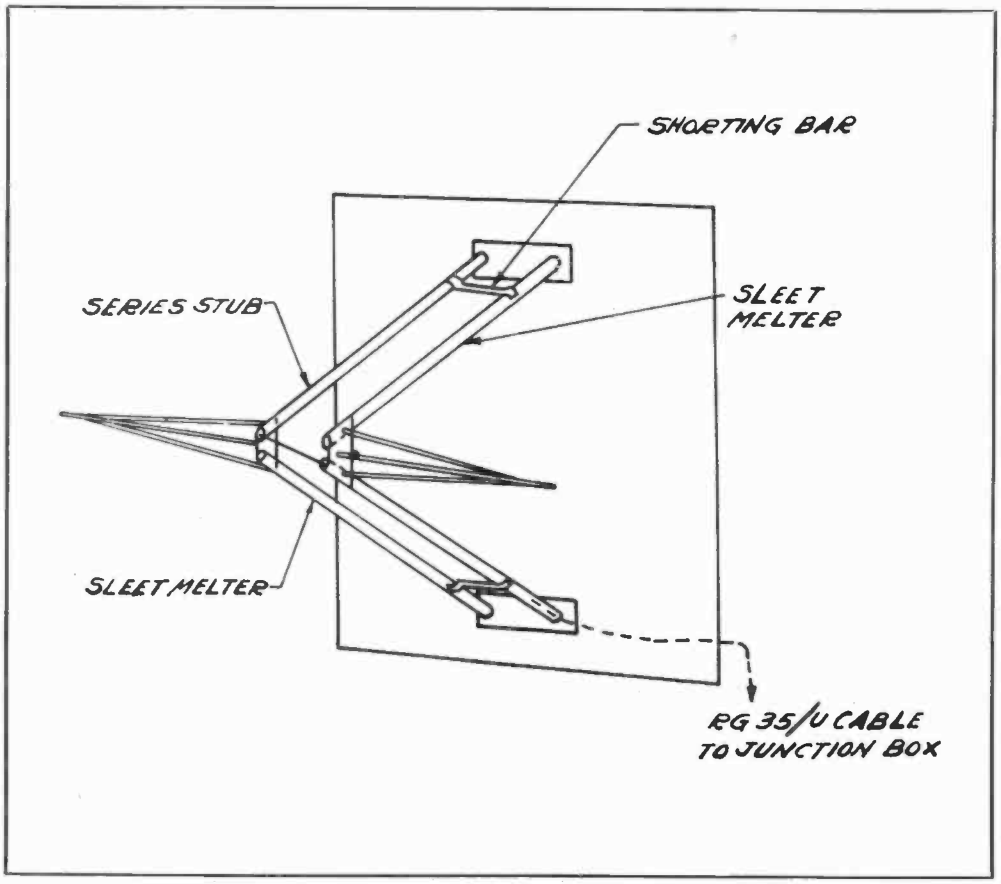
To satisfy the first requirement, it was apparent that the antennas for the various stations had to be either above each other or adjacent to each other or some combination thereof including the possibility of multiple use of one antenna for two or more channels. Various methods were considered—even the possibility of a 60-foot diameter ring on which all antennas could be mounted. Such approaches were finally abandoned for appearance as well as for structural reasons, and vertical stacking was chosen.

The next consideration was the height of the structure above the building. This was decided by the architects as approximately 200 feet. It was apparent that many of the design problems were interrelated. Since gain is roughly proportional to height measured in wavelengths, for vertically stacked omni-directional antennas,[1] the problem of using the aperture available to the best possible advantage required considerable study. Interleaving the antennas, diplexing two stations into one antenna as well as placing some of the services on the building proper were all considered and most of them were rejected for one reason or another. Interleaving or diplexing could result in complex situations should one station need to work on its antenna while the other station is operating. Furthermore, each of the lessees expressed a preference for operating his own antenna system. Locating the antennas on the

Choice of Antenna Type

Since time was an important consideration, it was desirable to use an antenna on which basic development work was not required. Two commercial types of television antennas available were the Superturnstile and the Supergain. The Superturnstile antenna is widely used for single station installations but is not suited mechanically for stacking eight antennas. The Supergain antenna, however, with its one-half wavelength square construction offers suitable structural support for the antennas above and also offers space for the transmission line, feed system, junction boxes, power equalizers, sleet melting equipment, lighting circuits and communication lines. The Supergain antenna consists of a series of half wavelength dipoles mounted on the four sides of a tower one-half wavelength square as shown in Fig. 1. The dipole is

FIG. 2. Sketch of Screen and Dipoles.



fed by a single RG-35/U cable which passes through one of the supporting legs (Fig. 2). The outer conductor is connected to one side of the dipole and the inner conductor to the other side. The flare of the dipole is for bandwidth reasons. While the flare for broad-band dipoles in free space is in the opposite direction, experiments have demonstrated that this is not true when a reflecting screen is used. The distance btween the dipole and the reflecting screens is about 0.3 wavelength for bandwidth requirements. The reactance component of the antenna is balanced out by means of a series stub consisting of a short piece of solid dielectric cable which is placed in one of the other legs. The triangular supporting structure is primarily for strength. The supporting structure is electrically isolated from the dipole by means of a shorting bar placed approximately one-quarter wavelength from the dipole. The two other supporting legs have heating units mounted in them for de-icing. This de-ices the spaces between the dipoles where ice would have the maximum effect on impedance.

Each dipole is fed by means of a cable which terminates in a common junction box (Fig. 3). The common impedance at the junction box is $\frac{1}{n}$ of the dipole impedance if n is the number of dipoles. Immediately below the junction box, a two-stage transformer is used to match the common junction box impedance to the main transmission line impedance of $51\frac{1}{2}$ ohms.

Since the number of elements used in the Empire State television antennas were less than those used in previous designs, and also since the feed cables used were larger because of power handling requirements, it was necessary to develop special junction boxes. The problem of easily disconnecting the cables from the junction box, maintaining gas pressure and still maintaining excellent impedance characteristics was a major development in itself. Fig. 3 indicates the type of connection used.

A more detailed description of the Supergain antenna has been given in a previous paper.[2]

Coupling

Possible coupling resulting in crosstalk or other disturbances was one of the major considerations in the design of the antennas. Little or no previous experience was available except the fact that some 80 Superturnstile antenna installations had worked successfully without any trace of crosstalk where the isolation between the visual and aural transmitters was of the order of 20 db. This was true of transmitters with both triode and tetrode tubes in the output circuit. In order to allow for a difference in power levels and as an additional safety factor another 6 db was added, thus making the target specification for coupling —26 db between any of the antennas at the carrier frequencies involved. In setting this specification, only coupling between antennas was considered since radiation from an antenna to another transmitter or interference between transmitters is a function of shielding and cannot be minimized by antenna design. Similarly, harmonics could not be considered since these are generated in the transmitter and could be controlled at that point.

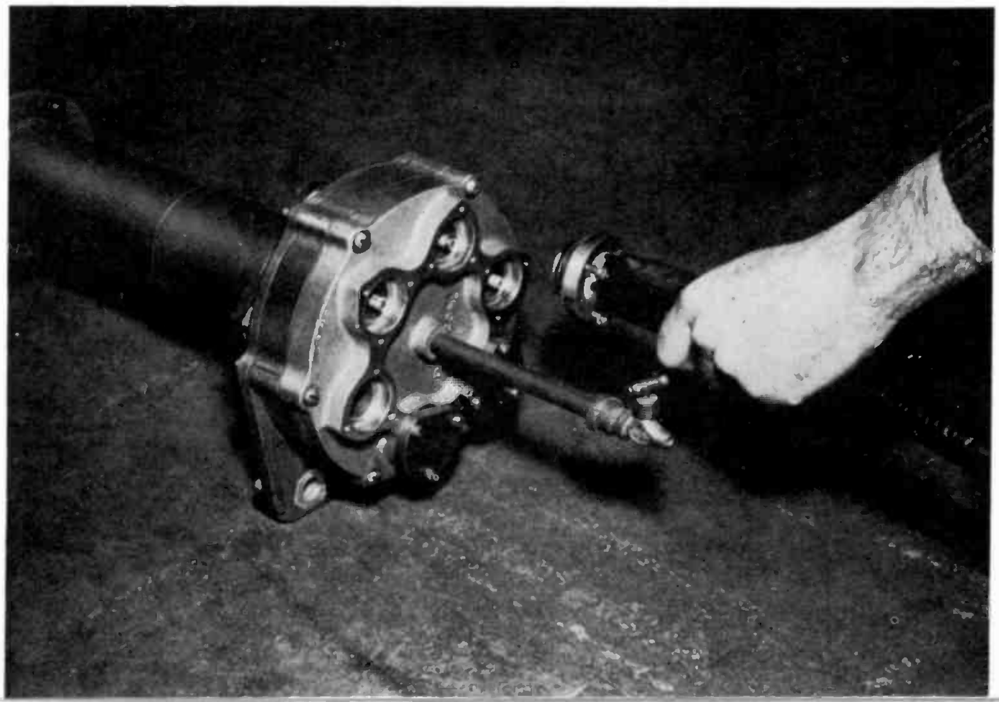


FIG. 3. One of the Junction Boxes and Feedlines Developed for the Empire State Antenna.

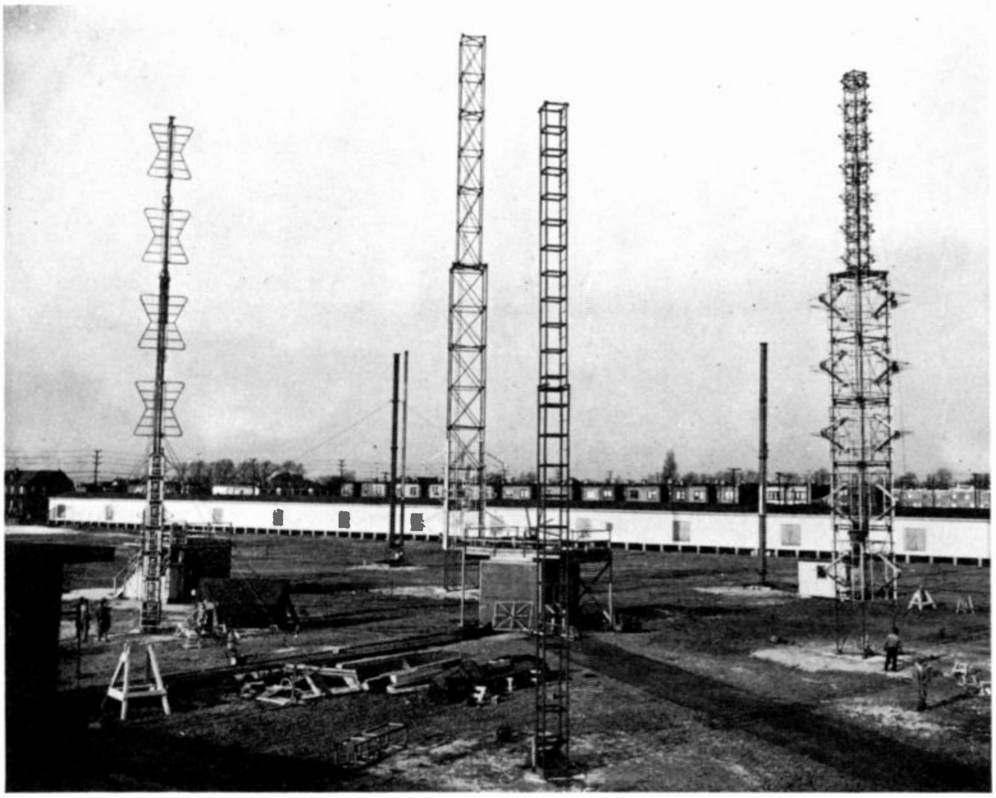


FIG. 4. General View of Test Towers used for Empire State Antennas. Each Tower Accommodates Two Adjacent Antennas.

To check the impedance of each antenna and the coupling between them, it seemed desirable at first to duplicate the entire 217-foot structure at the test location. Since this was not feasible for a number of reasons, one of which was the difficulty of working on the structure and making tests, the next best procedure was adopted in which adjacent pairs of antennas were tested on four towers, Figs. 1 and 4. The highest tower using this method is of the order of 100 feet for the channel 2 and 5 combination.

However, such coupling tests could not be completed until the antennas were available and adjusted for impedance. Since the tower design for the Empire State Building had to proceed immediately, some assurance was necessary in advance of the final tests that the target specifications for coupling could be met. This was obtained by two approaches: namely, by calculation and by tests with single screens.

The method of calculation was arrived at by Mr. R. W. Masters.* The formula for coupling between antennas is as follows:

$$\frac{P_r}{P_t} \leq \left(\frac{\lambda}{4\pi R}\right)^2 \frac{G_t\ G_r}{n_t\ n_r}$$

where equality, under the assumptions, obtains for $n_r = n_t = 1$.

where P_t is the power applied to the transmitting antenna.

P_r is the power received by the receiving antenna.

R is the distance between the antennas.

G_r, G_t are the directive gains of the adjacent end bays of the neighboring antennas in each other's directions relative to an isotrope.

n_t is the number of bays of the transmitting antenna.

n_r is the number of bays of the receiving antenna.

A number of assumptions were necessary to arrive at this formula.

1. That the field magnitude varies in proportion to inverse distance.
2. That the major contribution to coupling comes from the two adjacent end bays.
3. That the radiators are matched to the branch feed cables.
4. That no coupling exists between the N-S and E-W elements of the antenna.

The coupling between the closest pair of half bays at the longer of the two wavelengths; namely, channels 5 and 7 at the channel 5 carrier under the above assumptions was —17 db. However, since the power is not all concentrated in the adjacent bays but is fed equally to all bays, another 10 db can be easily obtained. Hence, from this viewpoint, the necessary decoupling could be achieved.

As an additional check, combinations of single screens were checked with various separations. This experiment was performed in the same manner as the subsequent measurements on the complete antenna for which the following procedure was used.

* With Ohio State University Research Foundation, engaged by RCA as consultant for this project.

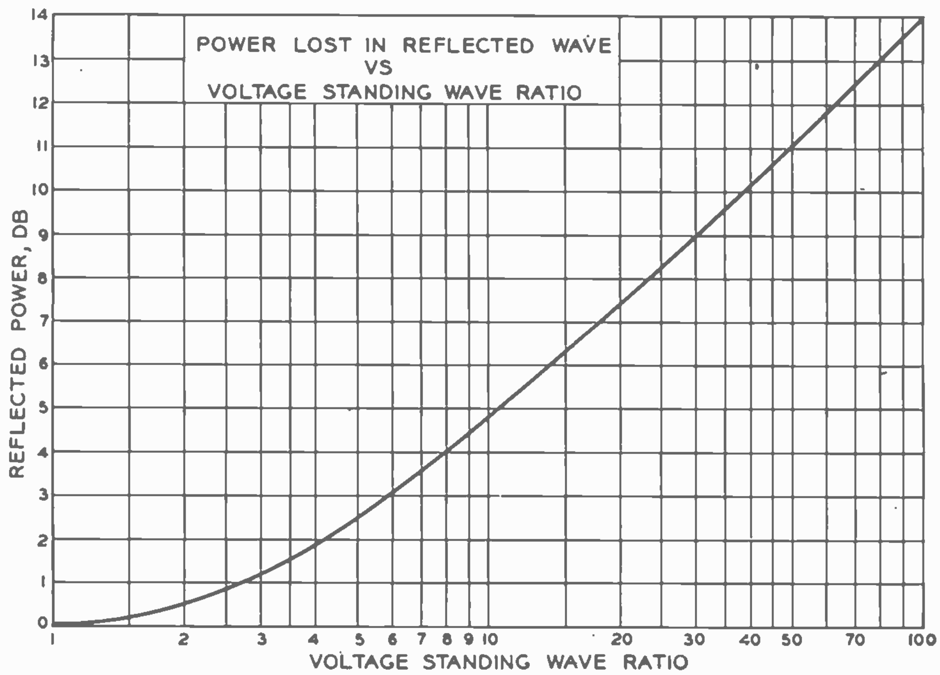


FIG. 5. Correction Chart Used in Coupling Tests.

FIG. 6. Typical Decoupling Data for Channels 5 and 7. Field Rotation of Both Antennas in Same Direction (Normal Condition).

IN:	Channel 5 Upper Group	Channel 5 Upper Group	Channel 7 Visual	Channel 7 Aural
OUT:	Channel 7 Visual	Channel 7 Aural	Channel 5 Upper Group	Channel 5 Upper Group
Frequency				
77.25 Mc.	65.8 db.	55.7 db.		
79.0	54.1	50.7		
81.75	46.5	46.2		
175.25			51.2 db.	51.2 db.
177.0			52.6	52.6
179.75			51.3	50.2

Above data adjusted for mismatch loss.
Quarter-wave phasing section in E-W halves.

An antenna was driven at a known level at its own frequency and the received power level in the adjacent antenna was measured. The mismatch in the antenna occupying the receiving position was often quite high because the frequency of the incoming signal was outside the design range of the antenna. By properly accounting for the additional power scattered by the receiving antenna as a result of an impedance mismatch between it and its transmission line, it was found that the measured crosstalk values could be adjusted to substantial equality for both directions of transmission. The adjustment amounted to the same thing as experimentally matching the receiving antenna to its line before measuring the crosstalk. Fig. 5 gives the required correction as a function of voltage standing wave ratio which the receiving antenna would set up on its line if used as a transmitter. The tests between single co-channel radiators spaced 0.65 wavelength apart indicated an isolation of about 18 db, and greater values for dissimilar elements up to 40 db for channels 5 and 7 screens placed in close proximity.

Since agreement was obtained between calculated and measured results on single screens, and since it appeared that an additional margin could be obtained when the power was divided into a complete antenna rather than into two adjacent bays, the tower design proceeded on the basis of the close spacing used in our experiments in order to obtain the maximum gain possible.

In the meantime, the antennas for Channels 11, 7, 5, 4 and 2 were fabricated and placed on the towers and adjusted for impedance. Coupling tests were then made by the method outlined above. Typical results are shown in Figs. 6 and 7. In all cases, the specification of —26 db has been met or bettered.

Gain

Gain was initially calculated by assuming a thin dipole, one-half wavelength long .3 wavelength in front of an infinite screen. This resulted in an element pattern. The array factor for the number and spacing of elements decided upon was then determined and multiplied by the element pattern. The resulting pattern was then integrated over a sphere to obtain the gain of the configuration.

FIG. 7. Typical Decoupling Data for Channel 7-11. In the upper table, fields are rotating in the same direction for both antennas; in the lower table, fields are in opposite direction.

IN:	Channel 7 Visual	Channel 7 Visual	Channel 7 Aural	Channel 7 Aural	Channel 11 Visual	Channel 11 Visual	Channel 11 Aural	Channel 11 Aural
OUT:	Channel 11 Visual	Channel 11 Aural	Channel 11 Visual	Channel 11 Aural	Channel 7 Visual	Channel 7 Aural	Channel 7 Visual	Channel 7 Aural
Frequency								
175.25 Mc.	48.9 db.	36.9 db.	36.9 db.	48.9 db.				
177.0	55.1	36.6	36.6	48.3				
179.75	59.3	36.8	35.5	51.9				
199.25					42.8 db.	31.8 db.	32.6 db.	48.8 db.
201.0					45.0	30.9	31.3	44.5
203.75					41.7	30.7	30.4	59.0

IN:	Channel 7 Visual	Channel 7 Visual	Channel 7 Aural	Channel 7 Aural	Channel 11 Visual	Channel 11 Visual	Channel 11 Aural	Channel 11 Aural
OUT:	Channel 11 Visual	Channel 11 Aural	Channel 11 Visual	Channel 11 Aural	Channel 7 Visual	Channel 7 Aural	Channel 7 Visual	Channel 7 Aural
Frequency								
175.25 Mc.	36.9 db.	52.4 db.	40.2 db.	36.4 db.				
177.0	37.1	58.1	40.1	36.6				
179.75	36.3	51.3	41.1	35.3				
199.25					32.0 db.	50.6 db.	54.8 db.	31.3 db.
201.0					·31.1	49.5	48.0	30.9
203.75					30.3	52.8	42.4	30.8

·Quarter-wave phasing section in E-W half of Channel VII and N-S half of Channel XI antennas.
Above data adjusted for mismatch loss looking into the individual halves of antenna.

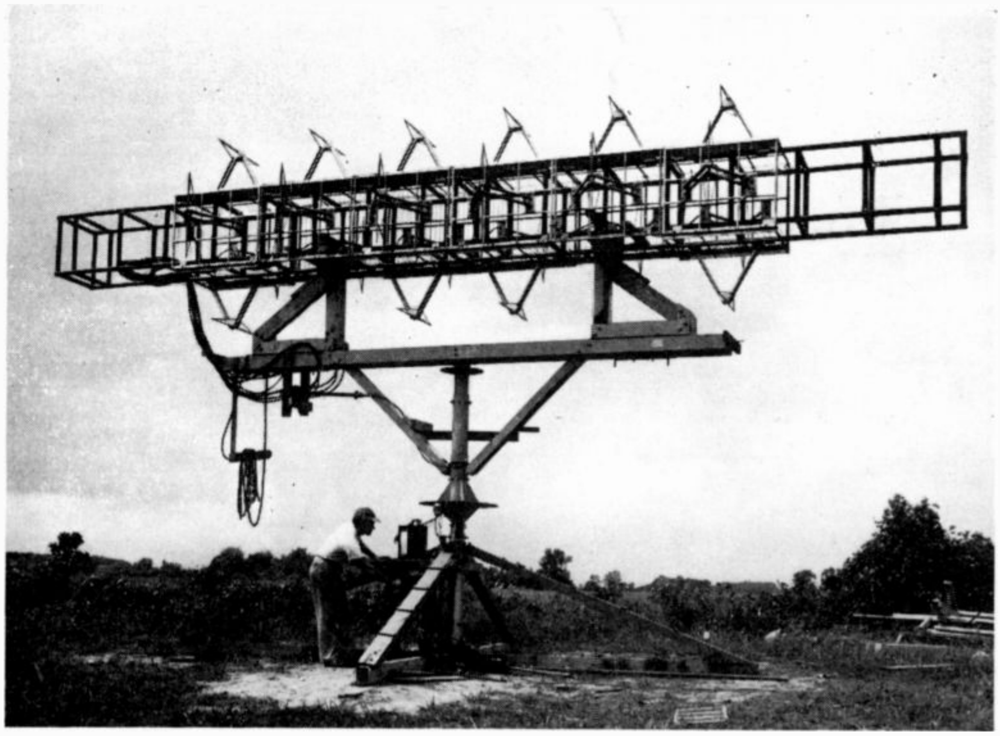


FIG. 8. Method of Determining Vertical Pattern.

This calculation makes a number of assumptions which gave a slightly optimistic result. Safety factors were allowed for these assumptions and the final measured gain checked quite closely. Subsequently, more precise methods were developed for the calculation of gain, especially for antennas using quadrature feed systems. These will be covered in future papers.

On the basis of the above calculations, it was determined that a directive gain with respect to a thin half-wave dipole of 4 and 5 could be achieved for Channels 2, 4 and 5 and Channels 7 and 11 respectively. These values were specified as target gains.

The experimental determination of gain was made by measuring the principal plane pattern of the Channel 7 antenna as shown on Fig. 8.

In this commonly accepted method, the antenna is mounted on its side and the dipoles radiating parallel to the ground are energized. For operating convenience, the antenna is used as a receiving antenna which will give correct results in accordance with the reciprocity theorem. The vertical pattern is obtained by rotating the antenna and recording the received signal. A great number of precautions were taken to assure correct results. This information was then scaled to the other channels. The exact procedure for determining gain is as follows:

1. Record the field pattern of the horizontally polarized field component in the principal vertical plane.
2. Square this pattern to obtain a power distribution and plot it against the cosine of the vertical angle, θ, (measured from the array axis) on rectangular coordinate paper.
3. By means of a planimeter, or other methods, find the area under the plotted power pattern and under the circumscribing rectangle which shares the same base line as the pattern plot.
4. The directive gain in the maximum direction relative to an isotropic radiator is the ratio of the rectangular area to the area under the pattern plot.
5. The gain thus found is divided by 1.641, which adjusts it to gain relative to a one-half wavelength thin dipole.

Gain measurements for a great number of conditions were necessary; for instance, the tower offset between Channels 5 and 7 had to be simulated to determine its effect. The same was true of the tapered dome of the Empire State Building with respect to the Channel 2 antenna. As pointed out later, the Channel 2 and 5 antennas were split into two separate antennas of two and three bays each for the purpose of providing emergency antenna service. The gain for each of these conditions as well as the combined antenna had to be determined. During the investigation, the Channel 7 antenna was rephased, at the request of the station, reducing the horizontal gain to obtain a higher field close to the antenna. Later, it was determined that the best method of providing FM service was the location of FM dipoles between the Channel 2 dipoles. The effect of these dipoles on this antenna was also determined. While some of these changes resulted in a second-order effect, nevertheless, the problems merited investigation to insure no serious changes developing at a later date.

Fig. 9 tabulates the results of gain measurements for various conditions. The direc-

FIG. 9. Results of Gain Measurements for Various Conditions.

	TELEVISION													FM		
Channel	11		7		7		5		4		4	2		97.1 Mc.[1]	95.5 Mc.	101.1 Mc.
			Equally Phased		Rephased				Equally Phased		Re-phased					
	Visual	*Aural*	*Visual*	*Aural*	*Visual*	*Aural*	*Visual*	*Aural*	*Visual*	*Aural*	*Visual*	*Visual*	*Aural*			
Antenna Directivity Gain	5.40	5.55	5.59	5.74	3.94	4.04	4.17	4.50	4.48	4.79	3.95	4.00	4.43	6.24	.707	.707
Upper Portion	—	—	—	—	—	—	1.45	1.57	—	—	—	2.49	2.75	—	—	—
Lower Portion	—	—	—	—	—	—	2.52	2.72	—	—	—	1.61	1.78	—	—	—
Feed Cable Eff. %	95	95	94.4	94.4	94.4	94.4	95.4	95.2	97.2	96.7	97.2	95.1	94.8	96	94.8	94.8
Power Equalizer Eff. %	—	—	—	—	—	—	98.9	98.1	—	—	—	97.2	96.9	—	—	—
Net Gain	5.12	5.28	5.28	5.42	3.72	3.80	3.93	4.21	4.36	4.63	3.85	3.71	4.06	6.00	.67	.67

[1] Triplexed on the Channel 4 antenna.

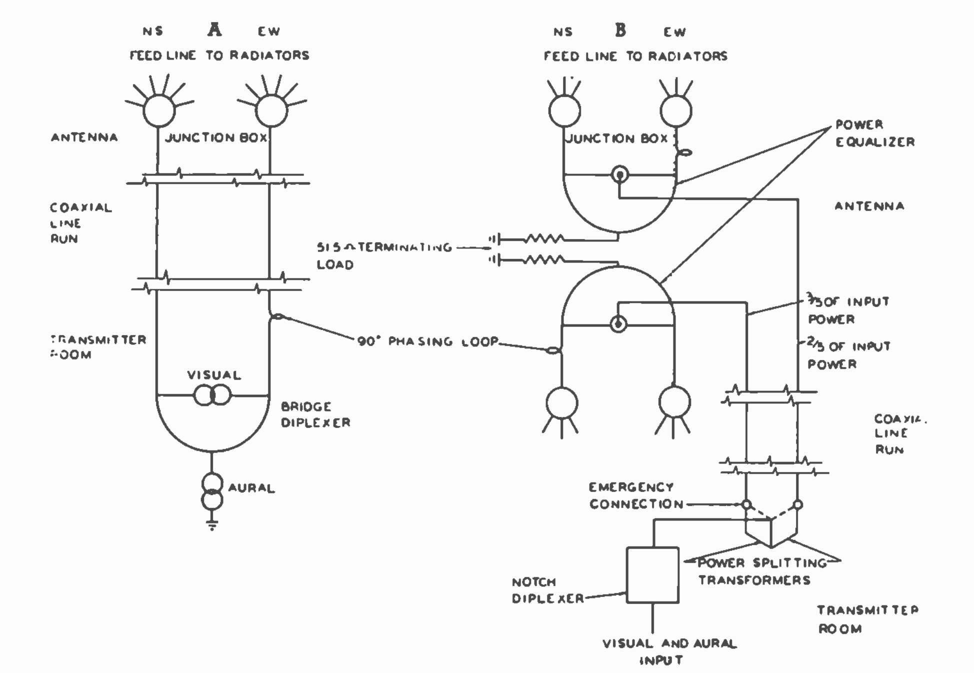


FIG. 10. Schematic Portrayal of Antenna System Showing Inner Conductors Only.

10a. Bridge Diplexer Feed System Chosen by Stations on Channels 4, 7 and 11.

10b. Notch Diplexer Feed System with Split Antenna Arrangement for Emergency Service Chosen by Stations on Channels 2 and 5.

tive gain, as well as the net gain, is given. The net value takes into account losses in the RG-35/U feed cable between the junction box and the radiator and also in the power equalizer. The power equalizer and its function are more fully discussed in the paragraph under broad-banding. The diplexer and the coaxial line efficiencies are not charged to the net antenna gain. For most commercial antennas, the net gain is specified. For the Empire State antenna system, however, the directive gain was specified. It will be seen that the target values of directive gain were achieved in the apertures that were available.

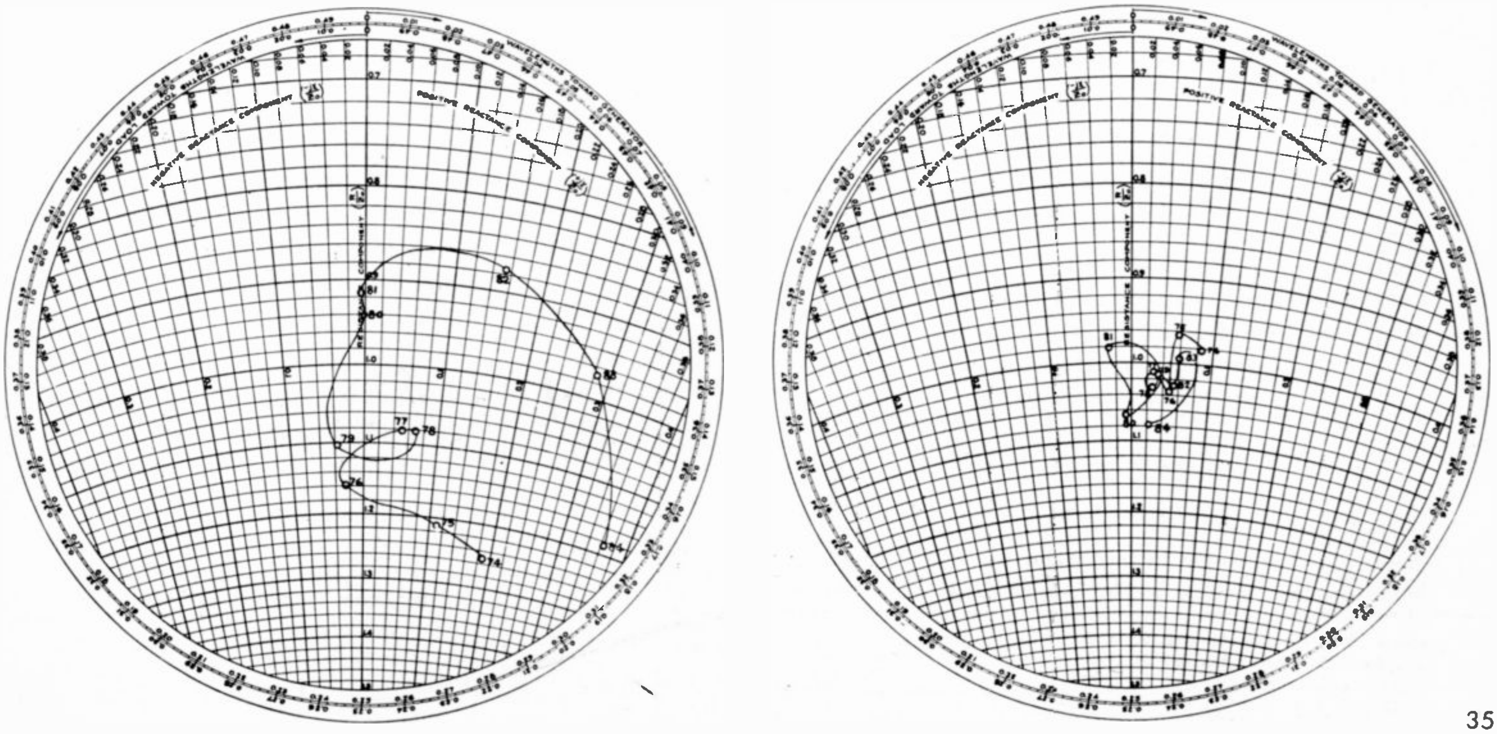
Bandwidth

While previous experience with the Supergain antenna indicated that the required bandwidth could be achieved, the problem was interrelated with effects due to the close proximity of the antennas, the necessity for different spacings between radiators to achieve the required gain, special junction boxes to handle the power, and a new type of feed cable. Since it was necessary to erect adjacent pairs of antennas on towers to determine the amount of coupling, as discussed earlier, the opportunity presented itself to make a thorough check of bandwidth under all of the special operating conditions required.

Since several possibilities presented themselves, the five stations were given a choice of feed systems. Stations on Channels 4, 7 and 11 chose the bridge diplexing arrangement shown in Fig. 10a; while stations on Channels 2 and 5 chose the notch diplexing arrangement with the bridge power equalizer shown in Fig. 10b. An additional variation offered was chosen by Channels 2 and 5 in which the upper and lower portions of the antenna were treated as two separate antennas with separate feed systems, power equalizers and coaxial lines. This permitted emergency operation with one portion of the antenna operating independently of the other.

As a result of experience with many television installations, it was known that the voltage standing wave ratio (VSWR) over the visual band had to remain within the limits of 1.1 to 1 to obtain satisfactory operation. This value was indicated as one of the target specifications.

FIG. 11. Smith Chart Indicating Improvement Due to Power Equalizer for Channel 5 Antenna. It will be noticed that before power equalizing the max. VSWR is 1.45, and after power equalizing, all impedances are within the 1.1 circle. Note tight cluster.



Since the Channel 4 Superturnstile antenna and the Channels 7 and 11 Supergain antennas had broad-band characteristics sufficient to achieve the necessary VSWR over the band, the standard bridge diplexing method was used. The operation of the bridge diplexer is well known, having been described in a previous article.[2] For Channels 2 and 5, power equalizing is desirable to achieve the required bandwidth since at the lower frequencies the percentage of bandwidth with respect to the transmitted frequency is greater. The power equalizer inherently improves the VSWR over the band by trapping reflected energy from the antenna. Fig. 11 indicates a Smith Chart plot of a portion of the Channel 5 antenna before and after power equalizing. The improvement is quite obvious. A more detailed description of this device is given in a previous article.[3] The amount of energy absorbed for reasonable VSWR's is negligible. For instance, if the VSWR is 1.22, the reflection coefficient is 10%, and only 1% of the power is dissipated.

In the split antenna arrangement, two coaxial lines are brought into the transmitter room where they are combined by a power splitting transformer which by transformation, splits the power from the transmitter to each portion of the antenna as required. The visual and aural signals are combined in a notch diplexer which is a frequency selective network permitting simultaneous operation of visual and aural transmission into one antenna system without interference.

The VSWR over the band was measured for a number of conditions including the N-S and E-W portions of each antenna before diplexing or power equalizing; and

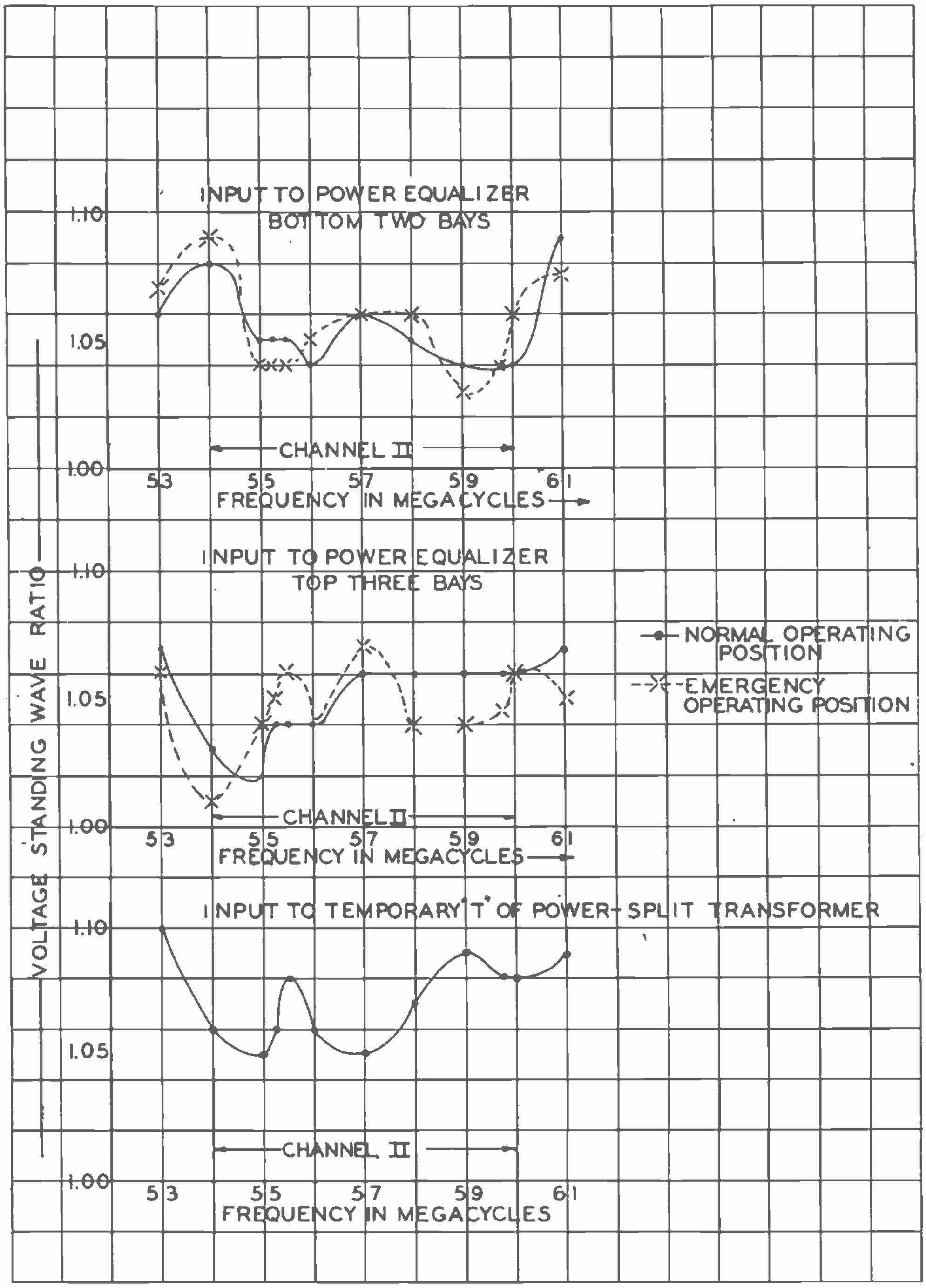


FIG. 12. Voltage Standing Wave Ratio Curves vs. Frequency for Channel 2.

Maximum Power Rating of Components

Feed cable max. VSWR	1.20
Feed cable VSWR derating factor	0.950
Feed cable temperature derating factor	0.788
Feed cable total derating factor	0.749
Feed cable power capacity before derating	1400 Watts
Feed cable power rating after derating	1049 Watts
Feed cable average power, visual, for 100 KW ERP	479 Watts
Feed cable average power, aural, for 100 KW ERP	396 Watts
Power Carried / Rated Power of feed cable for 100 KW ERP	0.835
*Average power output of transmitter for 100 KW ERP	24.8 KW
**Maximum ERP possible within limit of feed cables	120 KW

* Assumes that diplexer handles 25 KW.
** Assumes that diplexer handles 30 KW.

FIG. 13. Typical Calculations Establishing the Power Rating of the Feed Cable.

also the upper and lower portions of each antenna individually and combined by the power split transformer. Fig. 12 is a typical chart of VSWR vs. frequency for various conditions for Channel 2.

Circularity

Since the Empire State Building is substantially in the center of the service area, omni-directional coverage was satisfactory. The specification for circularity was ± 2 db. which was demonstrated with a single set of screens at Channel 7. The work was carried on in a manner similar to the vertical pattern work previously described.

Power Handling

One of the requirements for the Empire State antenna was the ability to obtain an effective radiated power of 100 KW from the antenna. This decision was made and the antenna substantially built before the later proposals were made by the F.C.C. Since there were relatively few elements (sixteen or twenty on the low band, and twenty-four on the high band) and since the gain was proportionately low, each feed cable had to handle a relatively large power. Investigation revealed that RG-35/U cable was satisfactory for the purpose. Fig. 13 indicates a typical calculation which establishes deratings for VSWR and temperature above ambient for which the cable rating is made.

FM Considerations

Three FM services were desired in addition to the five television services. Of these, the one for NBC, on 97.1 Mcs. was triplexed on the Channel 4 antenna by methods previously described.[4]

Two other services for 95.5 Mcs. and 101.1 Mcs. were required. A number of experiments were made to find a location where the FM dipoles, which are similar to the Supergain dipoles, could be located with negligible effect on the impedance and pattern characteristics of the television antenna. These experiments indicated that the best location was in the Channel 2 array. The method employed is shown in Fig. 14. Both FM frequencies were diplexed into the single set of four radiators. A VSWR of 1.03 was achieved for both frequencies, using a transformer designed for specific matching at the two carrier frequencies.

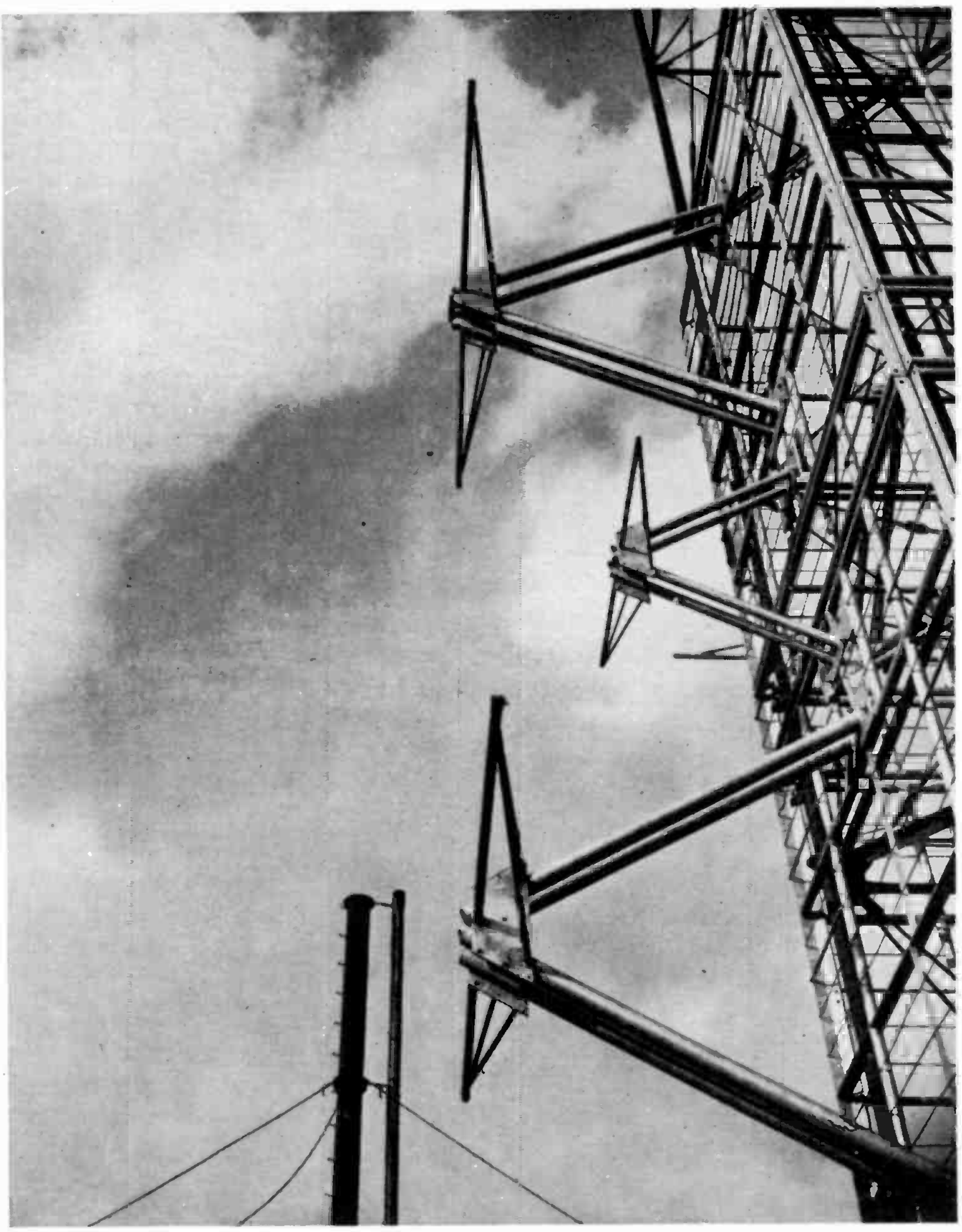


FIG. 14. FM Dipole Located in the Channel 2 Array.

Gain was measured by using a set of Channel 7 screens to simulate the Channel 2 antenna. The FM dipoles were then scaled to 320 Mcs. The gain, determined by the method previously described, taking into account the fact that the circularity was not optimum, for the FM frequency on the Channel 2 tower was .707 over a half-wave dipole.

Acknowledgment

The work described herein on the Empire State antennas is the work of many men. L. J. Wolf is responsible for much of the supervision and planning. R. W. Masters, formerly associated with RCA and presently engaged as a consultant to RCA for this project, is responsible for the basic theoretical work on Superturnstile and Supergain antennas. In addition, 14 other engineers were engaged on various parts of the project.

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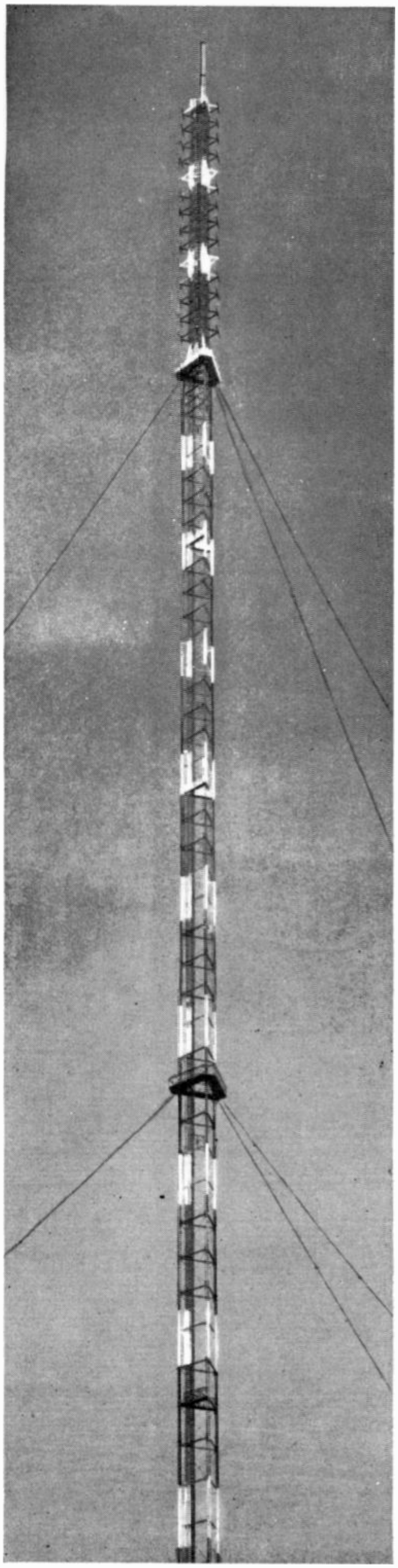
3. R. W. Masters, "A Power Equalizing Network for Antennas," Proc. IRE, Volume 37, p. 735, July, 1949.
4. L. J. Wolf, "Triplex Antennas for Television and FM," Electronics, Vol. 20, p. 88, July, 1947.



WSB-TV

ATLANTA, GEORGIA

BY

BOB HOLBROOK & **H. E. KING**

Assistant Chief Engineer, WSB-TV — RCA Engineering Products Department

On September 30, 1951, the WSB-TV engineering staff, headed by Chief Engineer, C. F. Daugherty, put into operation an RCA Television Antenna system, mounted atop the world's tallest television tower. This was accomplished in order to change the operation from Channel 8 to Channel 2. Originally the antenna and tower facilities had been installed by WCON. The total height from the ground up, including an RCA 14-Section Supergain Antenna and an RCA FM Pylon, is 1062 feet, see Fig. 1.

The Atlanta tower is the first television tower ever built to exceed 1000 feet, the first designed exclusively for TV and FM service and the first to utilize an RCA Supergain TV Antenna,[1] with a high gain of 11.0. Surprisingly, this "tallest TV tower" is located in a populated city area close to downtown Atlanta. The site is a thirteen acre plot located at the approximate geographical center of Atlanta. The ground elevation at this point is 973 feet above sea level—bringing the total tower height to 2035 feet above sea levei.

A guyed Ideco tower of triangular construction, 14 feet on each side up to the 800-foot level and 7 feet up to the tower top supports the four-sided Supergain Antenna.

Performance Results of Supergain Antenna

Measurements and listener reports have confirmed the advantages of the high tower and high gain antenna installed at WSB-TV. In keeping with the WSB slogan, it helps WSB-TV "cover Dixie like the dew."

Fig. 7 depicts the field strength measurements made on the WSB-TV installation, with 50 KW of effective radiated power. The 0.5 millivolts/meter or 54 dbu and the 5.0 millivolts/meter or 74 dbu contour lines are shown. The average radius of the 54 dbu and the 74 dbu contour is approximately 50 miles and 22 miles, respecively, values which check very closely with the coverage predicted by the FCC for this power. The indicated circularity of the antenna is good although as usual is affected by ground conditions such as the variations in the southwest direction on the 5 millivolt/meter contour and in the northern direction on the 0.5 millivolt/meter contour.

Fig. 4 shows the horizontal pattern obtained by helicopter. This measurement was made at distances of about a mile to avoid distortions from ground reflections. The horizontal circularity measured about ± 2.7 db. A desirable feature of an antenna is to provide constant field strength over the service range. This assures adequate signal strength without overloading the receivers close to the antenna. Some receivers overload when the signal at the input terminals of the receiver exceed 200 millivolts. Fig. 11 shows a typical radial measurement which illustrates that the signal strength is reasonably constant for the first few miles. Excessively high signal strengths are not encountered close to the antenna as is a normal characteristic for low gain antennas, but instead the signal for the WSB-TV high gain antenna remains about the same out to eight miles.

The industry has expressed considerable interest in how much signal is available in the first null of the vertical pattern of the antenna. One of the reasons for making

[1] "High Gain and Directional Antennas for Television Broadcasting", L. J. Wolf, BROADCAST NEWS, Vol. No. 58, p. 46.

FIG. 1. Towering 1062 feet above downtown Atlanta, is the world's first tallest TV tower and RCA antenna installation.

FIG. 2. Assembling reflecting screens and dipole radiators to special outriggers, which convert the triangular tower to a square in order to mount the 4-sided Supergain antenna.

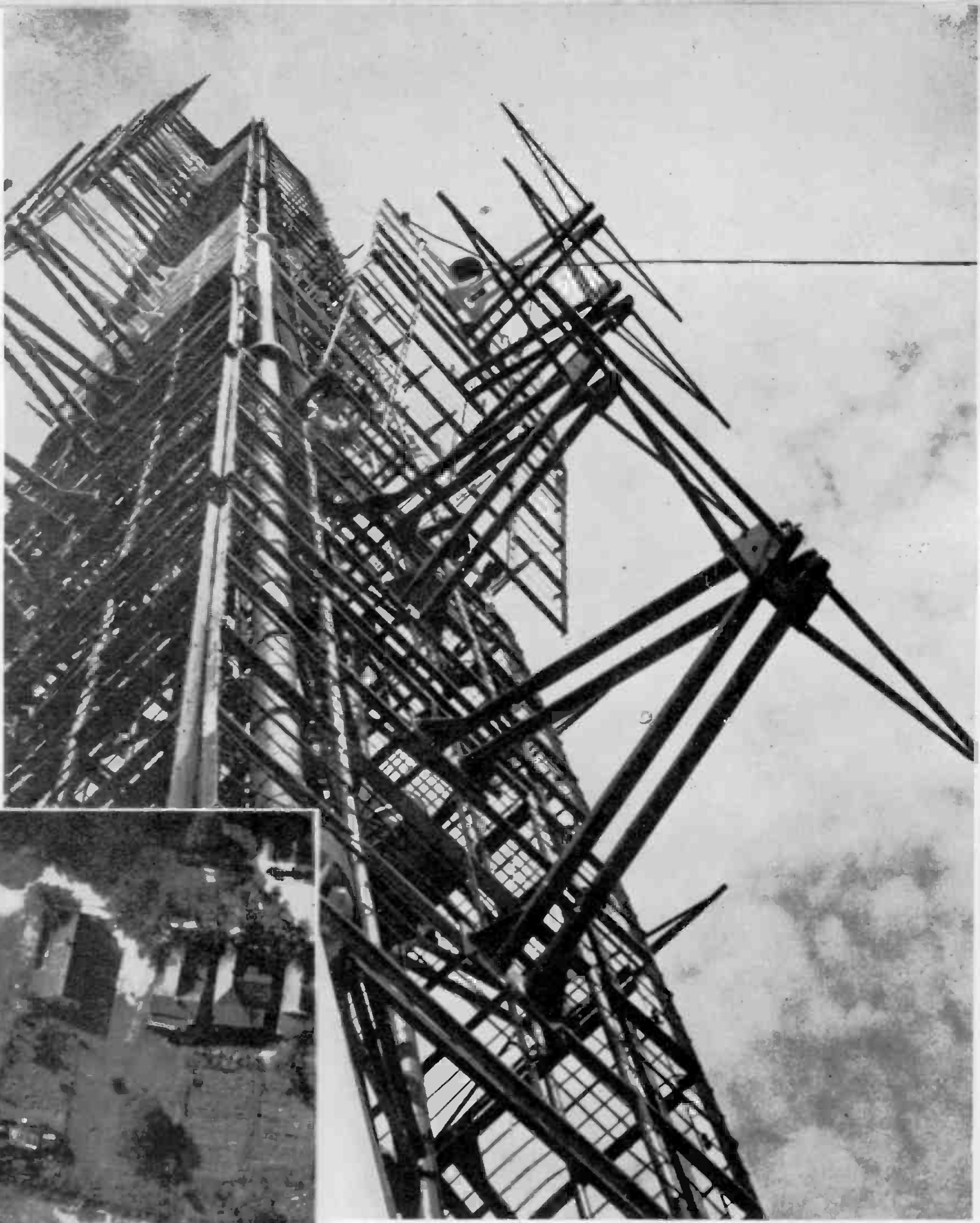


FIG. 3. Howard King, RCA Antenna Engineer, scales the FM Pylon which is mounted above the Supergain Antenna. Obviously, the cameraman must have been a little higher—but what's a few more feet at this height?

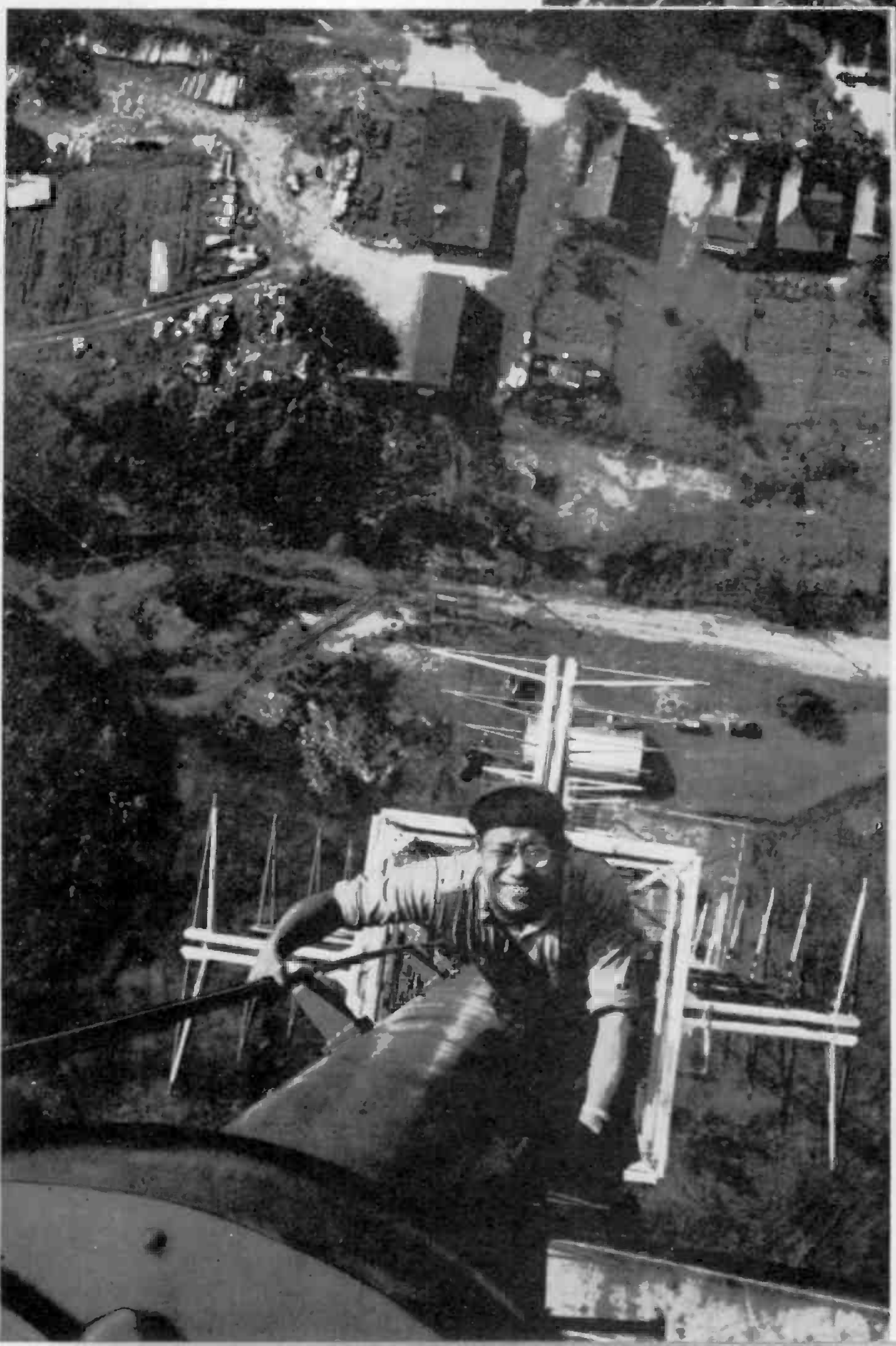
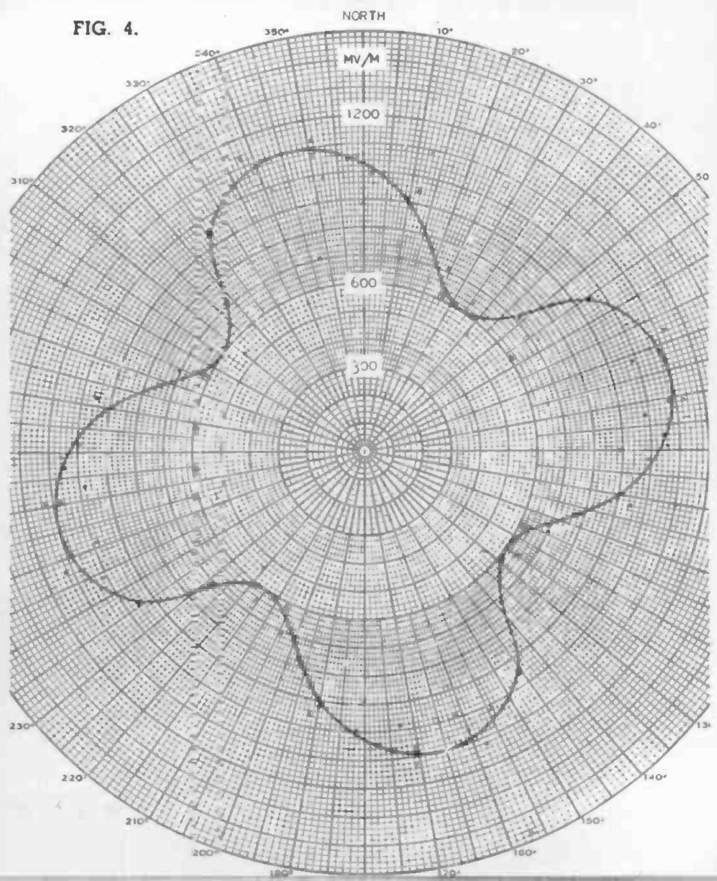


FIG. 4.



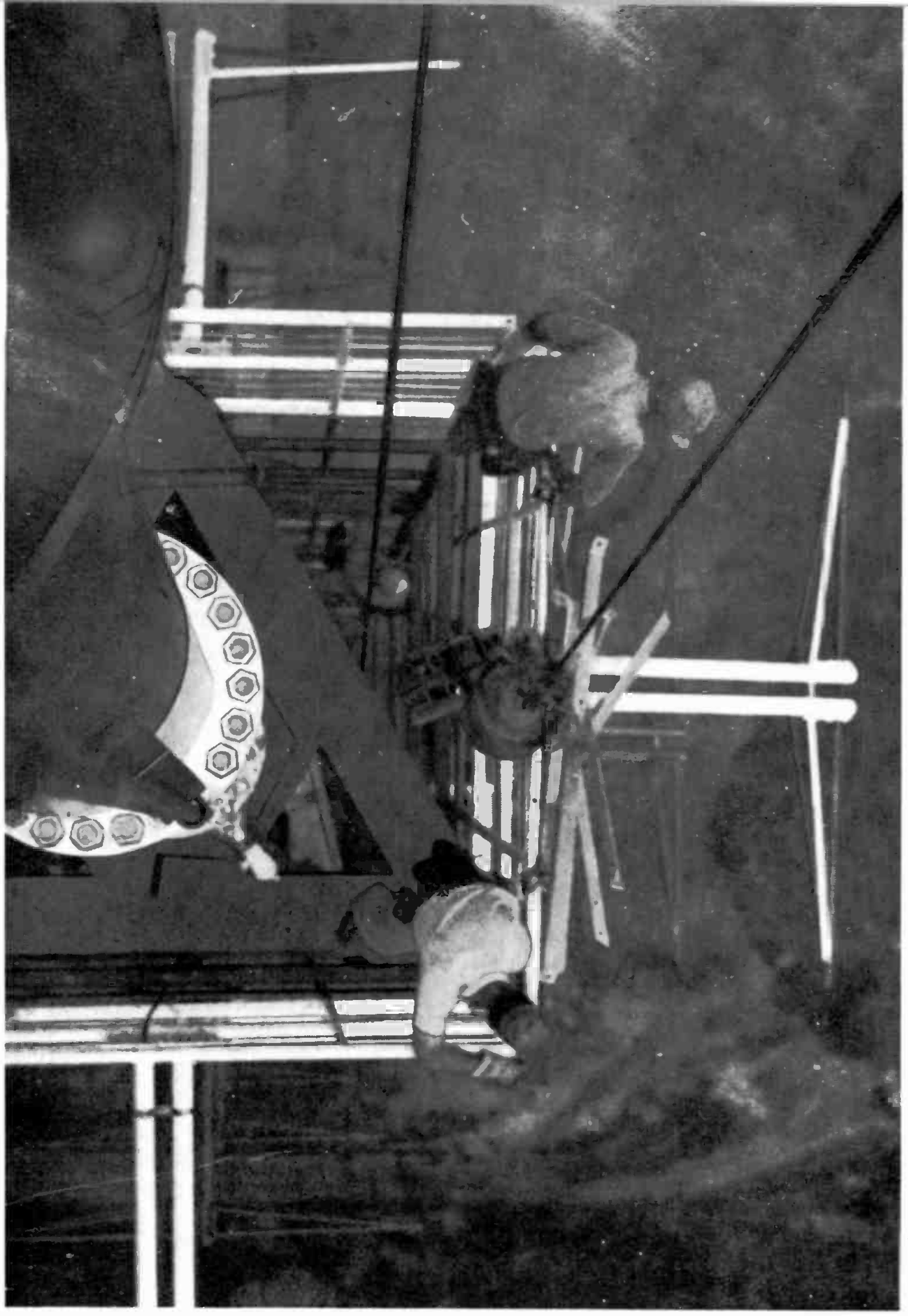


FIG. 5. Riggers add finishing touches to the RCA Supergain structure. Note the methods used to mount the FM Pylon and the Supergain Antenna to the triangular tower.

the measurements such as the one shown in Fig. 11, was to determine the intensity of the signal in the null. For the WSB-TV antenna, the first null of the antenna occurs at about 1.9 miles from the base of the antenna, but without special reference this null might be overlooked because ground measurements are erratic as a result of terrain effects and minimums of similar field strength were recorded on this radial from 4.8 to 5.8 miles. There is considerable signal radiated at the angle normally referred to as the null. On this particular radial, the minimum was 20 millivolts which is a signal considerably in excess of that required for city coverage. There has been no evidence of inadequate signal strength or presence of ghosts in the null area. The antenna is designed for beam tilting but the performance has been so satisfactory that this feature of the antenna has not been explored.

Mounting a Four-sided Antenna on a Three-sided Tower

Since WSB-TV requires an omnidirectional horizontal radiation pattern, it was necessary to place four screens and dipoles on the triangular Ideco tower. This was easily accomplished by having special outriggers built to support the screens (see Fig. 2). These outriggers essentially transform a triangular tower to a square tower to accommodate the 4-sided antenna array. The Supergain Antenna lends itself perfectly in placing a 4-sided antenna on a triangular tower, thus still maintaining good symmetry from the ground to the top of the FM-Pylon. See Figs. 2 and 5.

Advantages of High Tower and High Gain Antenna

The foregoing performance results and measurements obtained on the WSB-TV Antenna, confirm the advantages of using a high gain antenna and a high tower.

The advantages of height for TV antennas is indicated by the F.C.C. predicted

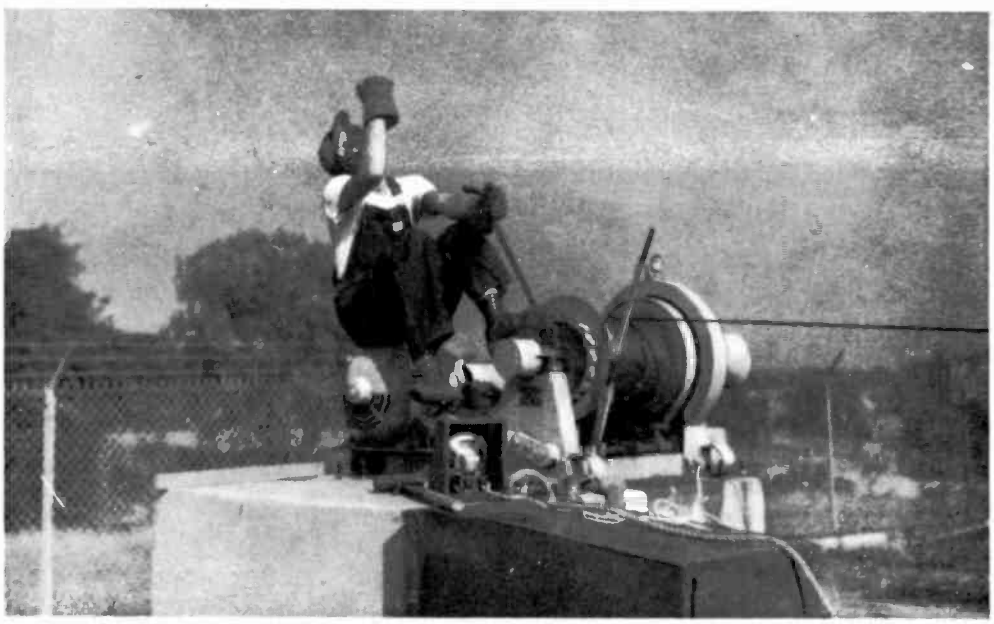


FIG. 6. An electric-motor-driven winch is used to haul a single-man-capacity hoist to the upper levels of the tower. See Fig. 8.

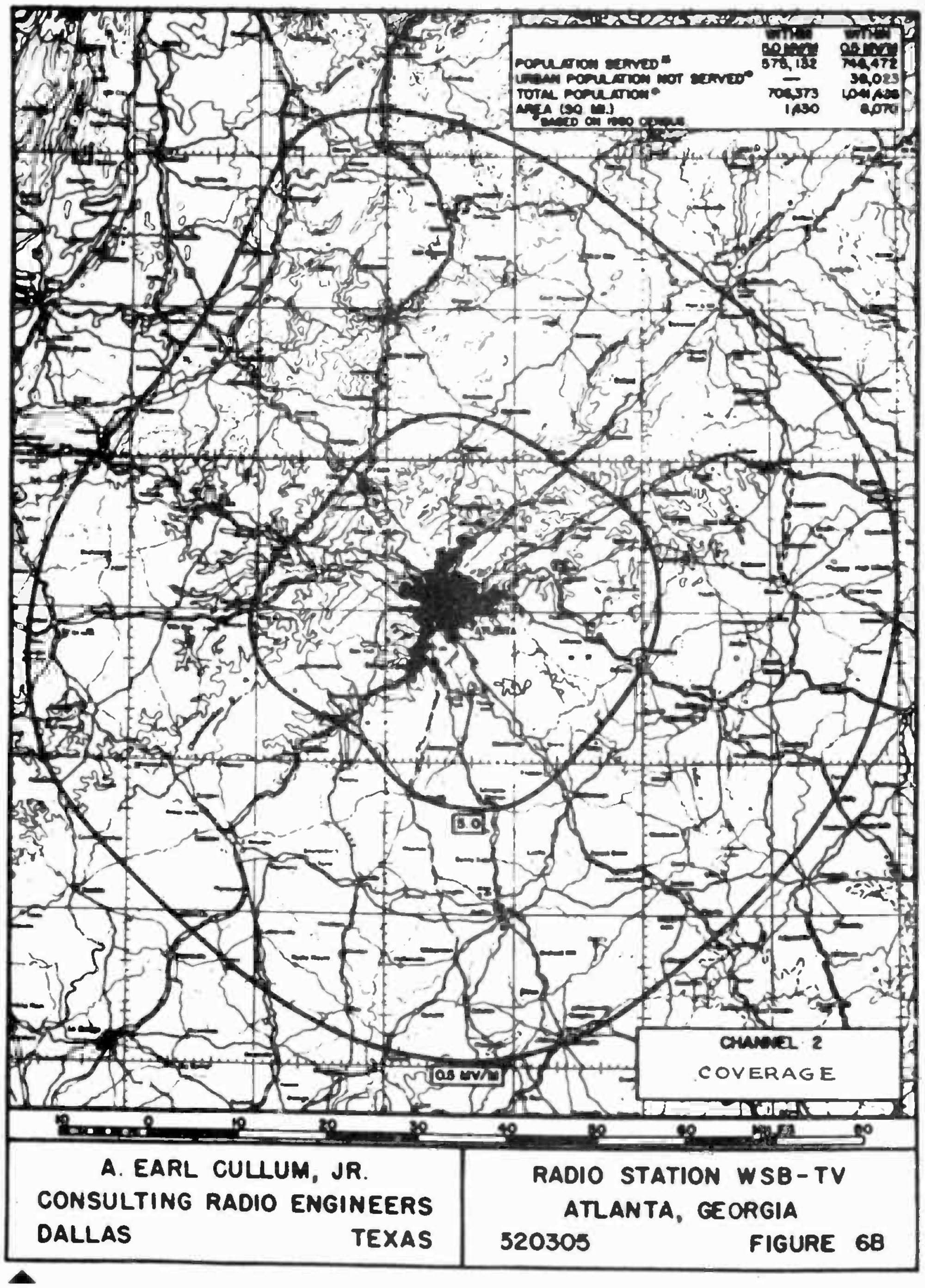


FIG. 7. Contour lines for 0.5 mv/m (59 dbu) and the 5.0 mv/m (74 dbu) are shown. The average radius is approximately 50 miles and 22 miles respectively, which meets the predictions of the FCC.

coverage data. For Class B coverage and with 100 KW ERP, the coverage is extended from 57 miles to 70 miles when the antenna height is increased from 500 feet to 1000 feet. To obtain the same increase in range by increasing power, it would be necessary (with a tower of only 500 feet) to increase Effective Radiated power from 100 KW to 630 KW. With power ceilings being in effect, the only increase in range that can be obtained is by increasing antenna height.

The high tower can be used for land marks, geographical interest, and as aircraft direction land marks. The high tower also provides greater latitude for television microwave relay operation. Local remotes may be beamed to the tower with a completely unobstructed path. The high tower provides potential for commercial microwave relay. This may be pursued in the future.

Tower and Antenna Inspection and Maintenance

Inspection, maintenance and other activities on the antenna, because of its great height, necessitate a means of quickly ascending the structure with ease. For this purpose, a hoist accommodating one man at a time has been built to go up the tower to the 800-foot level. At this level, the hoist stops just beneath the uppermost platform which is accessible by climbing about 15 feet up a ladder through an opening leading to the platform. The hoist is

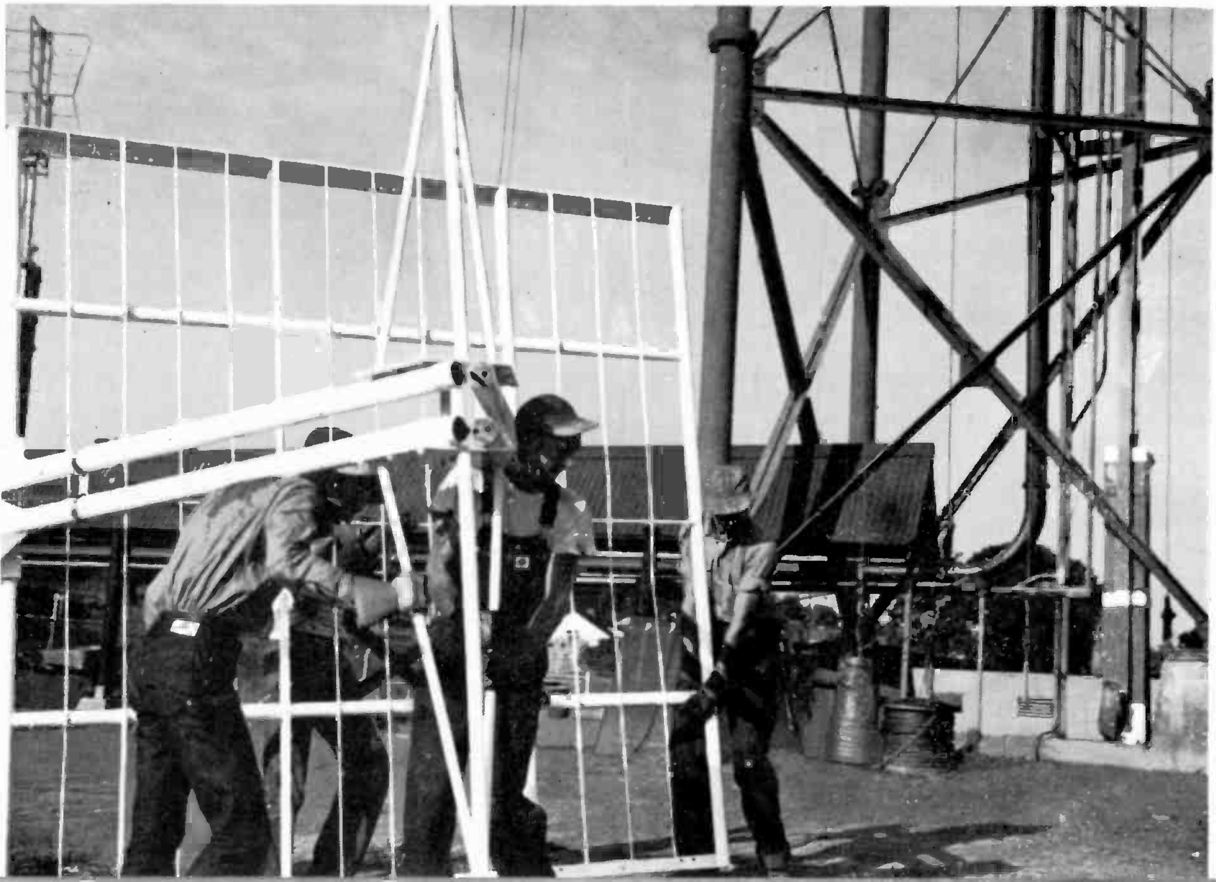


FIG. 8. In addition to efficient handling of screens and dipoles by the riggers, there are a few other points of interest in this picture: The one-man-capacity hoist which ascends between a twin-girder track with the cable attached to its top is shown at lower right. A peaked-roof shed is built to provide protection of the 6⅛" transmission lines from falling ice.

FIG. 9. The first time an RCA camera has ever been used atop a 1000-foot TV tower. On this occasion while strictly set up as an experiment, a major fire broke out in the area. A telephoto lens was snapped in place and WSB scooped the story—delivering scene to televiewers.

guided between two girder-like tracks running the full 800-foot height, and it is raised and lowered by means of a cable which is taken up or unreeled by an electric motor driven winch. See Figs. 6 and 8. Facing the hoist is a hand ladder that runs the full 800-foot height. The ladder is accessible to the hoist by merely stepping out of the hoist on to the ladder. A platform is also located at the 400-foot level.

Tower Data

Tower	1062 feet above ground 2035 feet above sea level 430,000 lbs. total weight
Tower Foundations	14 feet under ground contains 15,800 lbs. reinforcing steel, 284,000 lbs. concrete
Tower Legs ..	15 feet on each side 10¾ inches in diameter 1⅛ inches wall thickness 28 feet in length 5,000 lbs. weight each
Top Guy Wires	2¼ inches in diameter Attached at 800-foot level
Bottom Guy Wires	1¼ inches in diameter Attached at 400-foot level

FIG. 10. Photograph of junction box showing ½" air-dielectric copper coaxial feed lines which feed the individual dipoles. Also junction box transformer of 3⅛" copper line which connects to one of the combining tees as shown in Fig. 12.

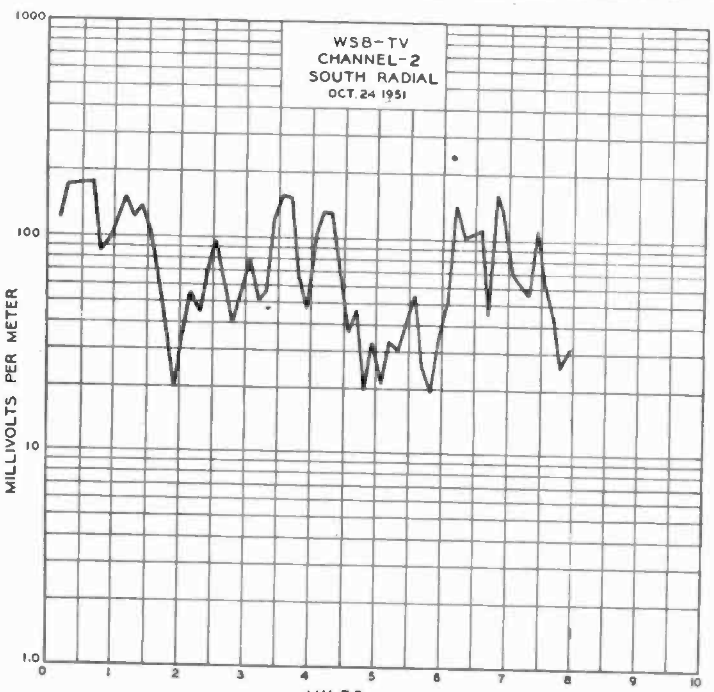
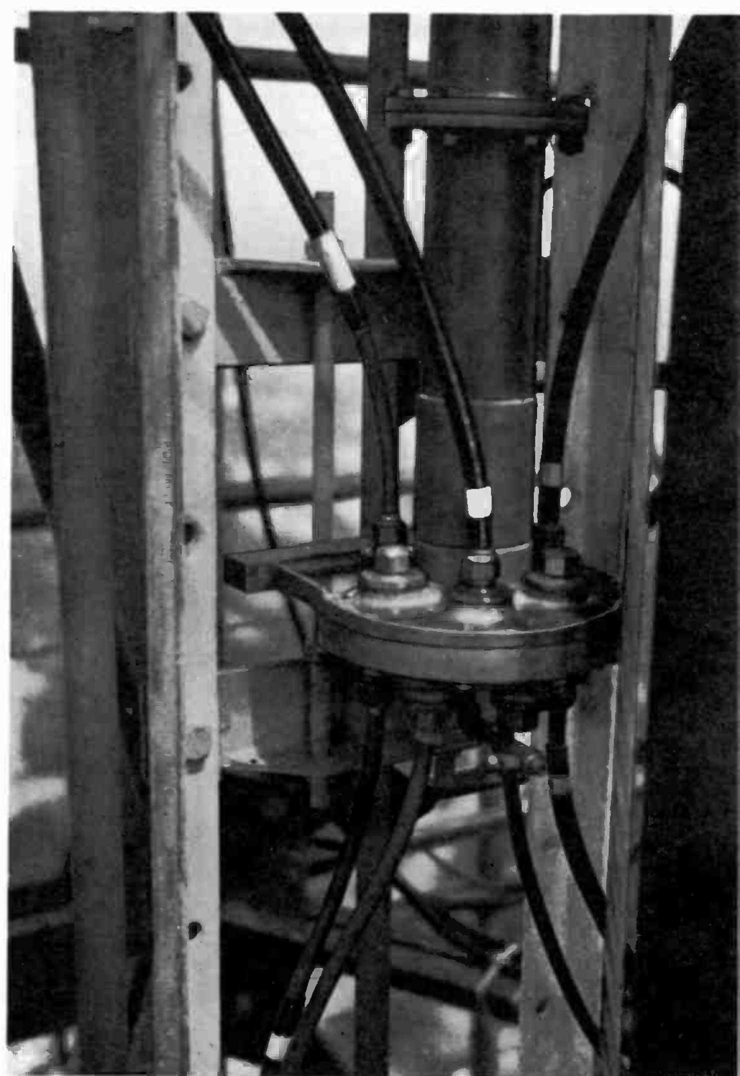


FIG. 11. For 50-KW ERP a plot of a radial in the southern direction is shown. Note that excellent close-in coverage is maintained, as well as coverage considerably distant from antenna site.



Guy Anchors . . 16,000 lbs. reinforcing steel
515,000 lbs. concrete

Paint . . . . 125 gallons required for one coat

Tower Lights . . Requires approximately 10,000 watts

Tower and guys are galvanized to prevent rust.

Top of tower designed to move only 28 inches in a wind of 120 m.p.h.

The Supergain Antenna

The Supergain Antenna (as shown in Fig. 13) is essentially a broadside array of half-wave dipoles, backed up by a reflecting screen, stacked vertically to yield the desired gain. Fig. 12 shows schematically the installation of the WSB-TV 14 bay Supergain Antenna. To incorporate an omnidirectional pattern, four dipoles (90 degrees apart) are placed around a tower. The dipoles are stacked vertically about 0.77 λ, which was an optimum choice for both impedance and gain. In the horizontal plane, the reflecting screens are spaced half-wave apart, or approximately nine feet, in the case of Channel 2.

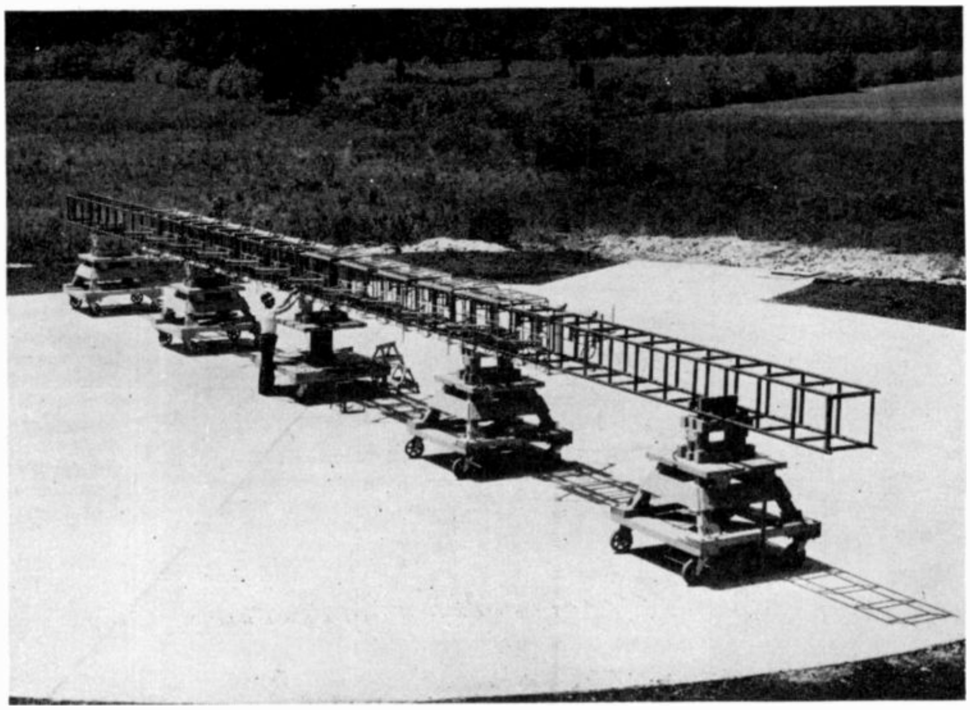
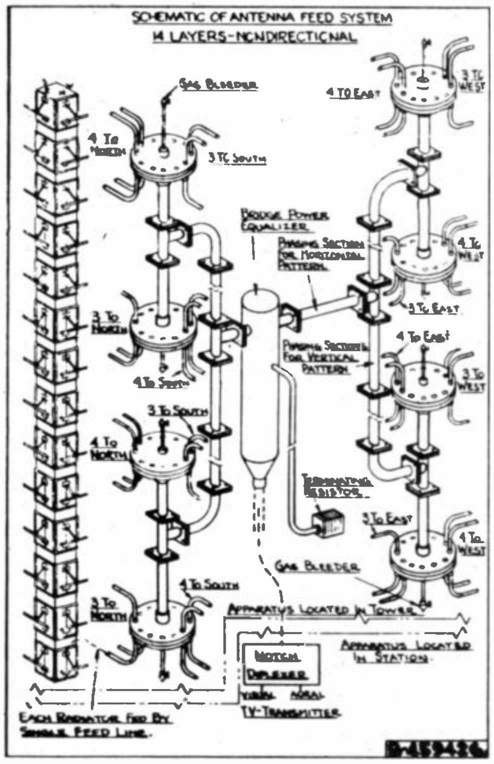


FIG. 13. Supergain and Superturnstile Antennas are tested on this specially built turntable. Antennas up to a length of 140 feet can be mounted, and rotated to determine their radiation characteristics. Transmitting site is located approximately 2400 feet across an open level field.

FIG. 12. Diagram shows the assembly of the 14-bay WSB-TV Supergain antenna. Each radiator is fed by a single feed line, all identical in length, to maintain equal phasing. Note that both N-S and E-W feeds provide for a phasing section that can be used to tilt the vertical pattern. Only one transmission line connects the antenna to the Constant-Impedance Notch Diplexer located near the transmitter.



Feed lines which have equal lengths coming from the junction boxes, are used to feed the matched dipoles, thus assuring equal power and phase in each radiator. The various tees are made to provide the proper power division to the various junction boxes, and with broadband characteristics to maintain constant impedance. The N-S and E-W feeds are fed in quadrature to make use of the power equalizer.[2] The antenna is made versatile by allowing for beam tilting facilities should it be desired in the future. The power equalizer, which is the input to the antenna system, is fed by only one 6⅛" coaxial transmission line from the Constant-Impedance Notch Diplexer.

The voltage standing wave ratio of RCA Supergain Antennas has a 1.1 to 1 specification over the entire Channel 2 band. With the use of the power equalizer[2] an unusual large bandwidth can be obtained thus making the antenna electrically stable under varying weather conditions.

A power gain of 11.0 was achieved by using 14 bays of dipoles in the aperture of 184.33 feet. The method of arriving and checking the gain figures will now be described.

[2] R. W. Masters, "A Power Equalizing Network for Antennas", Proceedings of the IRE, p. 735, July 1949.

Gain Definition

A review of some of the fundamental definitions of "gain" may be helpful in grasping the concept of power gain.

Directive gain is the absolute directivity of an antenna. The ratio of the maximum radiation intensity of the source under consideration to the maximum radiation intensity of a half-wave length dipole is defined as directive gain. The word pattern gain is synonymous with directive gain.

The definition of directive gain in the preceding paragraph is based entirely on the shape of the radiated power pattern. The losses due to feed lines, power equalizers, etc., are not accounted for. A quantity called either the net antenna gain or power gain is introduced which does involve these losses. In the RCA publications, the antenna gain or power gain is the figure specified. Losses in the main transmission line leading from the transmitter to the antenna system are not reflected in the power gain figures.

Theoretical Determination of Gain

The Supergain Antenna employs identical radiating sources connected to radiate maximum energy in the horizontal direction. It is well known that the field of an array at a sufficiently large fixed distance is the product of the array factor multiplied by a function representing the field of

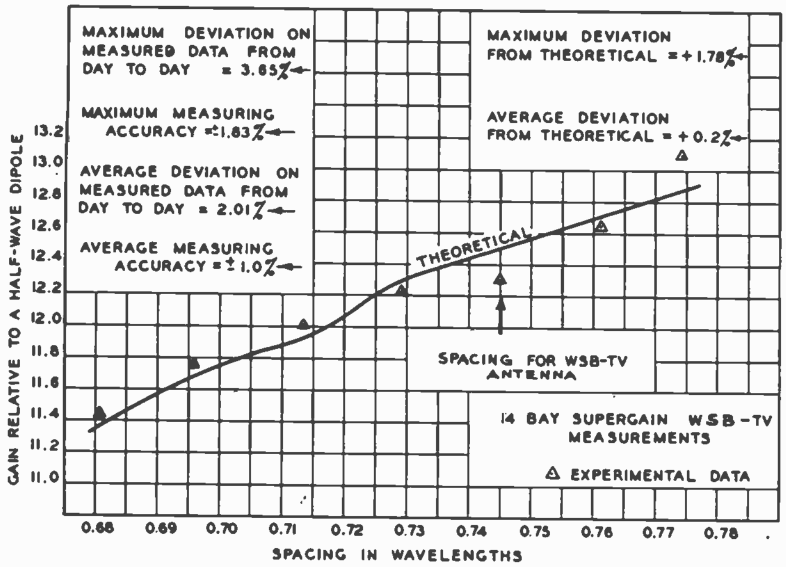


FIG. 14. Directive gain of a 14-bay Supergain antenna is shown for various spacings. The solid line shows the variation of the theoretical directive gain with spacing, while the discrete points indicate the measured data. Each point represents several measurements, and the accuracy of these data is approximately ±1.83%. The average of all the maximum deviations of the measured results was 2.01%, or indicates that an average measuring of ±1.0% is possible. The maximum deviation of any one point from theoretical is at 0.744 λ, or +1.78%. However, the average deviation of all the points from the theoretical is 0.2%. For all practical purposes the theoretical value of directive gain can be used for the practical case.

one of the sources. The array factor is the pattern of the array with sources replaced by isotropic radiators. For uniform arrays, this factor is a simple equation of a trigonometric expansion. The element pattern prescribing the individual sources will be the same for all the sections.

The Supergain dipoles are spaced approximately 0.3 wavelength in front of the reflecting screen in the horizontal plane. For the element pattern in the theoretical calculations, the assumption was made whereby an infinitely thin half-wave dipole was placed 0.3 wavelength in front of an infinitely large reflecting screen. The array characteristics of N parallel identical elements equally spaced and with equal currents and phase is

$$A = \frac{N \sin X}{N \sin X}$$

where N = number of elements

$$X = \frac{D}{2} \times \cos \phi$$

D = spacing in electrical degrees

ϕ = angle from the zenith axis

It is reasonably proper to assume the dipoles are fed with equal-phase and power because all the feed lines are cut to the same length, the dipoles are matched to the feed lines, and the dipoles are all made physically identical.

Vertical field patterns for the 14 bay WSB-TV antenna are plotted in Figs. 15 and 16 using the method described in the previous paragraph.

Experimental Determination of Gain

Various methods to check the theoretical gain figures can be done with scale models or with the actual antenna.

First, absolute field strength measurements can be made of the antenna under test. This is unsatisfactory because of the many obstructions and terrain effects that distorts the readings. Comparison must be made to the FCC propagation curves which was determined upon smooth terrain.

Second, the substitution method. A calibrated dipole is placed at the center of the antenna and power is fed alternately into the antenna and the dipole while comparative readings are taken. This standard dipole comparison is better than the absolute field strength determination, but again only a fair degree of accuracy can be obtained after a complete survey.

These two methods described for measuring the power gain have been found to be comparatively unreliable.

Third, the best method to determine the directive gain of an antenna, is to measure the vertical radiation pattern, since pattern gain is a function of the vertical directivity of the antenna. This can be accomplished either by the use of a complete antenna or a scale model since pattern work can usually be scaled quite accurately. In this method, the antenna under test is used as a receiving antenna, is mounted on its side and pivoted about its mid point. A transmitting point is located far enough away so that the length of the test antenna is negligible compared to the distance between the transmitting and receiving sites. Rotating the test antenna determines the amplitude and angle of all the lobes. This information can be plotted and a gain determination made by means of a planimeter.

The gain computations can be made from the vertical field pattern measured in one direction, if the horizontal pattern is omnidirectional. In broadside arrays, similar to the Supergain antenna, that have nominally circular horizontal plane patterns, principal plane patterns represents an average value as determined from the study of the horizontal pattern.

Obviously, this third method cannot be applied after the antenna is installed. In many cases, it cannot even be applied on the actual antenna since the rotation of a Supergain Antenna 186 feet in length becomes a major engineering feat. Hence, such work is usually done by means of scale models. RCA has recently built a special turntable which will make it possible to rotate antennas up to 140 feet in length, as shown in Fig. 13.

A ±3% accuracy was considered necessary for WSB-TV's Supergain Antenna, which is a difficult achievement for this type of measurement. This requirement dictated the need for the measurement of the vertical radiation pattern, under ideal laboratory conditions.

The antenna test site is located at the Marlton-Medford Airport,[3] in New Jersey,

[3] "Pattern-testing the TFU-24B UHF Antenna," E. H. Shively. BROADCAST NEWS No. 69, p. 42.

and its adjacent property, making it possible for the transmission path to be across an open-level field. The test antenna was mounted approximately eleven feet above the ground, the height being determined by a few preliminary experiments to determine when the standing waves in space of the incoming electro-magnetic waves would be negligible.

Standard RCA type Channel 7 Supergain dipoles and screens were used to scale down from the WSB-TV Supergain operation. The same spacing in terms of wavelengths were used as on the 14 bay Channel 2 Supergain Antenna. The dipoles were assembled and fed in the same manner as in the actual antenna.

By rotating the boom about its vertical pivot, the value of field strength as a function of vertical angle was obtained from the horizontal sweep through one revolution. A half-wave dipole, placed in a corner-reflector comprising the transmitting antenna and standing about ten feet off the ground, was placed across a field about 2400 feet away, in a vertical position parallel to the dipoles of the measured array which was used as a receiving antenna. The output from the array under test was fed into a receiver and Esterline-Angus recording meter. The angular position information was transmitted from the pedestal to the recorder by a pair of synchros geared to rotate with a ratio of 36-to-1, with respect to the pedestal. At the recorder, the gearing was arranged to provide a two-degree angular displacement per division in abscissa on the Esterline-Angus recording charts.

Results of Gain Data

From the vertical field pattern, the average pattern gain can be determined by taking the surface integral of the normalized, squared, voltage field pattern and comparing the result with that of a half-wave dipole. Although the measured pattern is for a plane normal to the dipoles, it also holds true for all other directions, since the azimuth pattern of 4 dipoles mounted around a tower is essentially circular.

Figs. 15 and 16 (curves of vertical field pattern) show a comparison of the measured field pattern and the theoretical field pattern for 14 bays of Supergain dipoles with each element spaced 0.745 apart, or equivalent to WSB-TV Channel 2 picture carrier frequency. The measured data represents an average of several readings. Note that Fig. 15 (main lobe curve) shows only the first 15° from the main lobe, and Fig. 16 (showing side lobes) reveals the remaining portion of the quadrant.

Directive gain vs. spacing of the elements in terms of wavelengths is illustrated in Fig. 14 (gain vs. spacing curve). The solid line represents the theoretical curve while the points indicate the experimental data. The maximum deviation on the measured data, from day-to-day is 3.65% or the minimum measuring accuracy one can state is ±1.83%. The average deviation on the measured data is 2.01% or the average measuring accuracy is approximately ±1.0%. Note also that the maximum deviation of the experimental gain figures from the theoretical value is plus 1.78%, and the average deviation from the theoretical is plus 0.2%.

The fact that the measuring accuracy is well within reason and coincides closely with the theoretical prediction (Fig. 15 and Fig. 16) indicate that the theoretical directive gain figures for Supergain antennas, for all practical purposes, can be used to represent the directive gain in practice.

From the directive gain the net antenna gain is determined by multiplying the directive gain by the efficiency of the antenna components. This reduces the directive gain from 12.5 to the net antenna gain of 11.0 at the visual carrier.

Tests made on scaled models, under controlled laboratory conditions, clearly indicates that pattern measurements are reliable, and therefore, one can accept these curves (Figs. 15 and 16) to be identical to that found at WSB-TV. Seeking the gain values by other means such as field strength measurements and the substitution method is comparatively unreliable as compared to scale model measurements.

Acknowledgment

The WSB-TV antenna was recommended by Earl A. Cullem, Jr., consulting engineer. The antenna itself was designed and built by the Engineering Products Department of the RCA Victor Division. Special credit should go to Mr. L. J. Wolf who supervised the details of the project and Mr. D. W. Balmer who coordinated the mechanical aspects of the job.

FIG. 15. Comparison of the theoretical and measured vertical field pattern for the WSB-TV antenna. Note the close resemblance between the theoretical and the measured data. The main lobe is plotted on an expanded abscissa scale because of the narrow beam width. For the remaining portion of the quadrant refer to Fig. 14.

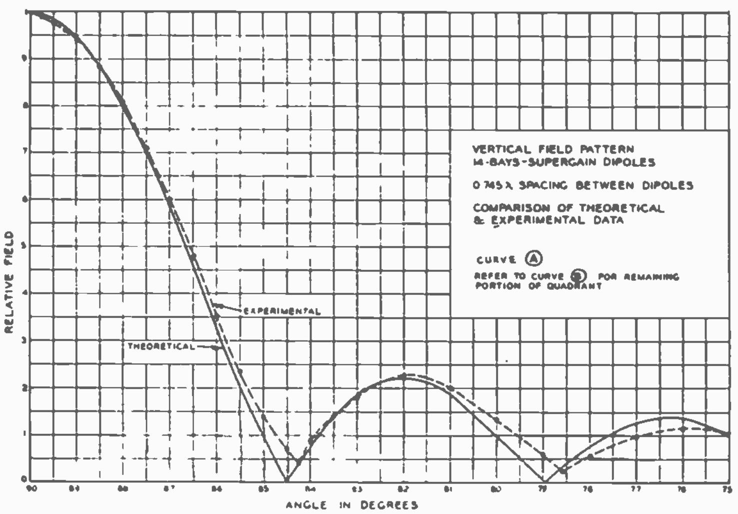
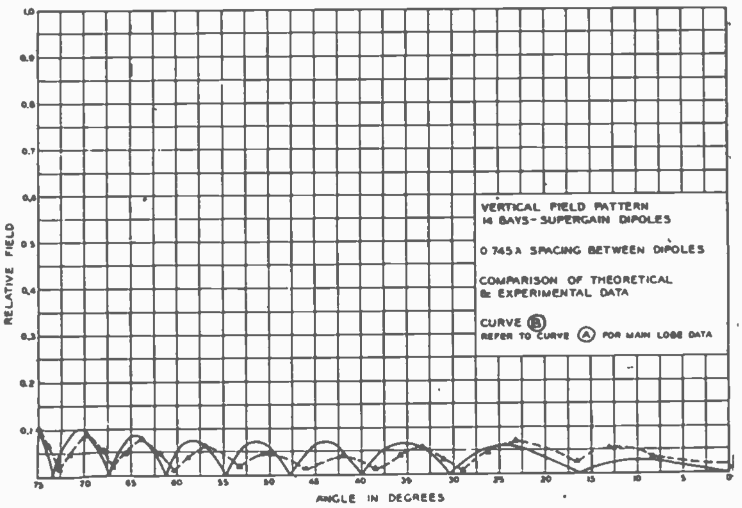
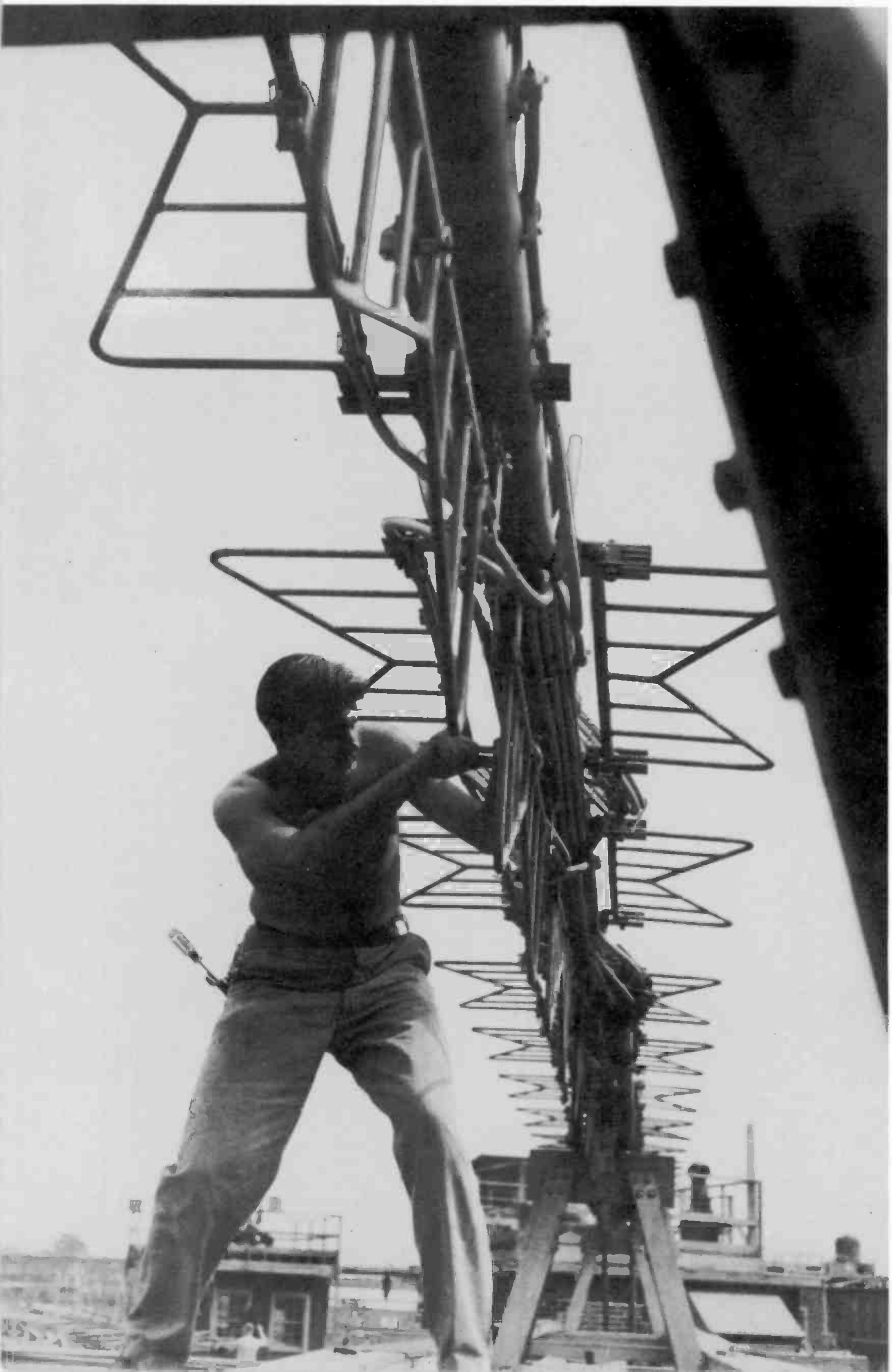


FIG. 16. Comparison of the theoretical and measured vertical field pattern for the WSB-TV antenna. Note that the location and the amplitudes of the side lobes for the theoretical and measured data have a very close relation. For the configuration of the main lobe see Fig. 13.



FEED SYSTEMS FOR THE NEW 12-SECTION SUPERTURNSTILE ANTENNA



By L. J. WOLF
Broadcast Engineering Section
Engineering Products Department

Concurrent with FCC's authorization of higher values of Effective Radiated Power for VHF Television, the need for a suitable high-gain, heavy-duty VHF Antenna became apparent. And now, the popular family of Superturnstiles can point to such an antenna in its newest member, the RCA 12-Section Superturnstile. Shown in the dramatic closeup of Fig. 1 and overall view of Fig. 2. The new antenna design includes three models—TF-12AL, TF-12AM and TF-12AH to cover the entire VHF band from channel 2 to 13. They are capable of high gain and correspondingly higher power handling (all are rated for 50-KW input). The high-gain antenna when used in combination with RCA VHF Transmitters can provide effective radiated power up to 600 KW, more than adequate to meet FCC maximum limits.

The new 12-Section Superturnstile Antennas provide for operation on any VHF channel from 2 to 13. Its design includes many distinct features which will be described in detail in future issues of BROADCAST NEWS. It is the purpose of this article to point out several "bonus" features or "by-products" resulting from the overall design of the 12-Section Antenna such as: versatile feed systems, power switching, beam tilting and vertical pattern shaping by power division. Each of these considerations is described in the paragraphs to follow.

FIG. 1. B. T. Bailey of RCA's Engineering Products Department, shown adjusting a batwing element on RCA's new 12-Section Superturnstile Antenna.

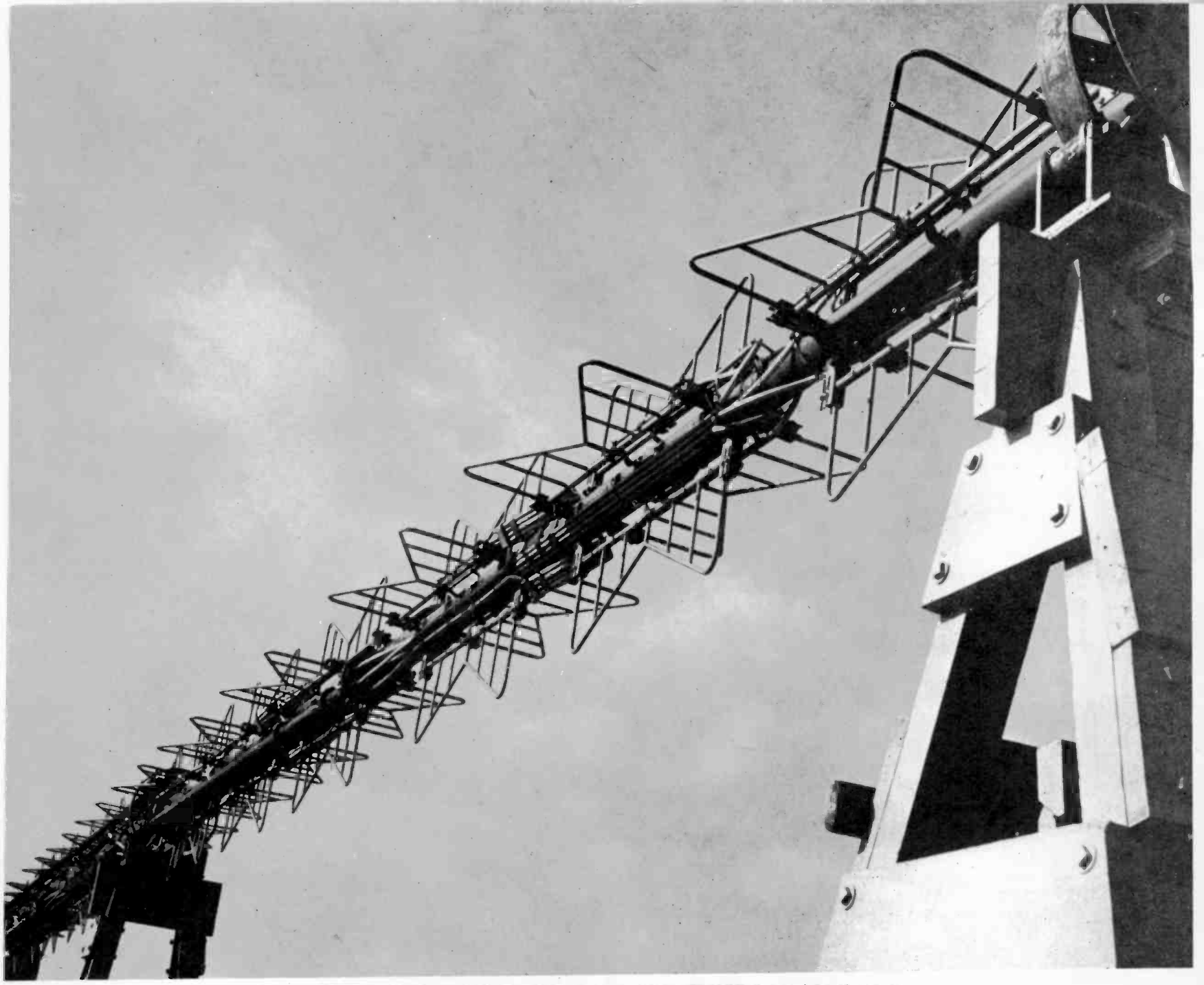


FIG. 2. View of the new 12-Section VHF Antenna, Type TF-12AH for high-band operation. This setup permits field measurements of both power gain and coverage patterns.

The Feed System of the 12-Section Antenna

All of the 12-Section Antennas have four transmission lines brought down through the tower top. One pair of these transmission lines is for the north-south and the east-west radiators of the upper half; the other pair feeds the radiators of the lower half in the same way. The combining tees are shown with the notation "C" in Fig. 3.

The feature of these antennas which permits sectionalized connections is the separately fed upper and lower layers, as well as the previously used arrangement wherein the north-south and east-west radiators are also separately fed.

Versatility has been provided in the newly designed 12-Section Antennas through the arrangement of sectionalized connections and an advanced design of the junction boxes, feedlines and other components (see Figs. 4 and 6). This permits the switching of transmitter power to another part of the antenna for lower power operation should the occasion arise. In this way, service can continue until complete operation can be restored.

Vertical Pattern Shaping by Power Division

Effective close-in coverage and the shaping of the vertical field pattern to obtain a substantially constant field throughout the service area are accomplished by use of optimum power ratios between the upper and lower halves of the antenna.

Combining tees are used to divide the power from the transmitter in any desired ratio between two sections of the antenna. Ordinarily, the upper and lower sections are fed by equal feedline lengths in the same phase and with a 70:30 power distribution. However, it is easily possible to adjust the ratio of power division between the upper and lower parts of the antenna to achieve the vertical pattern and uniform field mentioned above. For instance, if the power is split in the ratio of 70%-30% between the upper and lower sections of the antenna respectively, the first null is almost completely eliminated with practically no sacrifice in gain.

Beam Tilting for Special Conditions

Beam tilting is a feature, easily obtained with RCA 12-Section Superturnstile Antennas, which provides greater field

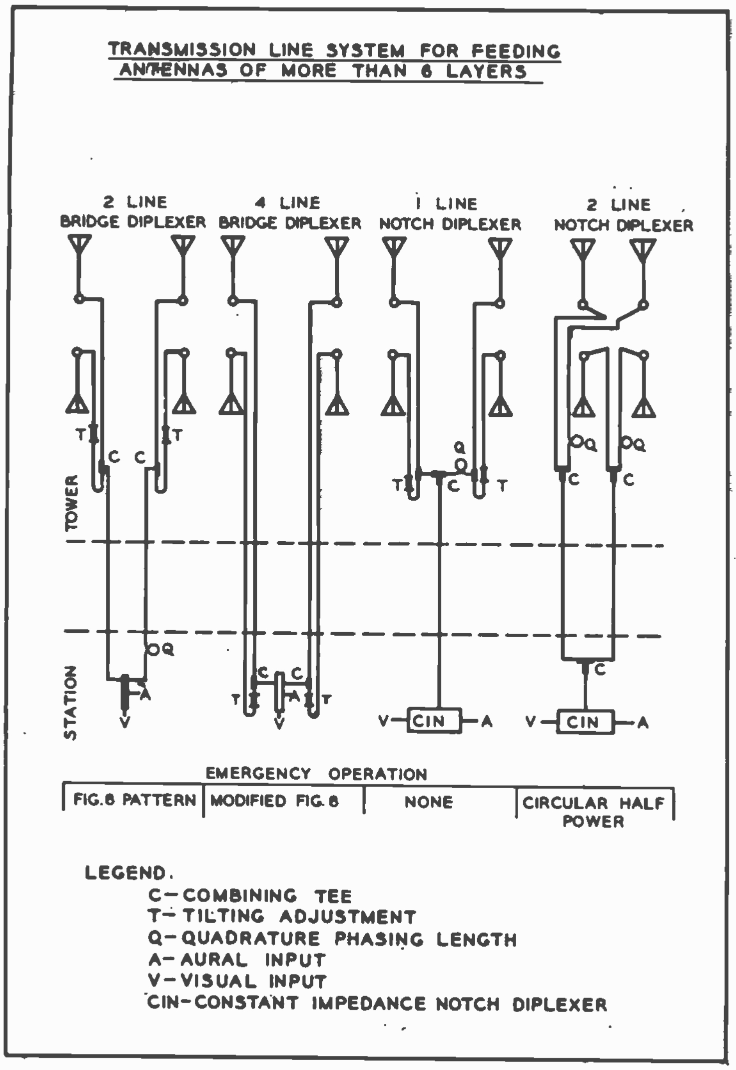


FIG. 3. Chart showing versatility of transmission line systems available with 12-Section Antennas.

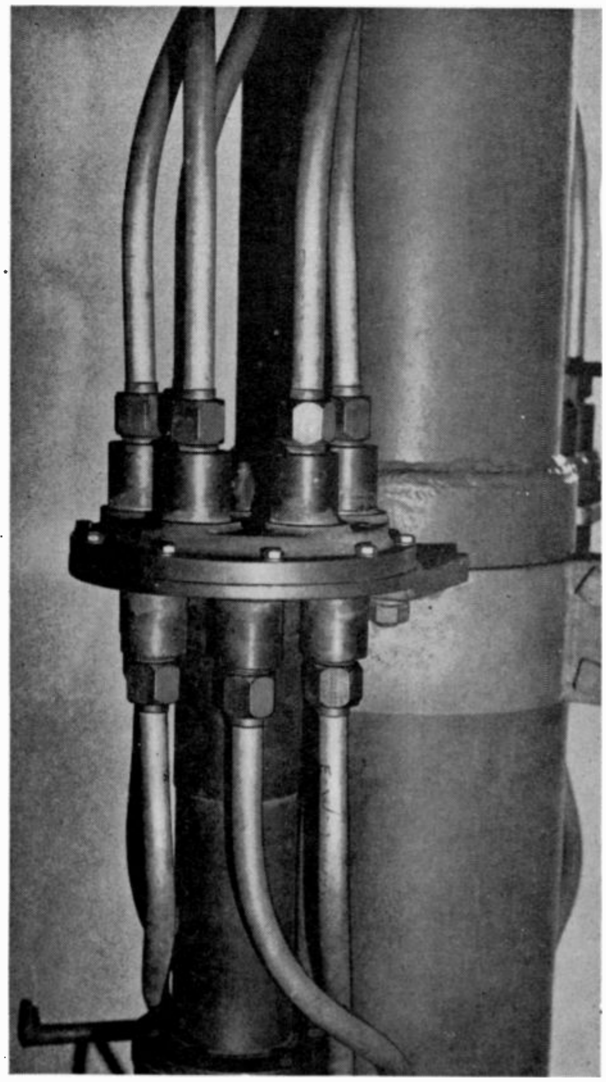


FIG. 4. Power enters above the junction box through 3⅛-inch transmission line and connects through smaller feedlines to individual radiators.

strength for selected portions of the primary service area. This is obtained by changing the phasing between the upper and lower halves of the antenna with the standard feed system (see tilting adjustment in "antenna feeding" chart—Fig. 3). A change in the tilt angle is made by exchanging the sections of line labeled "T" for other sections to give the desired tilt.

Feed System and Diplexing Considerations

In this article, the four different methods of feeding the power to the 12-Section Antenna are described. Each system is illustrated by diagrams showing the connections made to the antenna.

The proper choice of feed system to employ will depend upon the individual station requirement and should be made after a careful study of the merits of each system.

One of the most important factors to consider before selecting a feed system is the choice of the type of diplexer to be used. Therefore, it is perhaps appropriate, at this point, to review the function of the diplexer as applied to the overall TV antenna system and define the term "diplexer".

The television antenna system consists of a coordinated chain of components which receive the aural and visual r-f power from the television transmitter and includes a vestigial sideband filter to remove the unwanted visual sidebands. The signal then passes through a *diplexer to combine the visual and aural energy*, and then carries the combined power through the coaxial transmission line to the antenna to be radiated.

A diplexer can be defined as a network arranged so that both transmitters can couple into a single antenna without interaction between them. The diplexer must

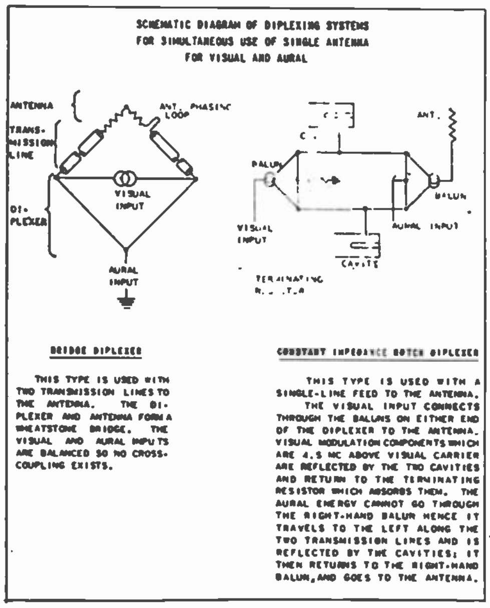


FIG. 5. Either of two types of diplexers can be used with RCA antennas.

do this intercoupling and, at the same time, maintain a constant impedance load on the two transmitters. Diplexers are of two general types; the bridge type, which is generally used and requires at least two coaxial transmission lines to the antenna; and the constant impedance notch type, which requires only a single line to the antenna. See Fig. 5.

Bridge diplexing, as illustrated in Fig. 7, is a popular system since it provides a simple way of utilizing the same antenna for both visual and aural. The Constant Impedance Notch Diplexer and the recently announced Filterplexer (a combination vestigial sideband filter and constant impedance notch diplexer) are other diplexing methods employed. Each has its merits and the various factors of performance cost, and transmission lines involved are discussed below.

A. Standard—Bridge Diplexer

This is shown under (A) in Fig. 3 and is the system usually used since it requires only two transmission lines and uses the inexpensive bridge diplexer. The combining tees which improve pattern circularity are shown in Fig. 3 between the four transmission lines in the antenna and the two lines that run from the tower top to the station.

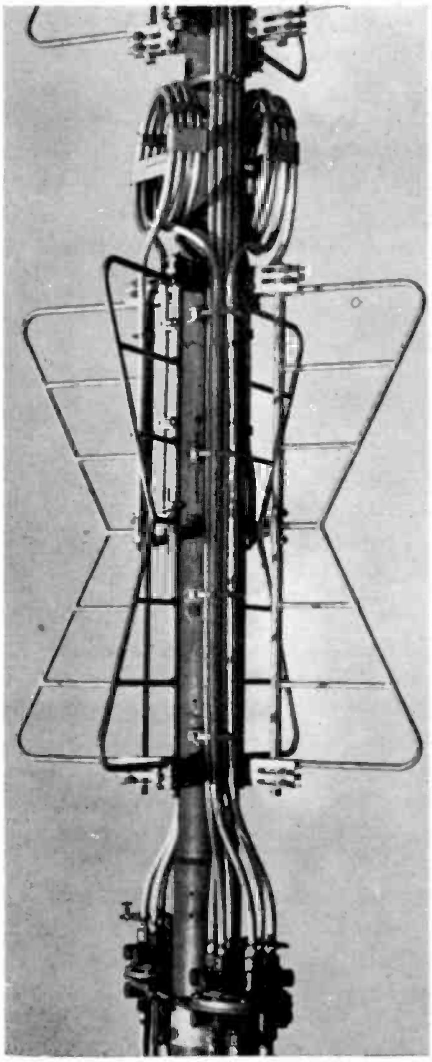


FIG. 6.

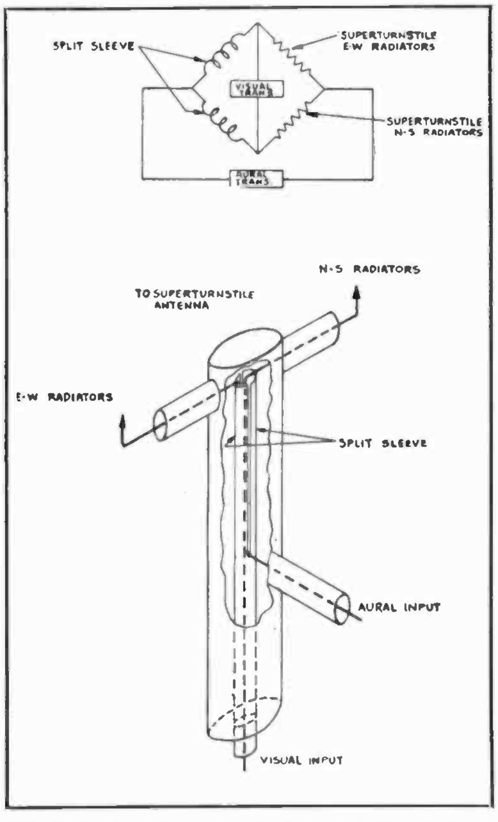


FIG. 7. Bridge diplexer—used in most installations.

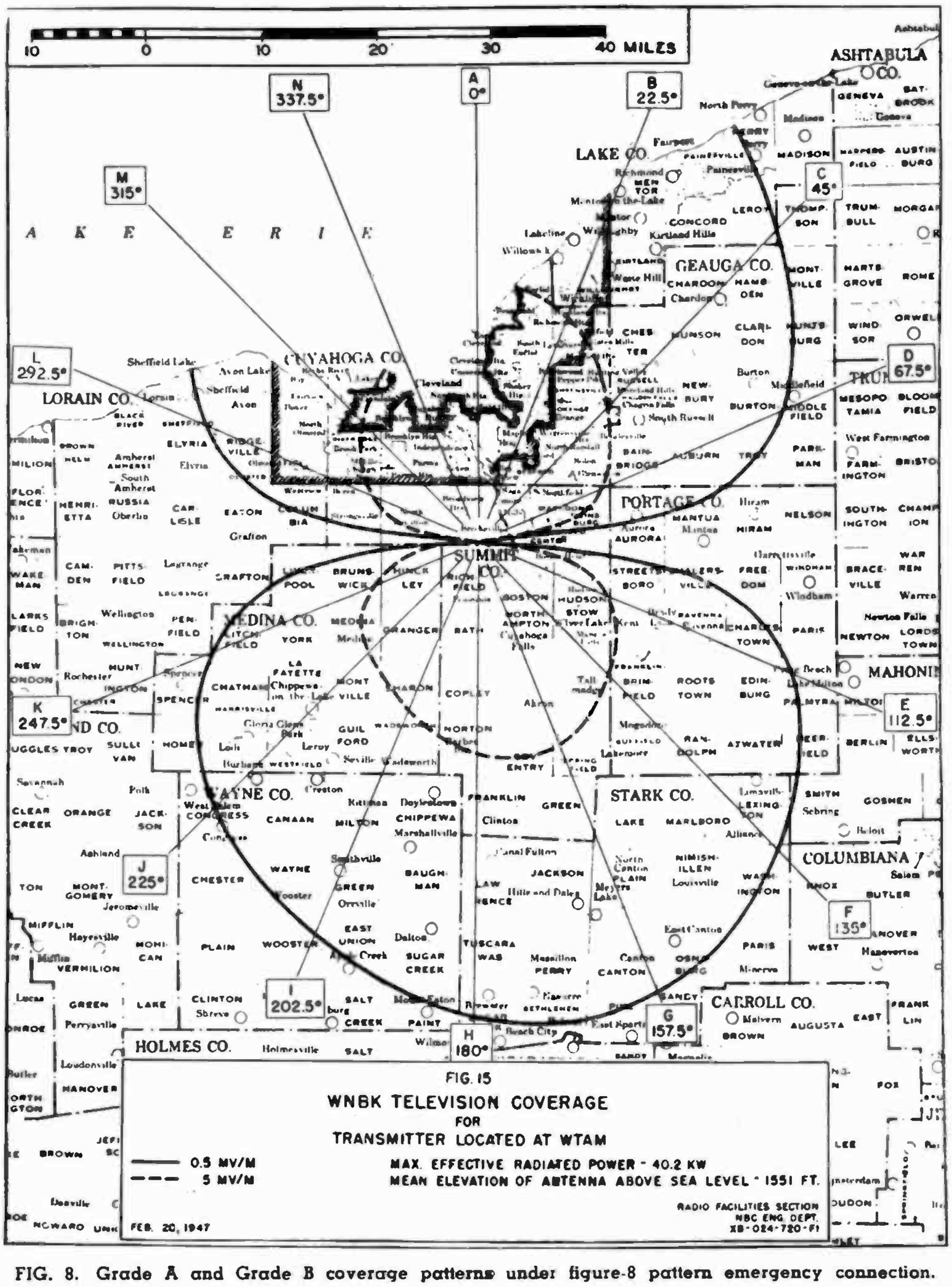


FIG. 8. Grade A and Grade B coverage patterns under figure-8 pattern emergency connection.

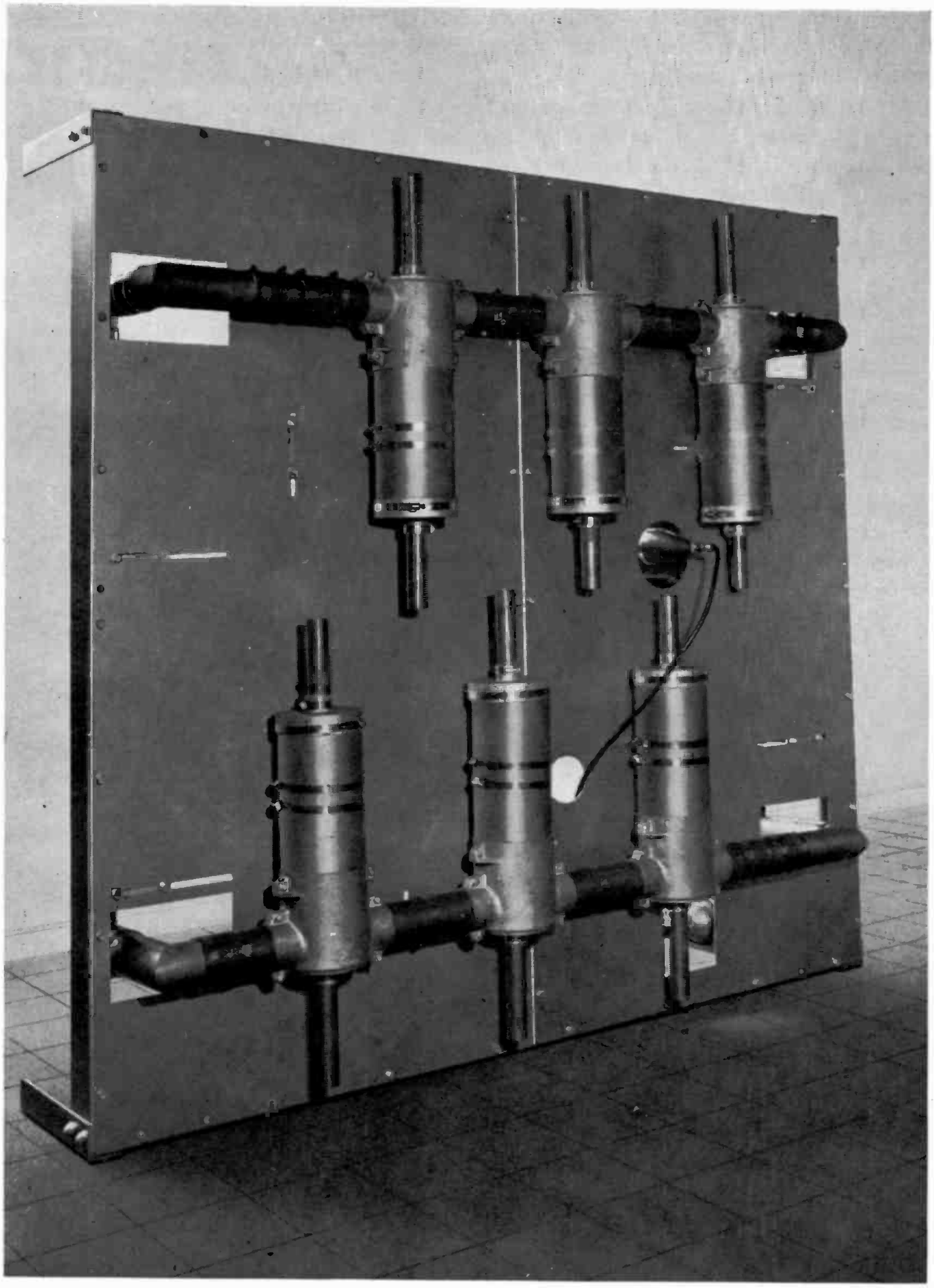


FIG. 9. The Filterplexer can mount either from the overhead or against the wall.

With this arrangement, emergency service giving a figure-8 coverage pattern can be obtained by disconnecting the defective transmission line at the diplexer in the station and substituting the r-f Load and Wattmeter enables the diplexer operation to be normal. Fig. 8 shows a typical coverage pattern for this figure-8 condition. Notice that the two nulls in the horizontal pattern are rather sharp, so that only a small portion of the coverage is lost. If the other half of the antenna were defective, the nulls would, of course, be changed by 90 degrees. Through suitable choice of antenna orientation, it is possible to provide for the least objectionable loss of coverage in case it is necessary to go to either of the two figure-8 conditions.

B. Four-Line Feed—Bridge Diplexer

As shown in Fig. 3, this system uses four transmission lines from antenna to station. It is particularly applicable to mountain-top or tall building installations where the length of transmission line is comparatively short. This system has a minimum of equipment in the tower top, since both the tilt adjustment and the combining tees are located in the transmitter room.

Emergency service is easily obtained by disconnecting the defective line and substituting the r-f Load and Wattmeter. Only one-fourth of the power is thus lost. The normal coverage pattern will be unaffected in two directions; in the other two directions, it will be reduced only slightly since the field strength is decreased about 30%.

C. Single-Line Feed—CIN Diplexer[1] or Filterplexer

This is illustrated in Fig. 3. The single transmission line is particularly applicable to installations which have a long run between antenna and transmitter, such as an antenna on a very high tower for instance, and which has other provisions for emergency service. The use of a single line results in less wind-loading on the tower and in a smaller cost for the line. With this system, three combining tees are used, as shown in the figure. If a filterplexer,* as shown in the photo of Fig. 9 and the schematic of Fig. 10 is used, the station equipment cost is not much more than for a bridge diplexed system.

As mentioned above, this system does not provide for emergency low-power service in any way; hence, it is necessary to have a separate antenna and transmission line if emergency service facilities are required.

D. Two-Line Feed—CIN Diplexer or Filterplexer

As shown in Fig. 3, this system ultizes two transmission lines, connected respectively to the upper and lower sections of the antenna. This permits emergency service which retains the circular coverage pattern when only one section of the antenna is used. Three combining tees are used, one of which is in the station.

For emergency operation in case of failure of one of the transmission lines, the transmitter output is connected to the other good transmission line. The coverage pat-

* Combination Vestigial Sideband Filter and Constant-Impedance Notch Diplexer.

[1] I. E. Goldstein and H. E. King, "Constant-Impedance Notch Diplexers", BROADCAST NEWS, September-October, 1952.

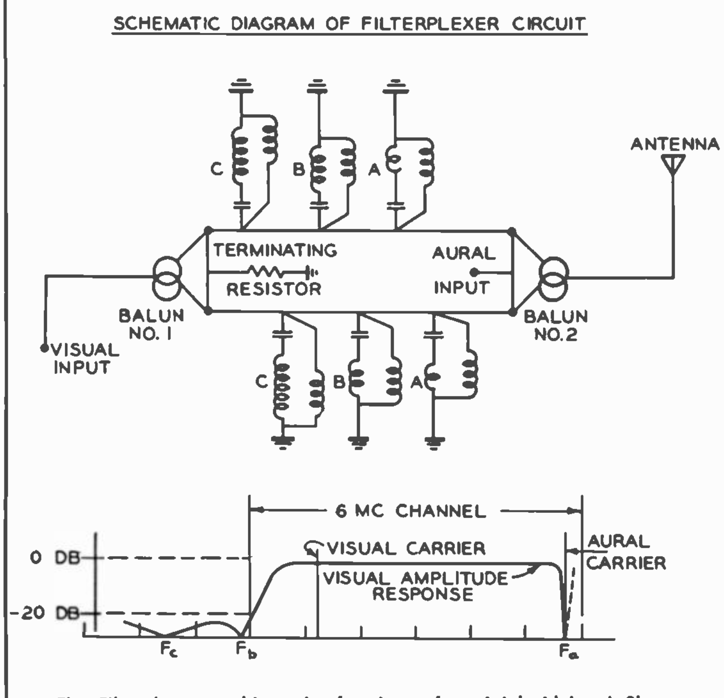
tern will thus remain circular. If the corresponding section of the antenna is rated for full transmitter output, then the field strength will be 70% when full transmitter power is being used, but with half of the antenna gain.

The foregoing descriptions have depicted in detail the four connection systems for diplexing visual and aural into the 12-Section Antennas. The following table summarizes this information:

	A *Standard Bridge*	*B* *4-Line Bridge*	*C* *1-Line CIN*	*D* *2-Line CIN*
Number of Transmission Lines Required	2	4	1	2
Emergency Usage	Figure 8 pattern	Figure 8 with nulls partially filled in	None	Circular pattern half gain
Diplexer	Bridge	Bridge	CIN or Filterplexer	CIN or Filterplexer
Best Usage	For most stations	For maximum flexibility	Long transmission line cases where emergency use not required	Where good emergency facility is required

6-Section Antennas

The foregoing description has referred only to antennas such as the 12-Section Superturnstiles which are fed with four lines down to the tower top. The 6-Section Antennas have two lines only; with these two feed methods being possible. These, correspond to the A. (Standard, 2-Line, Bridge) and the C. (Single-Line, CIN or Filterplexer) systems. With these 6-Section Antennas, it is not essential to make beam tilting or power division changes. See Fig. 11.



The Filterplexer combines the functions of vestigial sideband filter and notch diplexer. Both functions are accomplished with a constant impedance load on the visual transmitter.

The visual input connects through the baluns on either end of the Filterplexer to the antenna. Visual modulation components of frequencies F_a, F_o and F_c are reflected back to the left to Balun No. 1 where they are absorbed by the terminating resistor. Circuit A has relatively high Q to make the 4.5 MC notch sharp so as to minimize the effect on phase and amplitude of the visual components just below 4.5 MC. Circuit B has a medium Q to shape the cutoff at the lower edge of the 6 MC TV channel. Circuit C is relatively low Q so the Filterplexer will absorb in the region between F_c and F_b.

The aural input passes to the left of Balun No. 2 and is reflected by series circuits A. The reflected aural energy passes back through Balun No. 2 to the antenna.

FIG. 10. The frequency response and impedance characteristic of the Filterplexer result in the excellent performance of this unit.

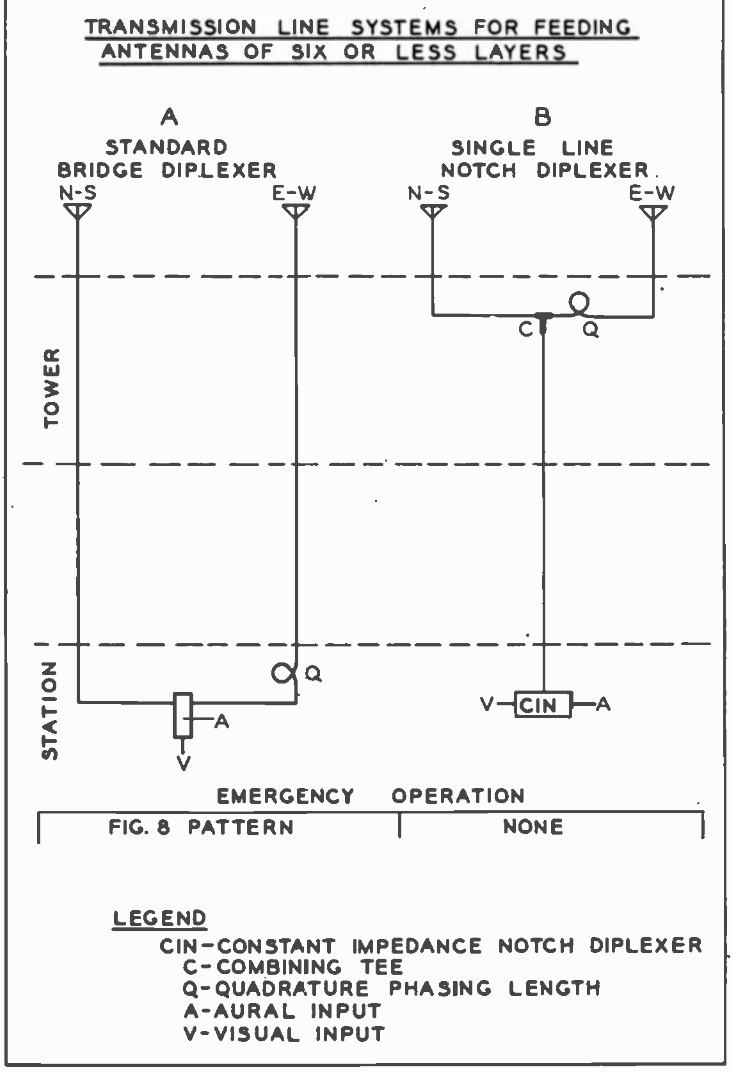


FIG. 11. Transmission line systems chart showing two transmission line arrangements available for 6-Layer Antennas.

"CLOSE-IN" COVERAGE WITH HIGH-GAIN, VHF ANTENNAS

By
IRL NEWTON
Product Administration Section
Broadcast Antenna Equipment

In achieving the higher values of Effective Radiated Power permitted by new FCC rules, Television Stations will require (a) the use of more powerful transmitters, (b) the use of antennas with higher gain, or (c) a combination of "a" and "b" above. For nearly every assignment except temporary, interim, or emergency—the Effective Radiated Power will exceed the actual radiated power. This increase will be achieved by concentrating the energy radiated from the antenna in vertical-plane directions which are effective in delivering a signal to the receivers in the service area.

Gain Considerations

The use of 316 kilowatts into a unity-gain antenna for VHF channels 7 to 13 would be extremely impractical and uneconomical in comparison with a twenty-five or fifty kilowatt transmitter and an antenna gain sufficient to obtain the same ERP and same distant coverage. In addition, the radiation of this high power at angles considerably below the horizon would result in excessive signal and "blanketing" problems within approximately two miles of the antenna. On the other hand, excessive antenna gain or concentration of the radiated energy in the horizontal plane, though permitting exceptional economy in the initial transmitter installation and operating cost, would result in an inadequate

FIG. 1. (316 KW. ERP.) Coverage obtained with 12-Section High Gain Antenna at 1000 ft. height, 0° beam tilt and 50/50 power split.

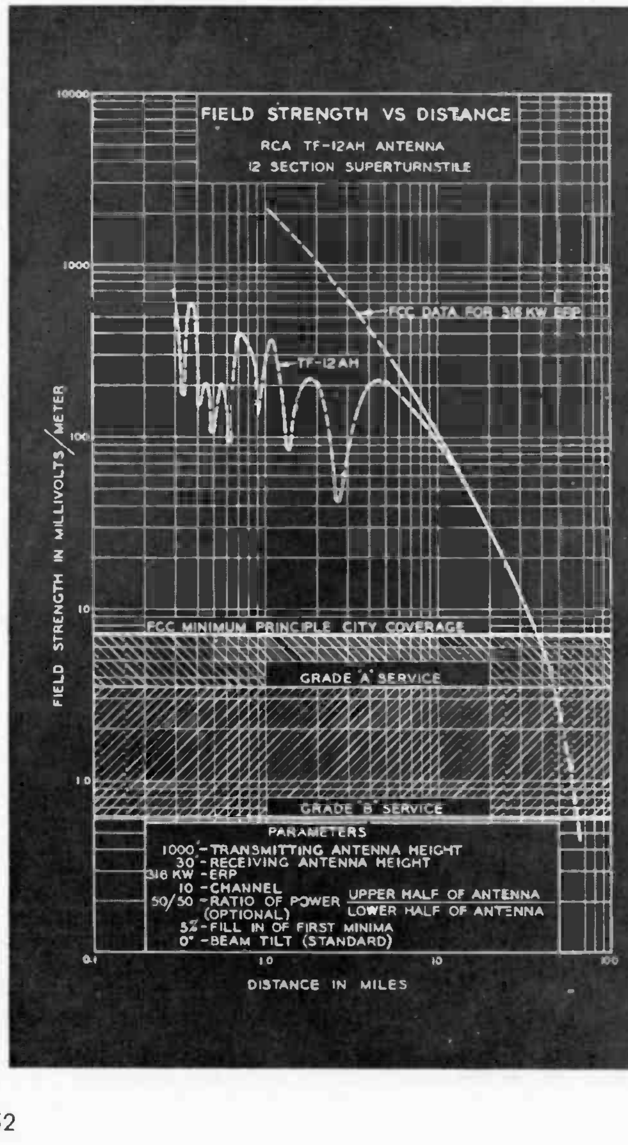
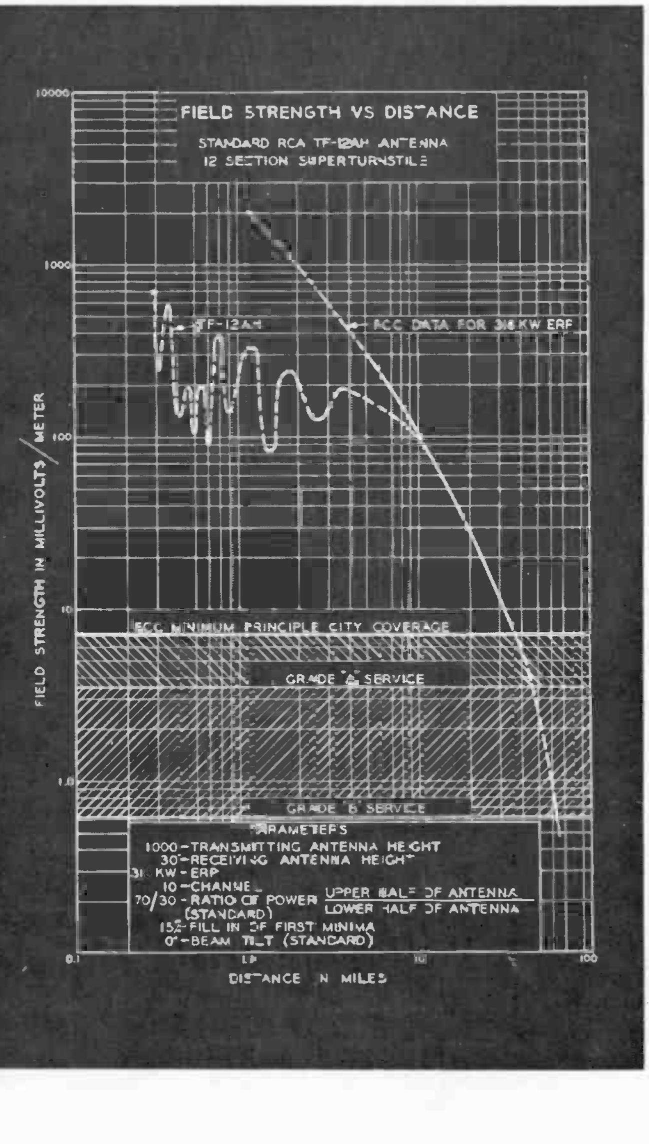


FIG. 2. (316 KW. ERP.) Coverage obtained with 12-Section High Gain Antenna at 1000 ft. height, 0° beam tilt and 70/30 power split.



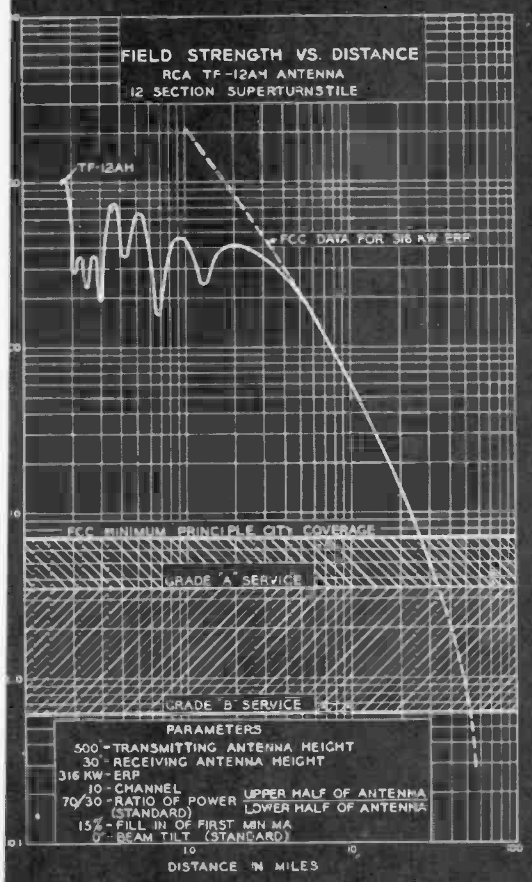


FIG. 3. (316 KW. ERP.) Coverage obtained with 12-Section High Gain Antenna at 500 ft. height, 0° beam tilt and 70/30 power split.

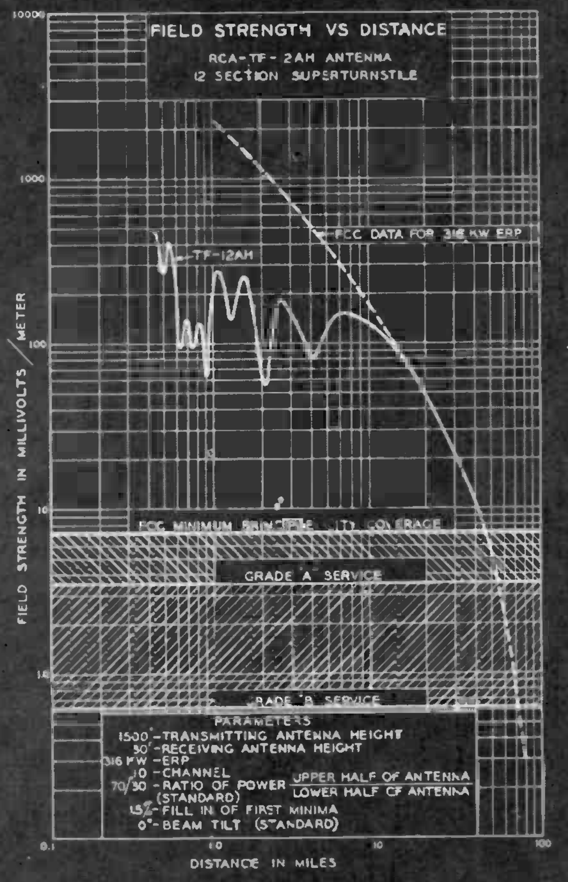


FIG. 4. (316 KW. ERP.) Coverage obtained with 12-Section High Gain Antenna at 1500 ft. height, 0° beam tilt and 70/30 power split.

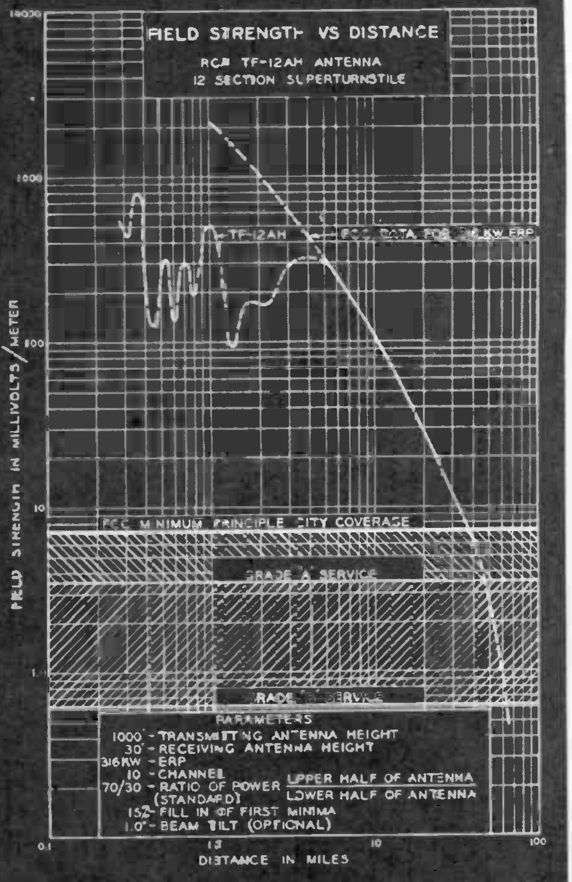


FIG. 5. (316 KW. ERP.) Coverage obtained with 12-Section Antenna at 1000 ft. height, 1° beam tilt and 70/30 power split.

signal in the first few miles from the antenna.

Normally, there are very few, if any, receivers within a radius equal to the tower height. Yet that extremely small area represents an arc of 45° to 90° of depression angle of the vertical pattern. This arc plus the symmetrical elevation angles accounts for one-half of the power radiated from a unity gain or dipole antenna. Elimination of power within this circle about the base of the tower would reduce the transmitter power by one-half for an equivalent service area. Similarly, the power requirement is cut 75% by antenna gain to eliminate radiation below a depression angle of 22.5° representing a radius of only 2.4 times the tower height. In practical installations it is not desirable to totally eliminate any area under the tower—particularly in the case of very tall towers in a populated district. However, these examples serve to illustrate the tremendous value of antenna gain and "Effective Radiated Power" as compared to Transmitter Power.

If a given value of ERP will deliver an adequately strong signal at a distance of 10 miles, less than 1% of the power is required to deliver the same value of signal at a distance of one mile—a depression angle of 5.4° for an antenna height of 500 feet. Thus it is readily apparent that in practical antennas virtually all of the power can be concentrated in a narrow beam without degradation of the close-in service.

The "Ideal" Antenna

The "ideal" antenna vertical pattern will vary with the range of possible antenna heights and will deliver a constant high-level signal out to the point where normal dispersion and attenuation predominate. This design would be unique for each installation and would be based upon an analysis of terrain to determine the radiation required at each depression angle to produce the required signal strength at the pertinent distance. In addition there would be no wasted power in radiation above the angle of the horizon. Such installations require extensive engineering development and (although providing excellent results), may not fall within the economic limits of most budgets.

The objective of present day antenna design is the production of a standardized antenna with a gain and vertical pattern which is optimum for the widest possible range of conditions and a degree of flexibility which permits optimizing performance for the individual installation. Such an antenna is now available in the RCA 12-section antennas. The versatility of

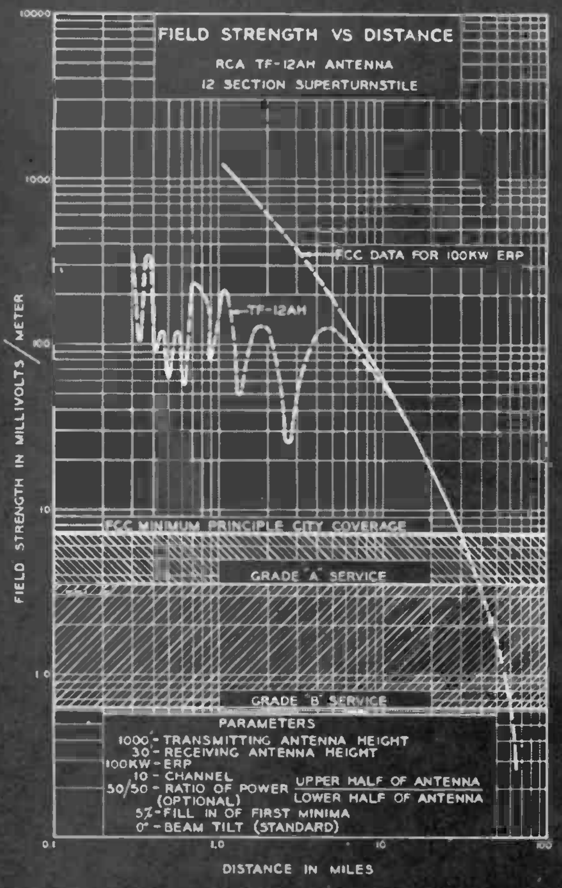


FIG. 6. (100 KW. ERP.) Coverage obtained with 12-Section High Gain Antenna at 1000 ft. height, 0° beam tilt and 50/50 power split.

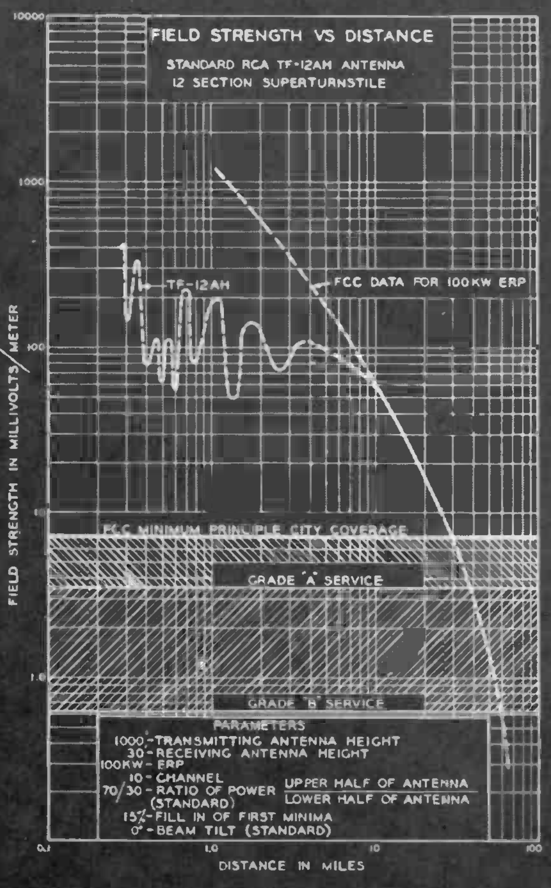


FIG. 7. (100 KW. ERP.) Coverage obtained with 12-Section High Gain Antenna at 1000 ft. height, 0° beam tilt and 70/30 power split.

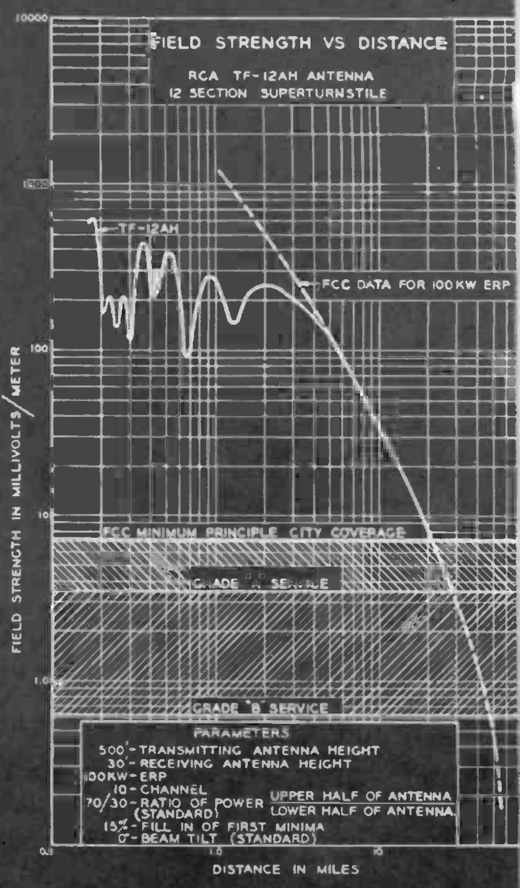


FIG. 8. (100 KW. ERP.) Coverage obtained with 12-Section High Gain Antenna at 500 ft. height, 0° beam tilt and 70/30 power split.

these antennas obtained through flexibility of the feed system is describd in a separate article in this issue of BROADCAST NEWS.

Theoretical Coverage Curves

Following are a number of computed "Field Strength versus Distance" Radial graphs illustrating typical theoretical performance under a variety of conditions for the VHF high band. The charts were computed using the FCC curves as contained in the April 14, 1952, "Sixth Report," and the ERP at the various pertinent vertical angles of the 12-section antenna pattern. The fill-in of theoretically zero nulls is based upon typical superturnstile turntable measurements. Fig. 1 illustrates the calculated performance with uniform power distribution in the antenna for channel 10 and a transmitting antenna height of 1,000 feet.

Why the 70-30 Power Split?

As illustrated by Fig. 2, a substantial improvement for the same channel and antenna height is obtained at a very small sacrifice of gain by changing the power distribution to a 70-30 split between the upper and lower six sections of the antenna. The standard antenna will be shipped with the 70-30 split although a 50-50 or 60-40 split is optional. Figs. 3 and 4 illustrate the calculated performance with the standard 70-30 split for antenna heights of 500 feet and 1,500 feet respectively.

Beam Tilt

For high-antenna locations additional improvement without loss of signal at the horizon may be obtained by tilting the angle of the main beam below the horizontal plane. It will be noted from the accompanying Table I that the horizon is depressed below the horizontal plane for

H	D	A°
200	20.0	.216
300	24.5	.268
400	28.3	.304
500	31.6	.343
600	34.6	.375
700	37.4	.405
800	40.0	.435
900	42.4	.452
1000	45.0	.487
1200	49.0	.530
1400	53.0	.577
1600	56.6	.620
1800	60.0	.650
2000	63.2	.683
5000	100.0	1.080

H—Height in Feet to Electrical Center of Antenna

D—Distance to Horizon (4/3 Earth Radius)

A—Depression Angle to Horizon

FIG. 9. Table of distance and depression angle to horizon. This illustrates optimum beam tilt angle for maximum coverage.

high antenna installations. Tilting the main beam will result in substantial signal increases in some sectors as illustrated in Fig. 5 for a tilt angle of one degree with an antenna height of 1,000 feet.

The FCC rules limit the maximum permissible radiation to 316 KW for channels 7 to 13 at any horizontal or vertical angle. However, the licensed ERP is based upon the radiation in the horizontal plane. Therefore the station license will show slightly less than maximum ERP when the beam tilt is optimized for maximum service and maximum signal directed at the angle of the horizon.

The New 12-Section Antenna and What It Does

The accompanying curves clearly demonstrate that antenna power gains in the order of 12 for an ERP of 316 kilowatts will produce effective close-in coverage with strong signals of 100 mv/m or more out to the distance of intersection with the FCC curve for a dipole vertical pattern.

An unequal power division within the antenna is used to fill-in the first minima below the horizontal and to provide greater uniformity of the received signal. Beam-tilt is optional for signal improvement.

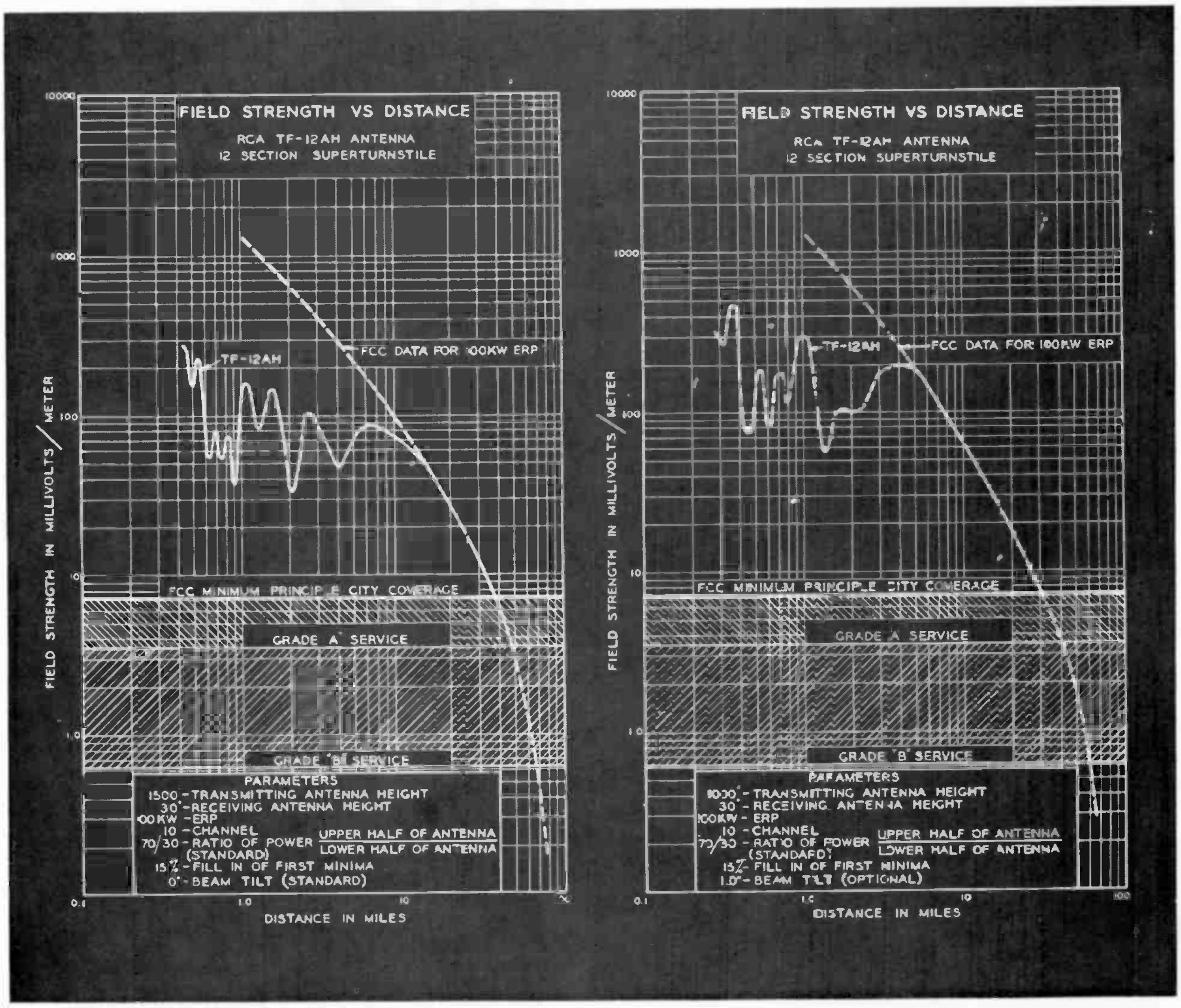
High-Gain Antennas for Low Power Stations

The "Field Strength versus Distance" data contained in Figs. 1 through 5 is based upon an ERP of 316 KW. Assuming average values of transmission line loss this will require a 50 KW transmitter operating at less than maximum ratings. Where economics dictate low power transmitters and where stations will commence operation with an interim power less than maximum performance must be examined for a lower ERP. The Field Strength shown in the preceding curves may be adjusted to any ERP by a factor equal to the square root of the station ERP divided by 316. Figs. 6 through 10 present the same information for an ERP of 100 KW.

It will be noted that a signal in excess of the FCC Minimum for Principle City Coverage can be achieved to a distance of beyond 10 miles with an antenna height of 500 feet and with very low values of ERP. This will permit operation with a 2 KW transmitter and in many cases minimum requirements will be met with a 500 watt transmitter. The use of a high-gain antenna will provide an effective signal in excess of the FCC minimum requirements for low power transmitters and will permit achieving the maximum possible service area with the available transmitter power.

FIG. 10. (100 KW. ERP.) Coverage obtained with 12-Section High Gain Antenna at 1500 ft. height, 0° beam tilt and 70/30 power split.

FIG. 11. (100 KW. ERP.) Coverage obtained with 12-Section Antenna at 1000 ft. height, 1° beam tilt and 70/30 power split.



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