SECTION 3

SPECIALIZED BROADCAST RADIO ENGINEERING

BROADCAST TECHNICAL ASSIGNMENT

BROADCAST ANTENNA SYSTEMS

PART I

Capitol Radio Engineering Institute
Washington, D. C.

314D

- TABLE OF CONTENTS

BROADCAST ANTENNA SYSTEMS

PART I

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PART I

The engineering of a broadcast antenna is a quite complex job. It includes not only the actual design of the antenna itself which involves both matters of field intensity and economic consideration, but also the selection of a suitable location for the transmitter, which in itself is not an exact science. Few locations are ideal from every point of view; compromises placing practical consideration ahead of engineering principles are often necessary.

There is no advantage in having an ideal antenna in a poor location. Neither is it logical to select an ideal location and then neglect the design of the antenna itself. The first requisite for locating a transmitter is sufficient propagation data to permit prediction of signal attenuation in all directions from a tentative site. Variations in attenuation are larger than would be expected. A difference in distance of as much as 6 or 7 to 1 in equi-signal range of two transmitters of equal power and equally efficient antennas may be caused by difference in soil conductivity and operating frequency.

It is not enough simply to take attenuation charts for a certain location and from those charts calculate the field strength from the proposed antenna at a given distance. Unless actual measurements are available large errors may be made in estimating attenuation of a signal crossing sharp discontinuities in conductivity such as shore lines or mountain ranges. Such conditions are particularly likely to result in locations adjacent to a sea coast. Typical of such sites would be large seaport cities like Boston, New York, Los Angeles, etc. Transmission tests should be made in every attempt to take advantage of salt water transmission.

In selecting the site of a broadcast transmitter it is not enough to say that maximum efficiency will be obtained if the antenna is erected on a low, flat, marshy ground if that particular location happens to be a number of miles from the main area to be served. Conversely one should not say that a poor location is at the top of a hill if that hilltop will provide an otherwise suitable site much nearer to the center of population to be served by the particular antenna.

As a whole however, hilltops are to be avoided where possible in favor of low flat locations for antennas in the conventional range for broadcast frequencies. The reason for this is simple. The efficiency of a broadcast antenna depends to a very large extent on the excellence of the ground system and on high conductivity of the surrounding terrain. The best possible location for a broadcast antenna is in low salt water marsh. This is due to the high conductivity of the surrounding earth. When an antenna is located on a hilltop most of the moisture drains away from the site of the antenna leaving the earth exceptionally dry and of low conductivity. This results in large attenuation of the radio frequency field immediately after leaving the antenna.

On the other hand, for ultra-high frequency broadcasting such as in frequency modulation and television stations a high hilltop is the best possible site. The reason for this is equally simple. The ultra-high frequency antenna mounted at the top of a tower or high pole operates purely as a Hertz antenna without the necessity for a ground system. The ultra-high frequency energy is radiated from the antenna in a line-of-sight direction without the necessity for ground wave propagation. The major problem here is to get the antenna as high as possible so that the maximum distance to the horizon is obtained.

Field intensity data necessary for determining attenuation may be obtained by means of a low power test transmitter. In most cases, however, measurements of signals from existing broadcast stations may be used to determine the propagation characteristics of a particular area. For such measurement work an automobile equipped with accurate field strength measuring equipment is necessary. A large group of measurements from several broadcasting stations in different directions from the site of the proposed antenna will allow quite accurate calculation of the average attenuation to be expected in various directions.

Another factor to be considered is the relation of the site to airports and airways. There are no regulations or laws with respect to distance from airports and airways but a distance of three miles from each is used as a guide. In case a suitable location is found at less distance than this it may be satisfactory if the towers are suitably painted and lighted in conformity with the requirements of the Civil Aeronautics Authority or if the towers are not higher than the surrounding objects. The latter is normally considered poor engineering practice however. In selecting a site the local aeronautics authorities should always be consulted if there is any question concerning erecting a hazard to aviation, and in the case of towers over 200 feet high this always should be done.

Where it is necessary to use a directional antenna the site should always be carefully selected with the proposed pattern of the directional array in view. Obviously if the maximum field strength is along a line north and south with a minimum in the easterly direction, the transmitter should not be located west of the desired service area. These factors involved in the selection of the site are every bit as important as the actual design of the antenna and in many cases more so. These involve not only careful measurements and calculations but also considerable common sense.

FACTORS INVOLVED IN ANTENNA HEIGHT

Up to a very few years ago the conventional antenna consisted of two towers based usually several hundred feet apart supporting a T antenna consisting of a large flat top and a vertical lead-in wire. This gradually evolved into a T antenna having a very short flat top and a maximum length of lead-in. Field strength measurements disclosed undesirable effects of the towers on the field strength pattern and many discussions involved the consideration of whether the losses in a steel tower due to absorption were greater or less than the dielectric losses in wooden towers. The eventual solution of this argument was to eliminate entirely the supporting towers and use a steel tower itself as the actual radiator replacing both the long lead-in and the flat top. The first broadcast tower radiator was installed by the Columbia Broadcasting System at WABC in New York City several years ago and today practically all broadcasting stations in the United States have adopted the vertical tower radiator either singly or in directional arrays which include several towers. Such radiators in conjunction with excellent ground systems have resulted in greatly increased broadcast service from transmitters of given power output.

The principal function of a broadcast transmitter is to deliver the maximum signal intensity within a primary service area immediately adjacent to the transmitter. In the case of low and medium power broadcast transmitters where the primary service area extends to not more than 50 miles the matter of increased field strength is a major consideration. In the case of high power broadcast transmitters where the primary service area is limited by fading which occurs in the 60 to 120 mile distances rather than by inadequate field strength the vertical radiation characteristics of the antenna become of more importance than does the matter of maximum field intensity. The height of the vertical antenna is a very important factor in the problems of maximum field intensity and anti-fading characteristics, particularly in the latter. The Federal Communications Commission imposes certain minimum heights for the various classifications of broadcasting stations. These will be discussed later. In practice the actual heights of tower antennas vary all the way from 150 feet minimum to more than 800 feet in the case of high power stations on the lower end of the frequency band.

The factors influencing antenna height are entirely different for high and low powered transmitters. The principal advantage of an antenna having height in the order of .5 λ is its anti-fading property. This is of importance only where the transmitter power is sufficient to make fading the limiting factor in the service area. For a transmitter of low power such an antenna is an unwarranted extravagance since the service area of such a station will generally be limited by signal inadequacy or by interference from other stations rather than by fading. Measurements by Brown have shown that, for given radiated power, as the antenna is made shorter than .25 λ the field strength remains practically constant.

In practice the engineer is interested in the condition of constant power input to the antenna. With losses occurring in the system the radiated power no longer remains constant with varying antenna height. To keep the radiated power high as the antenna is shortened, it is necessary to keep the losses low. These losses are due primarily to the earth current flowing through high resistance earth. Thus to maintain large radiated power as the antenna is shortened below .25 λ it is essential that an excellent ground system be employed. This will be discussed in detail later. Experiments indicate that even with an inferior ground system a .125 λ antenna performs practically as well as a .25 λ antenna. The saving in the use of the shorter tower can partly be expended in good low-loss inductances which will permit the use of a slightly more efficient coupling system than otherwise might be used. The minimum height as specified by the Federal Communications Commission is 150 feet. For low power transmitters there seems to be little advantage in going much above this and the principal problem is to assure a very excellent ground.

From measurements made by Morrison there appears to be little economic justification for antenna height between .25 λ and .5 λ on the basis of increased signal strength. The field intensity curve rises very slowly for antenna heights between .25 λ and .4 λ; only 12 per cent or 1 db improvement is to be expected under the best conditions. On the other hand 32 per cent or 2.4 db improvement is to be expected if the height is increased from .25 λ to .55 λ. Of greater importance to a high power station is a substantial increase in the fading-free area. Thus for low power transmitters it would seem that the most economic height would be in the order of 1/8 wavelength with a provision, of course, that this height would be not less than 150 feet.

For a high power broadcast station the chief limitation of primary night service area is fading. To extend the service area the fading zone must be located further from the transmitter. This can be done only by reducing the skywave radiation. The increase in ground wave signal is important but it must be sacrificed for skywave elimination. Ballantine has shown that for maximum horizontal ground wave radiation, assuming sinusoidal current distribution in the antenna, the optimum electrical length of the antenna is 230 degrees or .64 λ. Field strength calculations show that an antenna of this length would cause serious fading due to excessive sky-wave radiation. It would give a theoretical horizontal radiation increase of 41 per cent as compared with a .25 λ 90 degree antenna. However, the 230 degree antenna would radiate a high lobe of energy at an angle which would cause very serious sky-wave interference and fading starting in the radius of 60 or 70 miles. For sinusoidal current distribution a 190 degree antenna (.528 λ) gives 27 per cent increase in the horizontal radiation as compared with .25 λ antenna but radiates a minimum sky-wave so that it allows a greater service range than the 230 degree antenna. In the broadcast band the optimum antenna for reduction of sky-wave at distances from 60 to 120 miles is the 190 degree antenna assuming sinusoidal current distribution.

Ballantine's calculations show that with a straight vertical antenna over a perfectly conducting earth with sinusoidal current distribution in the antenna, for given radiated power the maximum field strength at the horizon is obtained with antenna height of .64 λ. Ballantine further shows that the smallest ratio of reflected sky-wave to ground wave is obtained from an antenna having a length between .5 λ and .64 λ, depending upon the amount of attenuation of the ground wave. This latter is important because the ground wave is subject to attenuation while the sky-wave has almost no attenuation, and hence the ratio between the sky-wave and the ground wave which will cause serious fading will be proportional to the attenuation of the ground wave.

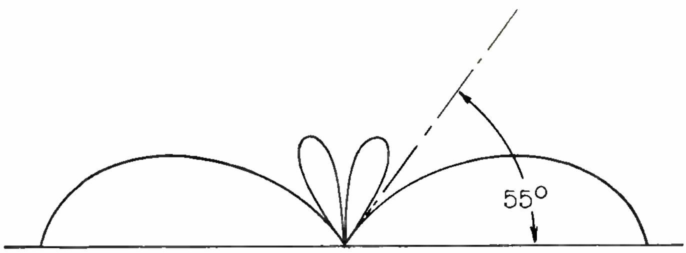
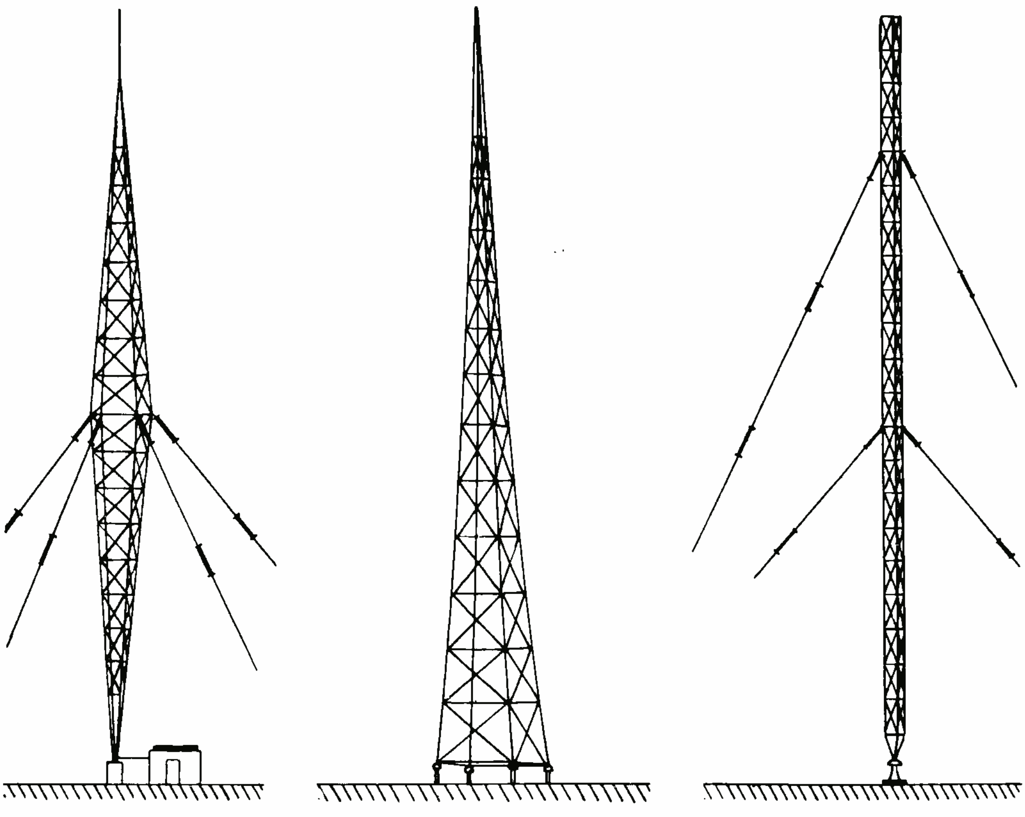


Fig. 1.

Field strength calculations for the sinusoidal current distribution antenna longer than .5 λ show a vertical field pattern as in Figure 1. Airplane measurements of the vertical field intensity patterns of actual vertical antennas of both the guyed cantilever towers and broad-base self-supporting types show complete absence of high angle lobe and the minimum as shown in Figure 1; also the resistance versus frequency on these towers does not check with the theory for ideal vertical radiators. Tests with miniature antennas by Gihring and Brown with frequency such that the actual mode of operation of broadcast antennas is simulated, indicated this to be due to non-sinusoidal current distribution in the antenna.

Three types of vertical tower antennas will be considered in this discussion and for purpose of reference they will be referred



Cantilever Guyed (A) | Broad-base Self-supporting (B) | Uniform Cross-section Guyed (C)

Fig. 2.

to as Type A, B, and C. These types are shown in Figure 2. Type A is the guyed cantilever tower which is narrow at each end and broad in the middle. This tower is supported at the base by a single large ceramic insulator. Type B is a broad-base self-supporting tower which narrows uniformly to a pointed top; this type of tower may be of either square or triangular cross section and is supported upon a base with an insulator at each leg of the tower. Type C is a guyed tower of uniform cross section. This tower is of particular importance because it is the only type in which sinusoidal current distribution can be approached.

The original theory on tower antennas assumed sinusoidal current distribution. The current distribution in Type A and Type B towers cannot be sinusoidal because the shape is such that the inductance and capacity *per unit length* are not constant over the antenna length. The surge impedance is small where the antenna cross section is large, and vice versa.

For many years in antenna work it has been customary to speak of the mode of operation in terms of the natural wavelength, that is, the operating wavelength to the fundamental wavelength. In dealing with most types of tower antennas this method of designation is erroneous because it is significant only when the current distribution is sinusoidal. It is much better to describe the antenna in terms of height (a) measured in wavelengths (a/λ) or in terms of angular length ($G = 360\ a/\lambda$). For example, $a/\lambda = .25$, $G = 90^\circ$; $a/\lambda = .528$, $G = 190^\circ$. When the antenna's shape is such that the current is sinusoidal the above method of designation gives a picture of what portion of the sine wave of current exists on the antenna. With non-sinusoidal current the length still may be expressed in electrical degrees and the figure for G states the ratio of antenna length to operating wavelength.

It particularly must be understood that in speaking of the height of an antenna in terms of degrees or fractions of a wavelength, this height is expressed in terms of free waves in space. That is, if one were speaking of a half-wave antenna which is to operate at a wavelength of 350 meters *the actual physical height of the antenna would be 175 meters.* Due to the fact that the rate of propagation of the signal through the tower is not as rapid as in free space, actually there would be more than one-half wavelength of current on the antenna.

It is well at this time to tabulate and define the three relations of the antenna with respect to its wavelengths, frequency, and physical characteristics.

1. The resonant frequency of an antenna is the lowest frequency at

which the antenna if properly excited will oscillate freely. The resonant frequency is entirely a function of the inductance and capacity of the antenna and is the frequency at which the inductive reactance equals the capacity reactance. The natural wavelength of the antenna is defined by the velocity of light, (3 x 10^8 meters/second) divided by the resonant frequency in cycles per second.

2. The operating frequency is the frequency of the excitation voltage which supplies power to the antenna. This frequency and its corresponding wavelength may be, and in practice always are, entirely dissimilar from the resonant frequency or natural wavelength of the antenna. *The ratio of the operating wavelength to the fundamental wavelength* of the antenna is called the "mode of operation". For a vertical antenna operated above a perfectly conducting earth with sinusoidal current distribution, optimum performance as calculated by Ballantine is obtained when the mode of operation is .39, and this condition should exist when the antenna is .64 λ high. Ballantine's calculations further assume that the velocity of propagation in the antenna is equal to the velocity in space and that the velocity is equal in all parts of the antenna. Such conditions cannot be obtained but can be closely approached in an antenna of uniform cross-section as will be explained later.

3. The third relation as used in practice is the expression of the physical height of the antenna in wavelengths. The height of the antenna expressed in wavelengths is a simple measure of linear distance expressed in terms of a decimal portion of the operating wavelength. For example, if the operating wavelength is 300 meters and the antenna is to be a .5 λ antenna the actual physical or linear height of the antenna will be 150 meters. The natural wavelength of the antenna may be any value depending on the shape and dimensions of the tower. Due to the fact that the velocity of propagation in the tower is considerably slower than in free space, the electrical length of the antenna will always be somewhat greater than the physical length in meters, the difference depending again on the physical shape of the tower. The electrical length in terms of 1/2 wavelength and its physical length in wavelengths will most nearly coincide in a vertical radiator of uniform and very small cross-section.

It has been stated that measurements on the field intensity patterns of typical broadcast antennas differ quite widely from the theory based on Ballantine's calculations. Very extensive tests and measurements by Gihring and Brown on miniature antennas of the A and B type have brought out several pertinent facts:

1. Where guy wires are used the effect on the current distribution is very slight. The guy wires seem to have no effect on the current distribution above the point of attachment and there is little appreciable difference in the field strength pattern as measured with and without guy wires attached.

2. The maximum value of current in the antenna occurs at a much lower point on the antenna than simple theory predicts. (A comparison of typical cases is shown in Figure 3). This, of course, is due to the shape of the antenna which results in a larger capacity to ground in the lower section than would exist with a simple vertical wire.

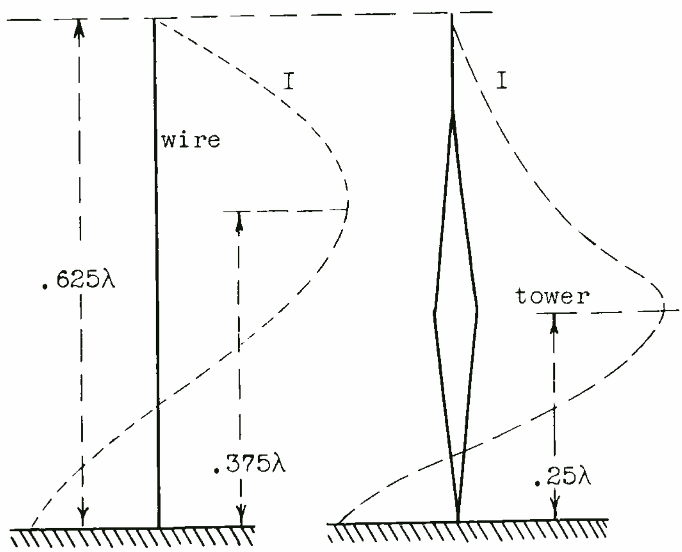


Fig. 3.

3. At no place on the antenna except at the very top end does the current become zero or even approach zero.

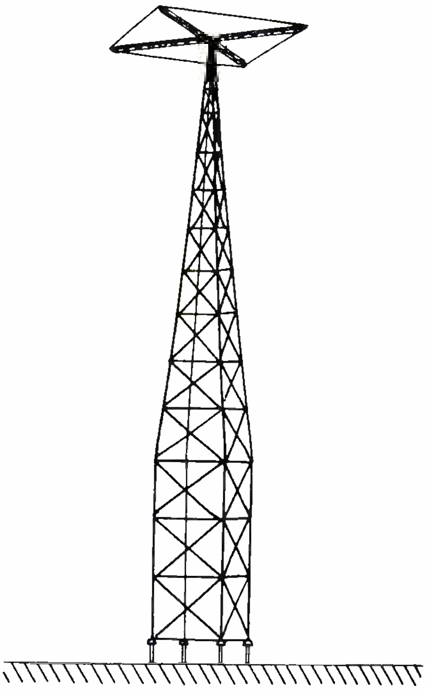
4. The rod which on some antennas of both the A and B types may make up as much as 20 per cent of the antenna length carries very little current.

Item 3 should be analyzed. The simple theory of a vertical wire antenna is based on the theory of a transmission line. In a long transmission line where the remote end is open circuited the current is made up of two components one of which travels along the line from the generator to the open end and the other of which is reflected from the open end toward the generator. When the line is made up of uniformly distributed inductance and capacity and the losses in the line are zero (no radiation or other losses) the two components will have equal amplitude, sinusoidal standing waves will be distributed along the line and at half-wave intervals the current will drop to zero with currents of opposite polarity on opposite sides of the zero point.

An antenna is *not* such a loss-free line. Due to current leaving the generator power is radiated, and the reflected current is considerably less than the original current. Therefore, while standing waves are set up, at no point does the current actually approach zero. Instead, the phase reversal (the current on the two sides of the minimum current point are still opposite in phase) will take place by means of a *phase rotation* rather than by means of the amplitude going to zero. When the losses are low, as in a non-radiating line, the current distribution is nearly sinusoidal except at the theoretical zero point. Here the current will be very small except when the losses are very large. On a non-uniform line which is very well represented by tower antennas of the A and B types the departure from sinusoidal distribution is accentuated by the non-uniform distribution of inductance and capacity.

Measurements indicate that the current distribution on the Type B tower is more nearly sinusoidal than on the Type A tower. This is due to the fact that the former changes cross section (and hence inductance and capacity per unit length) less abruptly.

It is sometimes found impossible, for various reasons, to use a vertical tower antenna of satisfactory height. The effect of additional height can be obtained by the use of a capacity screen or framework mounted on top of the tower. A typical antenna of this type is shown in Figure 4. The use of the capacity framework on the top of the antenna has the same effect on the current distribution as lengthening the antenna. This is particularly useful where the antenna, due to anti-fading characteristics desired, should be greater than one-half wavelength high and where circumstances will not permit the use of a tower of that height.



Tower antenna with capacity framework on top.

Fig. 4.

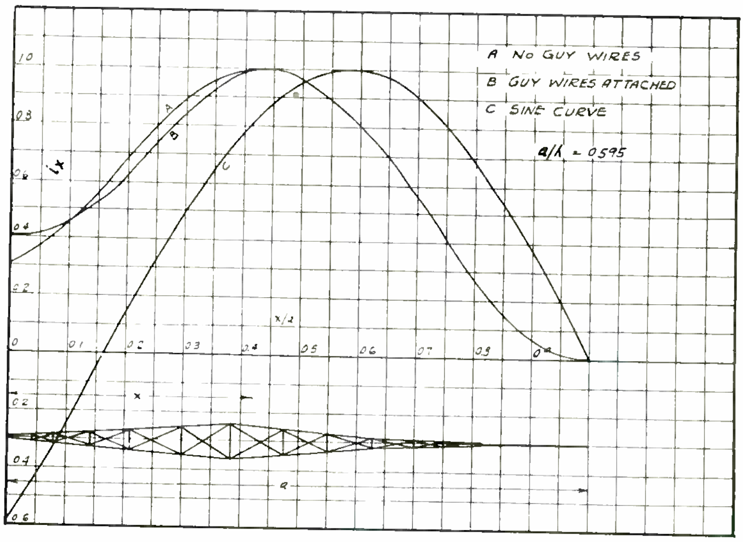
Measurements and calculations indicate there are definite advantages to be gained by using an antenna having sinusoidal current distribution. It is possible that other current distributions than sinusoidal may give equal or better results. However, from the viewpoint of antenna design, sinusoidal distribution of current is highly desirable because it greatly simplifies the calculations and makes it easier to predict the performance.

Measurements on a vertical wire indicate that the current distribution is very nearly sinusoidal and hence coincides with theory. Further measurements on antennas of uniform cross section over the entire antenna length indicate that the current distribution on such an antenna is substantially sinusoidal. The result of sinusoidal current distribution as compared with the current distribution in towers of the A and B types is to place the point of maximum current higher above ground. This results in greater radiation efficiency for a given antenna height and makes it possible to predict the antenna performance through the use of greatly simplified calculations.

Measurements and radiation calculations show that the best height of antenna to use to reduce the sky-wave to a minimum depends upon what type of antenna it is--Type A, Type B, or Type C. The Type A antenna gives a large high-angle radiation by the time the height is such as to give maximum field strength. If the antenna height is reduced to reduce high-angle radiation, there is an appreciable loss in field strength. The Type B antenna gives values closer to the theoretical and seems to suppress the sky-wave for heights up to .55 λ. Beyond that point the field intensity drops off rapidly. The maximum field strength for this type of antenna is far short of the theoretical maximum to be obtained with sinusoidal current distribution. Measurements and calculations indicate that the Type C antenna with uniform cross section will give results most nearly approaching the ideal theoretical maximum.

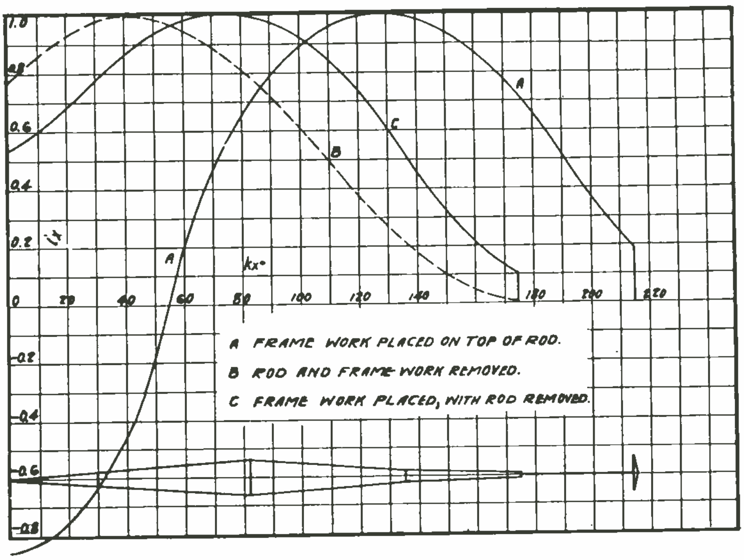
Figures 5 to 9 inclusive are reproduced from an article by Gihring and Brown in the Proceedings of the Institute of Radio Engineers for April, 1935. These curves are the result of measurements made on miniature tower antennas with the excitation frequency such that the mode of operation of the antenna would correspond to its equivalent in the broadcast band.

Figure 5 shows the effect of the tower shape and the guy wires on the current distribution in a Type A antenna. Curve C is calculated for sinusoidal current distribution over a vertical wire of the same height.



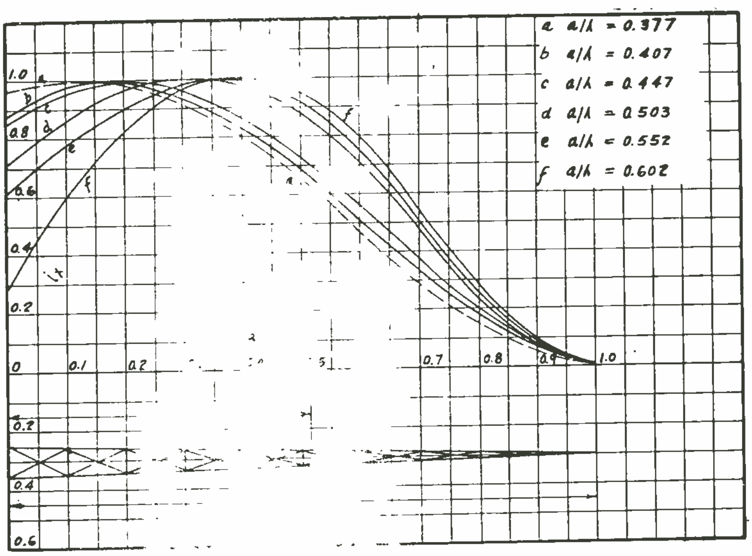
The effect of tower shape and guy
wires on current distribution.
Fig. 5.

Figure 6 shows the result of placing a capacity framework on the top of a Type A tower. The effect is to raise the point of current maximum to a considerably higher point along the tower than would be the case without the use of the framework.



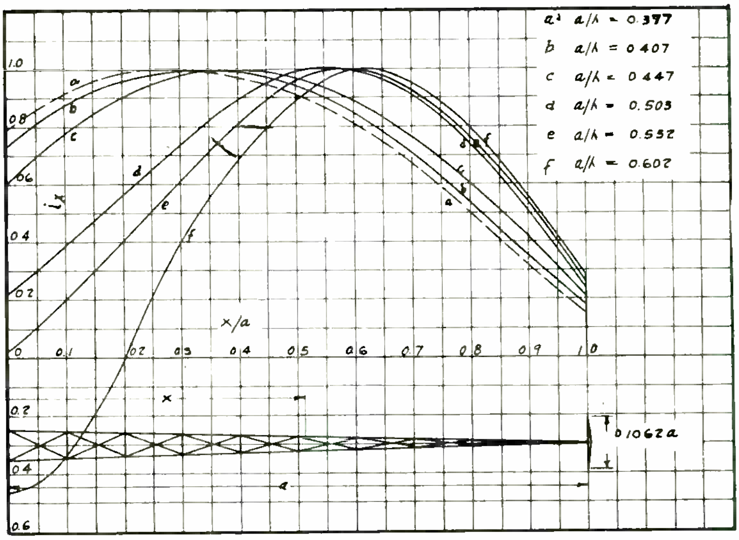
Effect of capacity framework on
top of type A antenna.
Fig. 6.

Figure 7 illustrates the current distribution on a Type B tower of varying height. It is see[illegible] that the height of the tower is increased the point of maximum current is raised to a higher point above ground.



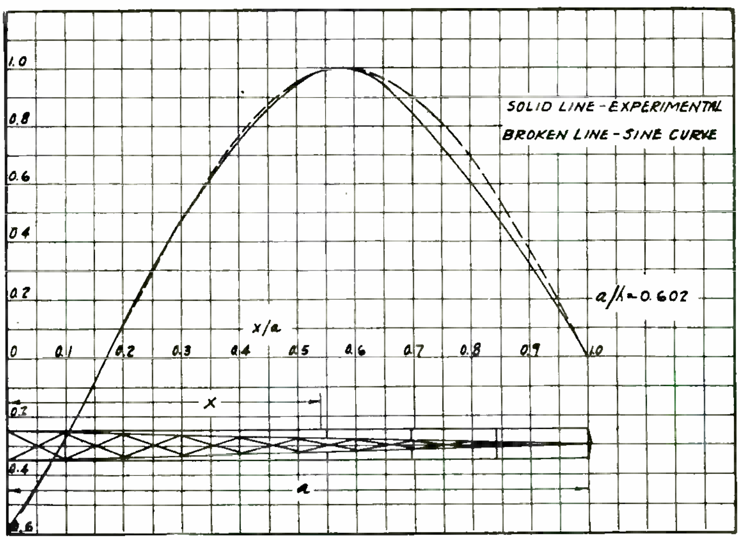
Curr[illegible] on [illegible]pe B antenna.

Figure 8 illustrates the effect on current distribution of the same type of tower equipped with a capacity framework on top.



Current distribution on type B antenna with a large capacity area.
Fig. 8.

Comparison of Figure 7 and Figure 8 for any given height of tower will show that the effect of the capacity framework is to



Current distribution on type B antenna equipped with outrigger and vertical wires ($a/\lambda = 0.602$).
Fig. 9.

increase the effective height of the tower.

In obtaining the curve of Figure 9 the top of a Type B tower was fitted with a framework equal in area to the bottom of the tower. From this framework were suspended a number of wires to form a radiating system of uniform cross section. It is seen that when uniform cross section is obtained the current distribution coincides very closely with that of the sine curve.

During the past several years a number of uniform cross section tower radiators have been installed throughout the country. Typical of good design is the antenna of the National Broadcasting Company station WJZ shown in Figure 10. This 640 foot tower operates at a frequency of 760 KC/s giving it a height of .494 λ. The lower end of the tower comes to a point in order to minimize the capacity to ground thus allowing the maximum height for the desired ratio of

ANTENNA FOR WJZ

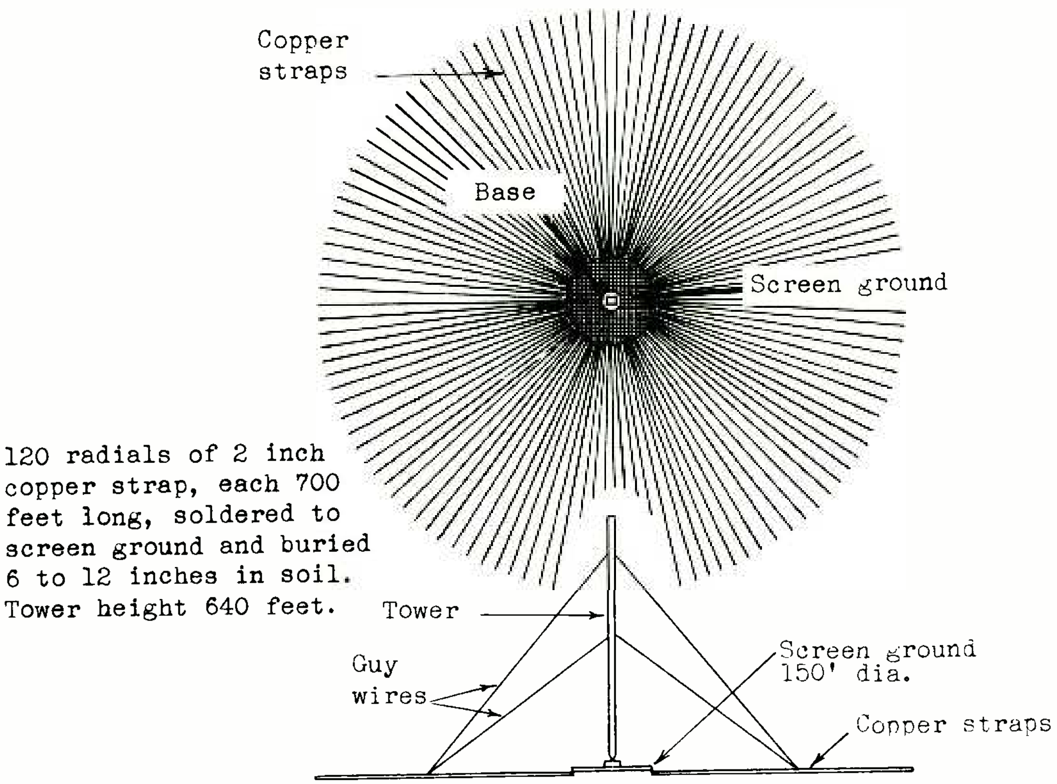


Fig. 10.

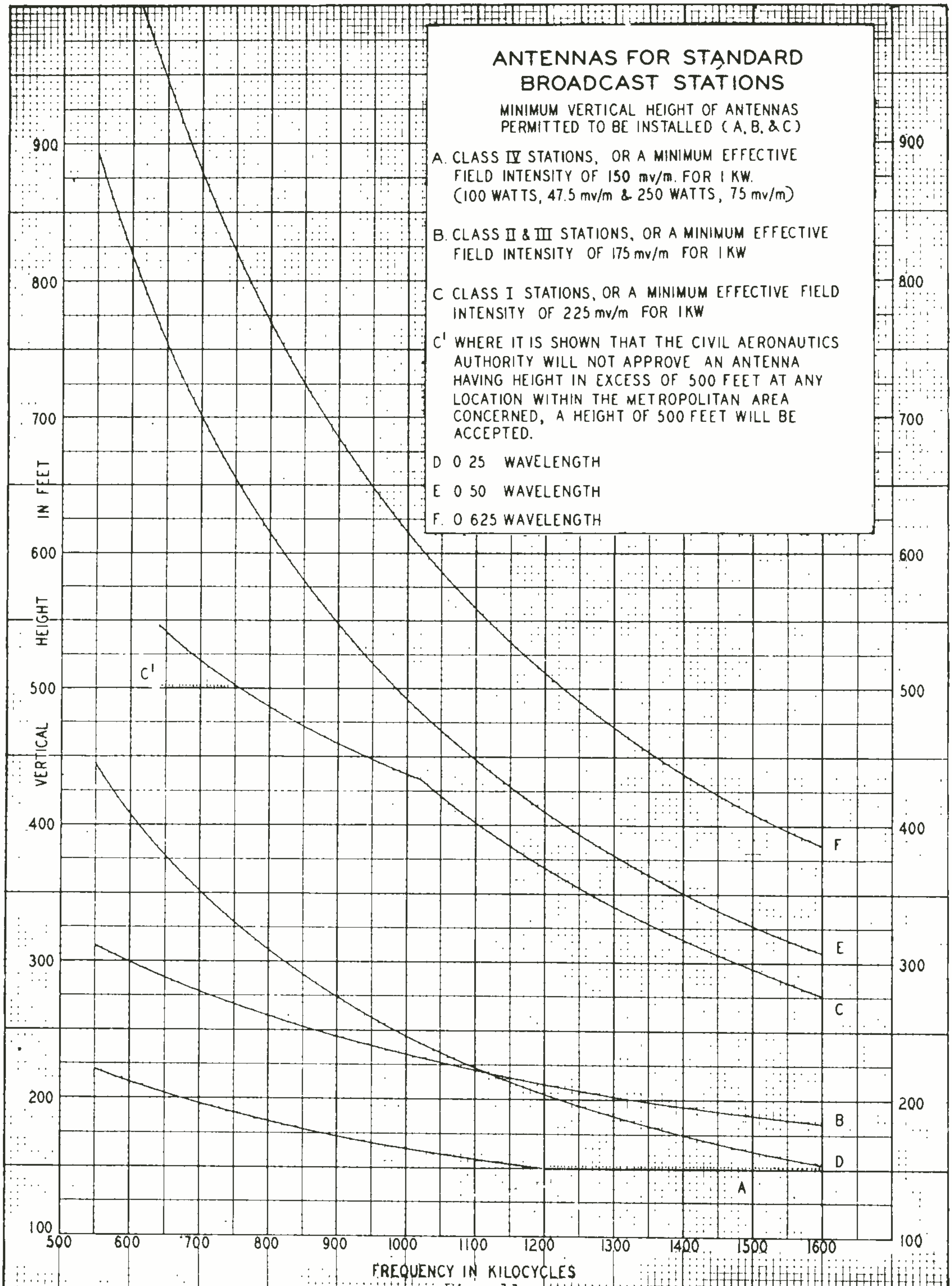
operating wavelength to fundamental wavelength. The elaborate ground system shown allows the antenna to operate at very high efficiency.

Figure 11 is reproduced from "Standards of Good Engineering Practice Concerning Standard Broadcast Stations" published by the Federal Communications Commission. Curves D, E, and F show the height in feet for respectively .25, .5 and .625 λ antennas. Curves A, B, and C respectively show the minimum heights permitted by the Federal Communications Commission for Class 4 stations, Class 2 and 3 stations, and Class 1 stations. It should be noted that minimum effective field intensity can be substituted for minimum antenna height *where adequate measurements prove* that these actual minimum field intensities are obtained.

THE GROUND SYSTEM

The ground system beneath a broadcast antenna has two principal functions. The first function is to provide a good conducting path for the earth currents so that these currents will not flow through a poorly conducting earth. This is particularly necessary close to the antenna where the earth current density becomes high. The second function is to act as a good reflector for waves coming from various points on the antenna so that the vertical radiation pattern will be close to that obtained if the earth under the antenna were perfectly conducting. Actually these two functions are synonymous. The ground system usually consists of buried radial wires with the base of the antenna as the common point.

Where ground wires are used the earth current consists of two components, one of which flows in the earth itself and the other which flows in the buried wires. Tests clearly indicate that quite near the antenna (within a radius of a few feet) most of the current flows in the wires. However, at greater distances from the antenna the proportion of current which flows in the wires depends very largely upon the number of wires. (This proportion is also of course a function of the earth conductivity). Typical measurements by Brown clearly bring this out. For example, with ground conductivity of $.5 \times 10^{-4}$ mhos per cm. cube, a wavelength of 300 meters and with 120 radial wires 80 per cent of the current flowed in the wires 85 meters from the antenna base; with 60 wires the current in



ANTENNAS FOR STANDARD BROADCAST STATIONS
MINIMUM VERTICAL HEIGHT OF ANTENNAS PERMITTED TO BE INSTALLED (A, B, & C)
A. CLASS IV STATIONS, OR A MINIMUM EFFECTIVE FIELD INTENSITY OF 150 mv/m. FOR 1 KW. (100 WATTS, 47.5 mv/m & 250 WATTS, 75 mv/m)
B. CLASS II & III STATIONS, OR A MINIMUM EFFECTIVE FIELD INTENSITY OF 175 mv/m FOR 1 KW
C CLASS I STATIONS, OR A MINIMUM EFFECTIVE FIELD INTENSITY OF 225 mv/m FOR 1 KW
C' WHERE IT IS SHOWN THAT THE CIVIL AERONAUTICS AUTHORITY WILL NOT APPROVE AN ANTENNA HAVING HEIGHT IN EXCESS OF 500 FEET AT ANY LOCATION WITHIN THE METROPOLITAN AREA CONCERNED, A HEIGHT OF 500 FEET WILL BE ACCEPTED.
D 0 25 WAVELENGTH
E 0 50 WAVELENGTH
F. 0 625 WAVELENGTH
VERTICAL HEIGHT IN FEET
FREQUENCY IN KILOCYCLES
100
200
300
400
500
600
700
800
900
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
A
B
C
C'
D
E
F

Fig. 11.

the wires dropped to 80 per cent at 43 meters and at 85 meters the percentage dropped to 28 per cent. With 30 radial wires the percentage of total current in the wires dropped to 50 per cent only 31 meters from the base of the antenna. Thus the ground losses go up very rapidly as the number of radial wires is reduced.

When the antenna is longer than .25 λ the earth currents are larger at remote points than the current at the base of the antenna. For example, beneath a .5 λ antenna the maximum losses in the earth occur in the region about .35 λ from the antenna base. This same value (.35 λ) is true for other antennas higher than .5 λ. The reason for the large current at this distance from the antenna is the fact that the point of maximum current along the antenna, and hence the maximum field density of the high vertical radiator, is approximately .35 λ above ground and the field distribution between the vertical radiator and ground is such that the lines of force form substantially a 90 degree segment of a circle, so that the point of maximum field density at ground is approximately as far from the radiator as is the point of maximum current in the radiator above ground. While the total current at this distance from the radiator is high, the actual current density, if the earth is of good conductivity, may be considerably less than the current density at the base of the antenna because the total current is distributed through an area having a large circumference while at the base of the antenna the total current flows solely in the copper which has a considerably smaller cross section and hence a higher current density. If the ground conductivity at the .35 λ distance is very low so that most of the current at this point flows in the radial wires, then the current densities at this point and at the base of the antenna may be quite similar. Calculations and measurements clearly show that it is important to use at least 120 radial wires and to make the length of the radial wires preferably .5 λ. However, if only a few wires are used the wires need not be very long since they will carry little current except very close to the antenna. In such a case, of course, the ground losses may be expected to be rather high and the antenna efficiency low.

In the case of the Type B broad-base self-supporting antenna tower the capacity to ground is higher than in other types and hence the capacity current to ground at the base of the antenna is high.

This large capacity current does not have any objectionable effect if the resistance in the path of current is kept negligible. To minimize ground losses in the immediate vicinity of the antenna base due to capacity current across the base insulator a large metal screen or mat should be placed *on the surface of the earth* immediately below the antenna and this screen connected directly to the ground system.

Figure 10 illustrates an excellent ground system. It consists of 120 radials of 2 inch copper strap 700 feet long soldered to a screen ground and buried 6 to 12 inches beneath the surface of the earth. The screen ground in this case is 150 feet in diameter.

The efficiency of the ground system becomes of increasing importance as the antenna height is decreased. In practice the antenna design engineer is interested primarily in a condition of constant power input to the antenna. With losses occurring in the system the radiated power no longer remains constant with varying antenna height. To keep the radiated power high as the antenna is shortened, it is necessary to keep the losses low. These losses are due primarily to the earth currents flowing through high resistance earth. Thus to maintain large radiated power as the antenna is shortened below .25 λ it is *essential* that an excellent ground system be employed. Measurements have shown that the earth within .35 λ radius should be *a very good* conductor in order to operate a short antenna efficiently. This may be approximated by a buried ground system consisting of many radial wires.

Measurements by Brown on a ground system consisting of 115 radial wires approximately .5 λ long demonstrated that the field strength from a .06 λ antenna was only 8.5 per cent less than from a .25 λ antenna employing the same ground system.

For any antenna a ground system consisting of 120 buried radial wires .5 λ long is desirable. Where direct field intensity along the ground is the sole aim, as in low power broadcast transmitters, the ground system is of more importance than the antenna itself.

When the conductivity of the earth is good the current leaves the wires and enters the earth closer to the antenna than it does when the earth is a poor conductor. This causes the region of high current density to be subjected to still more current with higher losses in those regions. There seems to be a compensating effect which tends to make the system somewhat independent of earth conductivity over a limited range. *This, of course, assumes the use of a sufficient number of radial wires.*

COUPLING TO THE TOWER ANTENNA

Antennas may be divided into two fundamental groups, the Hertz antenna and the grounded or Marconi antenna. The Marconi antenna operates with the ground forming one section of the antenna capacity. The power is supplied to the antenna near the ground connection and the actual *electrical length* of the antenna is normally .25 λ, or if operated at a harmonic frequency of the antenna .75 λ, 1.25 λ, etc. The current and voltage distribution will be such that the current will be zero at the extreme end of the antenna and maximum at the ground connection; the voltage will be zero at ground and maximum at the extreme end of the antenna. The current and voltage distribution along three such antennas is shown in Figure 12, all antennas being excited at the same frequency. The current and voltage curves will be displaced by 90 degrees.

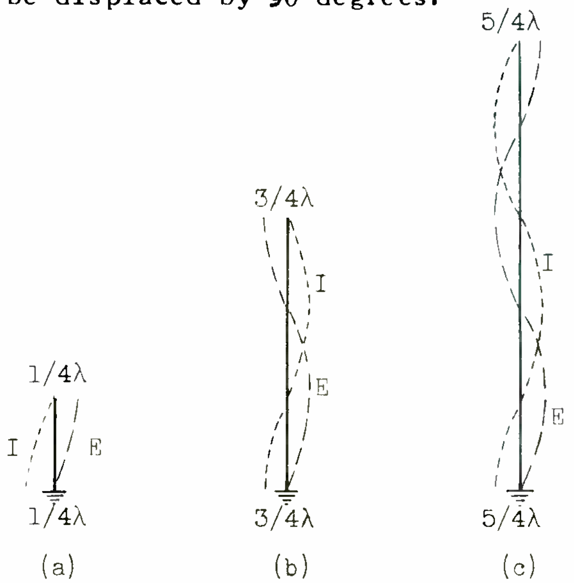


Fig. 12.

Figure 12 represents actual electrical length of the respective antenna systems and does not represent the physical height in wavelengths of the antennas. Since it is necessary to couple power into the antenna and since this usually is done by means of mutual inductance in which the secondary of the coupling circuit forms a part of the antenna circuit in series between the antenna and ground, it is necessary that the actual physical height of the antenna system be less than the electrical length of the system. In the case of an antenna whose actual height is considerably less than .25 λ coupling inductance may be added to bring the actual electrical length of the circuit up to the .25 λ as shown in Figure 12(s

shown in Figure 12 (a). In the case of an antenna whose physical height approaches or exceeds .25 λ the actual electrical length of the circuit including the coupling inductance will have to be .75 λ as shown in Figure 12 (b).

Figure 13 illustrates a typical coupling circuit inwhich a tower antenna is coupled to a coaxial transmission line by means of L_1, L_2, C and m. Ordinarily both L_1 and L_2 are adjustable as is the coupling between those two inductances. By means of L_1 the antenna circuit is tuned to resonance. C, L_2, and m are so adjusted that the antenna represents the proper matching resistance for the transmission line. Calculations for the design of such a circuit have been discussed in a preceding lesson.

At this point it is well to again differentiate between the electrical length of a circuit in wavelengths and the expression of a vertical radiator in the same terms. As previously mentioned in this lesson it has become customary to speak of such radiators in terms of their height in wavelength as measured in free space. Thus a .58 λ radiator is actually .58 λ high in terms of the velocity of electromagnetic field propagation through space. A .58 λ radiator for a frequency of 1000 KC/s (300 meters wavelength) will have an actual height of 300 x .58 = 174 meters = 571 feet. A .4 λ radiator for the same frequency would have an actual height of 300 meters x .4 = 120 meters x 3.28 = 394 feet. Hence, the actual *electrical length* of the .58 λ radia-

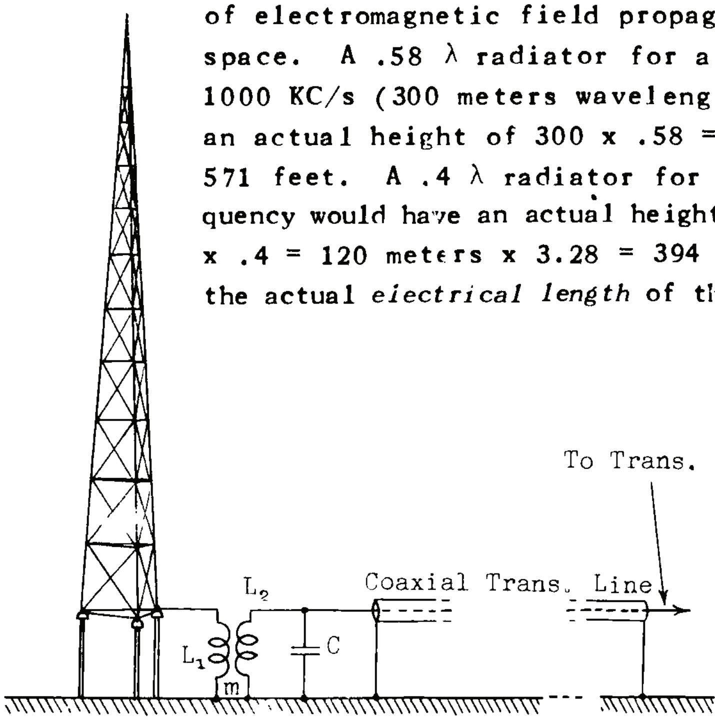


Fig. 13.

tor will be considerably greater than .58 λ because the velocity of propagation is considerably slower along the tower than through space. Thus it is important to distinguish carefully between the height of a radiator and the electrical length of an antenna system when both are expressed in terms of λ.

THE SHUNT-EXCITED ANTENNA

The above discussion on coupling assumes that a tower antenna of the A, B, or C type (see Figure 2) is insulated above ground as in Figure 13 and connected to ground through the coupling inductance. For a number of reasons it would be desirable to have the antenna base at ground potential. The problem in this case is that of coupling power into a grounded tower antenna. Such a circuit was developed by the Bell Telephone Laboratories and described before the Institute of Radio Engineers in 1936 by J. F. Morrison and P. H. Smith. It was shown that the grounded antenna may or may not be operated at its resonant frequency. Instead of the conventional coupling circuit located between the base of the antenna and ground the grounded antenna may be fed by a single wire transmission line by using a small portion of the antenna at its base as a coupling impedance.

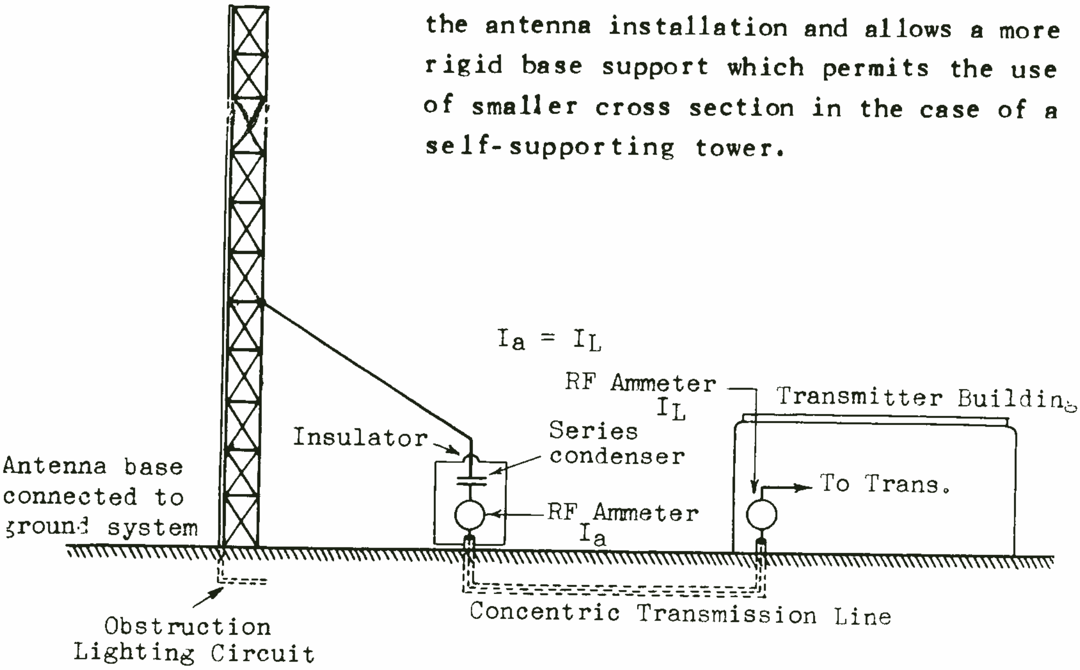
The operation of this antenna is based on the fact that the coupling impedance as viewed from the antenna itself in no way effects the radiation characteristics of the antenna. So far as radiation characteristics are concerned the antenna may be connected directly to ground without affecting its performance.

Figure 14 illustrates the manner in which the shunt-excited antenna is fed by an inclined single wire transmission line connected at some point above ground on the antenna and directly to the concentric transmission line through a series condenser. Proper termination of the transmission line is accomplished by adjusting the length between the end of the transmission line and the antenna, and the height of the point above ground at which the single wire transmission line is tapped. In practice the first dimension is fixed and the proper impedance match is obtained by adjusting the height of the tapped point above ground.

The advantages of shunt-excitation are:

1. No base insulator is required. This reduces the cost of

the antenna installation and allows a more rigid base support which permits the use of smaller cross section in the case of a self-supporting tower.



Coupling arrangement for the shunt-excited antenna.

Fig. 14.

2. Filter devices for the obstruction lights are not required. The lighting circuit may be run directly to the antenna base and then vertically up the antenna structure.

3. The need for a static drain device is eliminated and difficulties caused by lightning are reduced.

4. The resistance of the radiating system is permanently adjusted to equal the characteristic impedance of the transmission line. This eliminates the need for coupling transformers. It also makes it possible to standardize the antenna current meter scale for all installations using the same type of transmission line. When the transmission line is correctly terminated by the antenna system the line current reading at the transmitter end is a direct indication of the current entering the radiating system. The losses in well designed transmission lines are negligible at broadcast frequencies.

5. High voltage hazards at the base of the antenna are eliminated because the base of the tower is at ground potential.

The operation of the shunt-excited antenna is quite simple.

(Refer to Figure 15). If the inclined conductor is considered as a single wire transmission line its input impedance is a function of its resistance, characteristic impedance, electrical length, and the terminating impedance; the terminating impedance, of course, is represented by the antenna to which the inclined line is tapped. The impedance between the tapped point and ground is selected to match the impedance of the transmission line. The impedance across the coupling section of the antenna is considered to be the resultant impedance of sections a and b (Figure 15) in parallel. Due to its short length the impedance of section b is considered as pure reactance. By means of the inclined conductor and series capacity the impedance across the coupling section of the antenna is transformed to the characteristic impedance of the concentric transmission line.

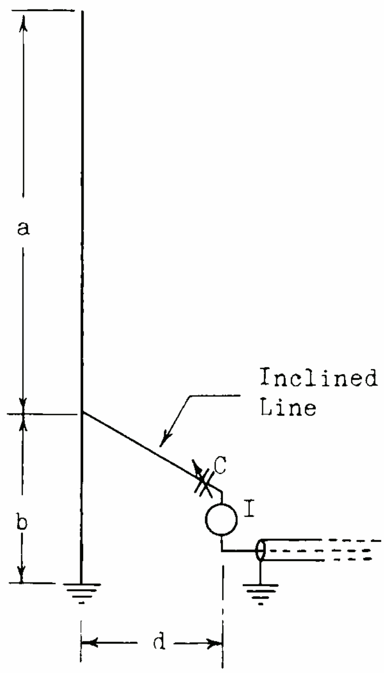


Fig. 15.

Concentric transmission lines as used in broadcasting usually have a surge impedance somewhat less than 100 ohms. In a typical antenna installation using such a line the impedance is matched with the inclined conductor at an angle of about 45 degrees with the sides of the triangle thus formed less than .035 λ long.

The impedance at the base of the inclined conductor (to match the impedance of the concentric line) may be adjusted to the desired value most easily by leaving dimension d (Figure 15) fixed and varying the height of the vertical coupling section of the antenna--that is, by moving the tap position up or down the antenna. This adjustment is not critical and a desired impedance can be obtained within very close limits.

The sign of the reactance at the base of the inclined conductor is always positive (inductive reactance) so that it is only necessary to use a series condenser to adjust the antenna impedance to unity power factor. This may be done by the use of an impedance bridge.

Inductive reactance as measured at the base of the inclined line without condenser C is matched by inserting in series with the line a condenser whose capacitive reactance at the operating frequency is equal to the inductive reactance as measured at the line input. In a similar manner by the use of the impedance bridge connected at the input of the inclined line the height b above ground of the top is adjusted until the measured impedance is equal to the impedance of the concentric transmission line.

The calculations to determine the proper amount of series capacity necessary to adjust the antenna impedance to unity power factor are not difficult. Consider a typical example. Assume that a transmitter having a normal carrier output of 5000 watts is coupled to an antenna by means of a concentric transmission line having a characteristic impedance Z_0 = 70 ohms. The frequency is 800 KC/s and by means of an impedance bridge it has been determined that the inductive reactance component of the inclined line at the base is 85 ohms. What capacity is required at C and at what current and voltage will the condenser be required to operate?

$$Z_0 = 70 \text{ ohms}$$

$$P = I^2R = 5000 \text{ W}$$

$$I = \sqrt{\frac{P}{R}} = \sqrt{\frac{5000}{70}} = \sqrt{71.4} = 8.4 \text{ amperes}$$

$$E_{line} = IZ = 8.4 \times 70 = 588 \text{ volts}$$

$$\text{Max } E_{line} = 588 \times 1.4 = 823 \text{ volts}$$

At 100 per cent modulation:

$$\text{Max } E_{line} = 823 \times 2 = 1646 \text{ volts}$$

At F = 800 KC/s

$$X_L = 85 \text{ ohms}$$

$$X_c = 85 \text{ ohms}$$

$$E_c = IX_c = 8.4 \times 85 = 714 \text{ volts}$$

$$E_{c\ max} = 714 \times 1.4 = 1000 \text{ volts}$$

At 100 per cent modulation:

$$E_{c\ max} = 2 \times 1000 = 2000 \text{ volts}$$

$$C = \frac{1}{2\pi f X_c} = \frac{1}{6.28 \times 8 \times 10^5 \times 85} = .00234\ \mu F.$$

The calculations above indicate that with normal carrier output of 5000 watts the voltage across the transmission line will be 823 volts maximum and increases to 1646 volts maximum at 100 per cent modulation. The series capacity required is .00234 µF and at 100 per cent modulation the peak voltage across the condenser will be 2000 volts. In practice this capacity could be made up of a .002 µF fixed condenser in parallel with a variable condenser having a maximum rating of about 500 µF. In view of the fact that the fixed condenser may be expected to have an error of calibration of up to 5 or 10 per cent, a considerable range of capacity variation should be provided in the variable condenser. It should be observed that the line current at the carrier is 8.4 amperes which at 100 per cent modulation will be increased by 22.5 per cent. About 85 per cent of this current must be carried by the fixed condenser so that it is essential in a selection of the fixed condenser that its rating be sufficiently high to permit it to operate continuously with current in excess of 8 amperes at 800 KC/s. The variable condenser must have sufficient spacing and insulation so that it will not flash over on the 2000 volt peaks.

The current distribution in the shunt-excited antenna is substantially the same above the tap as in the insulated base antenna over the same section but differs widely in the section below the tap where the current builds up to much larger values. (The voltage with respect to ground must, of course, go to zero at the base). Field strength measurements indicate no discernable difference in fading characteristics for a given antenna when shunt and series excited.

Calculations by Baudoux verify the measurements previously made and show that the radiation properties of the shunt-excited antenna are very nearly the same as those of an insulated base antenna having the same length and radiating at the same wavelength. These calculations further show, however, that in the case of antennas whose lengths are equal to or in excess of 1/2 wavelength the sky-wave radiation is to some extent a function of the tap point above ground. In both 180 degree and 198 degree antennas the sky-wave is less with the tap 1/4 of the antenna height above ground than with the tap 1/12 of the antenna height above ground. This fact appears to be of little value in practice, however, because the selection of tap height above ground is determined by the impedance necessary to match that of a concentric transmission line from the transmitter and a tap height 1/4 of the antenna height above ground would hardly be practical.

Figure 16 shows the current distribution in a typical uniform cross section vertical radiator with insulated base from measurements

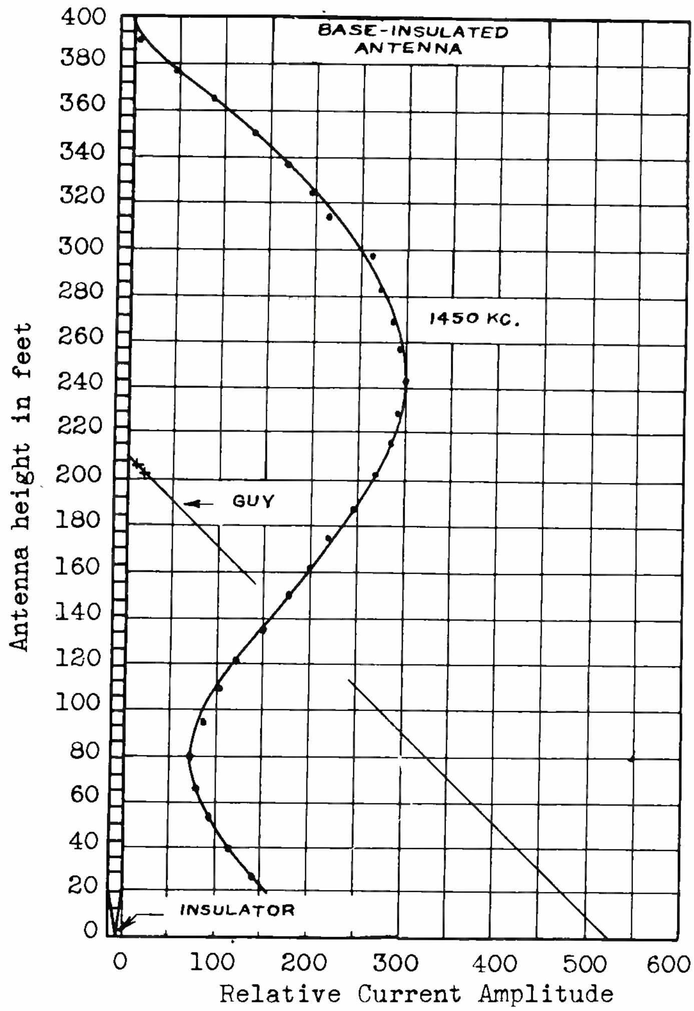


Fig. 16. Current distribution uniform cross-section vertical radiator

by Morrison and Smith. Figure 17 shows the measured current distribution on the same antenna shunt-excited with the base grounded. It should be noted in Figure 17 that at the lower frequency at which the tower forms an approximately .22 λ radiator the current distribution is substantially the same as in an insulated base antenna of similar length. At the higher frequency at which the tower height is in excess of 1/2 wavelength the current distribution above the tap is similar to that of an insulated base antenna; it reaches a

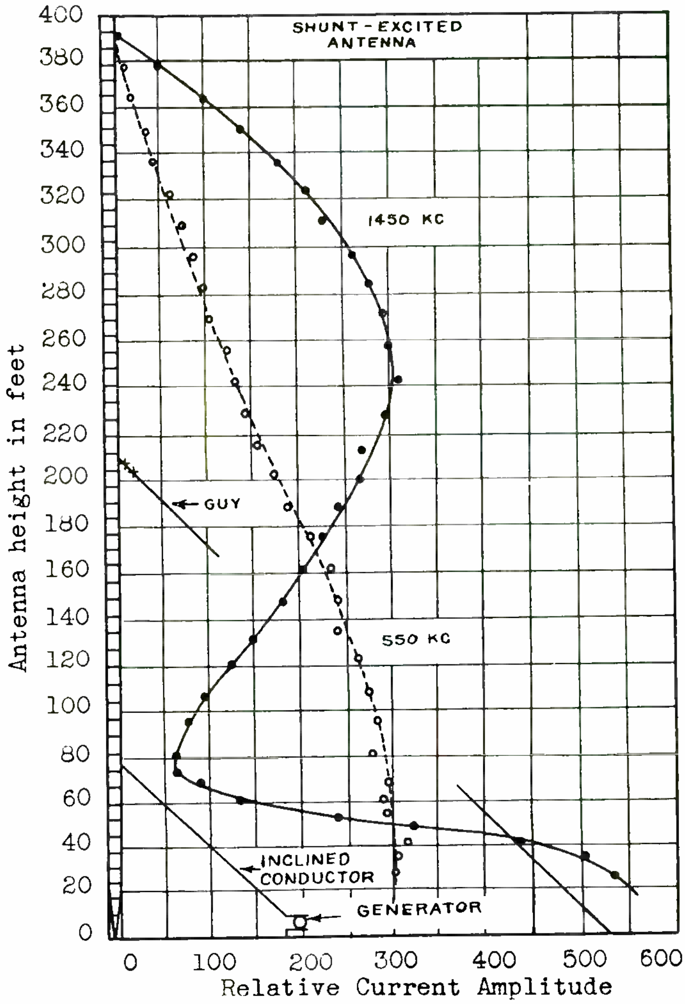


Fig. 17. Current distribution on the shunt-excited antenna.

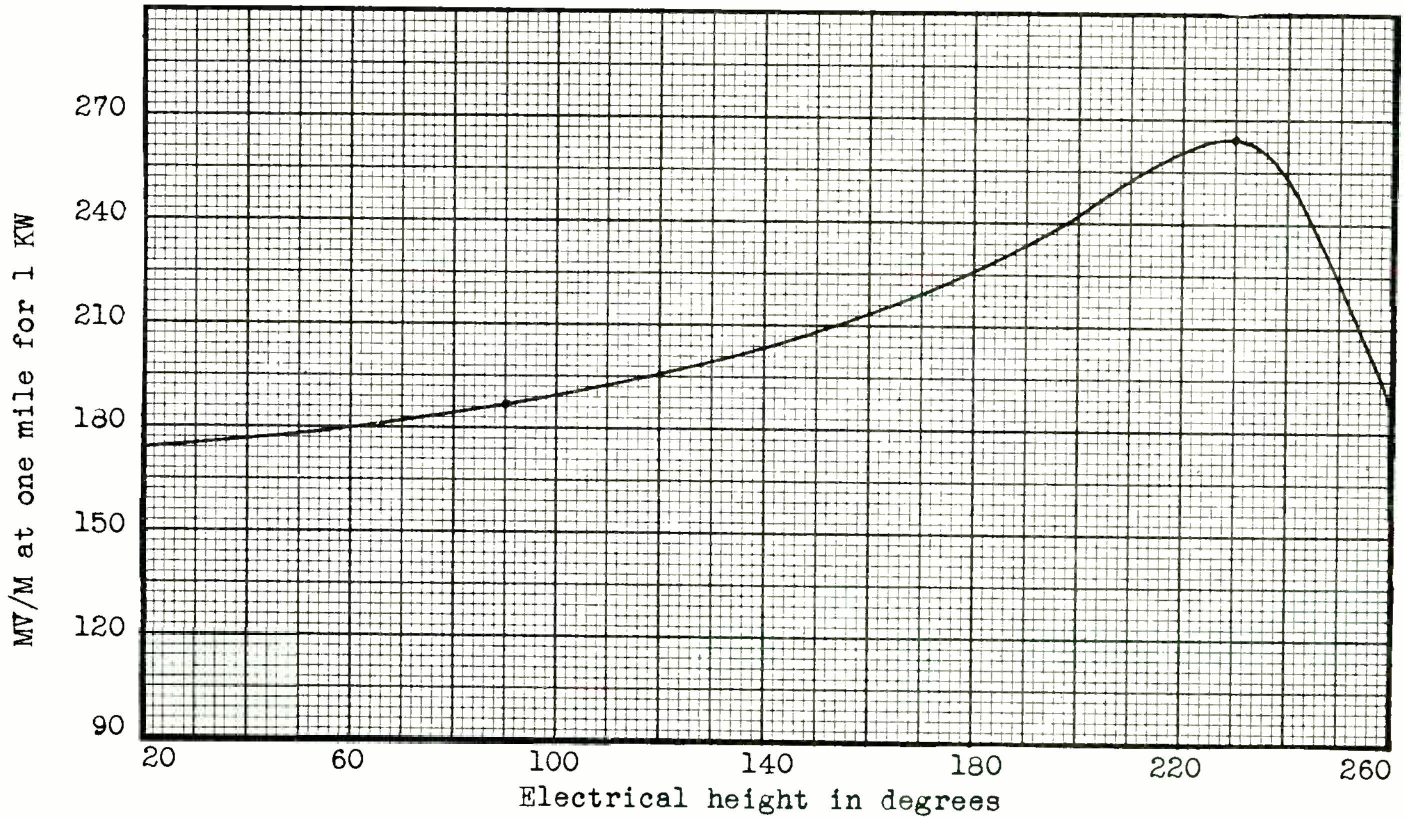
minimum at the tap point and in the section below the tap attains very large amplitude approaching ground. This is logical because the voltage on the antenna must reach zero at ground.

ANTENNA EFFICIENCY

The performance of a vertical broadcast antenna in actually giving service over a desired area, for a given power input, is a function of a number of factors as has been explained--height, shape, ground system, surrounding absorbing objects, and the attenuation factor due to the conductivity and inductivity of the surrounding earth. However, in computing the efficiency of the radiating system itself the factor of attenuation is not considered--or rather, from the actual measurements of field intensity which form the basis for calculating antenna efficiency, the factor of attenuation is removed and the "Effective Field" at one mile is derived from the measured field and the known (measured) attenuation factor.

As a basis on which to rate the efficiency of radiating systems the ideal radiator is taken as a standard. As shown by Ballantine, this is a vertical radiator 230° high, with sinusoidal current distribution, over a perfectly conducting earth. There is no known method of accurately measuring the vertical field distribution; therefore the radiation field at a given point in distance must be calculated from the known antenna characteristics and from this the power calculated through any differential area. This is then integrated through the entire area under consideration to give the total radiated power. By this means the "effective field" from the antenna at a given distance for a given radiated power is determined. These calculations are quite involved and are beyond the scope of this discussion. However, the theoretical calculations have been made and put in graphical form to cover the range of practical antenna heights.

Such a curve is shown in Figure 18 which includes antenna heights to about 240°. Two cardinal points on this curve are: at 90° where the calculated field intensity at one mile is 187 mv/meter and at 230° where the calculated field intensity at one mile is 265 mv/meter. This curve demonstrates that over a quite wide range on both sides of the 90° point (quarter wavelength) the curve is very nearly flat indicating that so far as field intensity is concerned the antenna height in this region is not at all critical. It also shows the fact, previously mentioned, that the field strength possible with optimum antenna height is 41 per cent greater than with a 90° antenna.



MV/M at one mile for 1 KW
270
240
210
180
150
120
90
20
60
100
140
180
220
260
Electrical height in degrees

Fig. 18,

The determination of antenna efficiency, as prescribed by the Federal Communications Commission, is based on the optimum figure of 265 mv/meter although this figure cannot be attained in practice. The antenna efficiency is given by the following equation

$$\text{Antenna Efficiency} = \frac{100\ F^2}{(265)^2\ P}$$

where F is the "effective field" and P is the power input *to the antenna* in kilowatts. By "effective field" is meant the R.M.S. value of *all* the field intensities at one mile from the antenna in the horizontal plane *without attenuation*.

The effective field is determined as follows: field strength measurements are made along a number of evenly spaced radials from the antenna--at least eight radials--starting not less than one wavelength or five times the vertical height in the case of a single element (non-directional) radiator or ten times the spacing between elements of a directional array. Along each radial measurements should be made at intervals of approximately one-tenth mile up to two miles from the antenna, at intervals of approximately one-half mile from two miles to six miles from the antenna, and at intervals of approximately two miles from six miles to fifteen or twenty miles from the antenna.

The data for each radial should be plotted, using log-log co-ordinate paper, plotting field intensities as ordinates and distance as abscissae. These data are then corrected for attenuation due to the earth (to be discussed later) and the "inverse field" calculated. By "inverse field" is meant the unattenuated field at one mile along any radial. This calculation of course, requires an accurate knowledge of the attenuation constant along that radial.

After determining the inverse field for each radial, the R.M.S. value of all these fields is determined, this being the effective field F in the equation above. Assume that F is found to be 372 mv/m and the power input to the antenna is 5 K.W. Then

$$\text{Antenna Efficiency} = \frac{100 \times 372^2}{265^2 \times 5} = 39.4 \text{ per cent}$$

ATTENUATION

In an early lesson discussing the phenomena of radiation it was stated that the intensity of the induction field around an antenna varies inversely as the square of the distance and that the radiation field from the antenna varies inversely as the first power of the distance. In practice, however, the problem is not as simple as this. It was shown that the field intensity pattern would be altered by any absorbing objects in the field surrounding the antenna. In practice the most important absorbing object in the field of the antenna is the earth itself. The earth over which the electromagnetic wave must travel causes attenuation of the field intensity which is in addition to that due to the inverse distance law. The actual attenuation of the electromagnetic field is a function of: first, distance; second, the conductivity of the earth itself; third, the inductivity of the earth; fourth, the curvature of the earth which at a distance produces a shadow effect.

Consider these factors briefly in the order as listed above. The effect of distance alone is quite simple. Over *long distances* the field intensity due to distance alone varies inversely as the distance.

The effect of the *conductivity* of the earth is very important. If the earth were a perfectly conducting surface the attenuation due to this cause would be zero and maximum field intensity at any given distance would be obtained. This is quite conclusively demonstrated by the long distances obtained in transmission over salt water with given power output as compared with transmission over average inland paths. The conductivity of sea water is many times greater than that of soil.

By *inductivity* of the earth is meant its specific inductive capacity, or in other words its dielectric constant. The higher the inductivity the more easily the electric field is established per cubic unit of soil and hence the lower the loss of energy due to this source.

The *curvature* of the earth produces an actual shadow effect which at a considerable distance in effect interposes a wall of absorbing material between the transmitting and receiving antennas. The effects of ground conductivity and inductivity will now be considered in greater detail.

Table 1 is taken from "Standards of Good Engineering Practice

Concerning Standard Broadcast Stations (550-1600 K.C.)" published by the Federal Communications Commission. It is useful in that it gives one an idea of typical values of earth inductivity and conductivity for various types of soil and terrain. The Federal Communications Commission also publishes a conductivity map showing average earth conductivity in different parts of the United States. It should be emphasized, however, that both the map and Table 1 simply give average or typical figures over large areas and are of little use in determining the attenuation properties of the earth within the primary area of a broadcast station. The figures given in Table 1 for inductivity show that this factor varies over a quite large range from three for city industrial areas where the so-called earth is made up largely of paved streets, brick buildings, etc., to the other extreme of 81 for sea water.

TABLE I

Type of terrain	Inductivity ε	Conductivity σ	*Absorption factor at 50 miles, 1000 Kc.
Sea water, minimum attenuation.	81	4.64×10^{-11}	1.0
Pastoral, low hills, rich soil, typical of Dallas, Texas; Lincoln, Nebraska and Wolf Point, Montana areas.	20	3×10^{-13}	0.50
Pastoral, low hills, rich soil, typical of Ohio and Illinois.	14	10^{-13}	0.17
Flat country, marshy, densely wooded, typical of La. near Mississippi River.	12	7.5×10^{-14}	0.13
Pastoral, medium hills, and forestation, typical of Md., Pa., N.Y. exclusive of mountainous territory and sea coasts.	13	6×10^{-14}	0.09
Pastoral, medium hills and forestation, heavy clay soil typical of central Va.	13	4×10^{-14}	0.05
Rocky soil, steep hills typical of New England.	14	2×10^{-14}	0.025

TABLE I (cont'd)

Type of terrain	Inductivity	Conductivity	*Absorption factor at 50 miles, 1000 Kc.
Sandy, dry, flat, typical of coastal country.	10	2×10^{-14}	0.024
City, industrial areas, average attenuation.	5	10^{-14}	0.011
City, industrial areas, maximum attenuation.	3	10^{-15}	0.003

* This figure is stated for comparison purposes in order to indicate at a glance which values of conductivity and inductivity represent the higher absorption. This figure is the ratio between field intensity obtained with the soil constants given and with no absorption.

It is interesting to note that recently several high power broadcast transmitters in sea coast cities have been moved to such locations that a large proportion of the distance between the transmitting antenna and the center of population is over salt water. A typical case is the re-location by the National Broadcasting Company of WEAF from Bellmore, Long Island to Port Washington, Long Island. From Bellmore the center of population of New York City was separated by a number of miles of dry, sandy soil of low conductivity. From Port Washington the radio path to Manhattan is over the salt water path of Long Island Sound. This greatly increases the efficiency of the transmitter in its primary service area.

As shown in Table 1, in the absence of measured values an inductivity figure of 14 or 15 would be an average value for most inland locations. Again it must be emphasized, however, that while such a figure might be a fair average over a long distance path it still could be quite erroneous over short distances particularly in an area surrounding a fairly large city where most broadcast transmitters are located.

UNITS

Before discussing the factor of conductivity it will be helpful first to discuss the units in which conductivity and inductivity are stated. We are all familiar with the English system of units based on the foot, pound and second. The metric system, however, is the one universally used by physicists and is now commonly used by engineers and is based on the centimeter, gram and second and hence is called the c.g.s. system. It should be noted that both systems are based on length, mass and time and that the unit of time in both systems is the second. Both systems cover a very wide range of units; in fact the units of all the types of measurement that can be made in all types of work ranging from measurement of the wave-length of light to the physical measurement of a ton of coal. We are interested here primarily in the electrical units and their relations.

There are three systems of electrical units; the c.g.s. electrostatic system commonly referred to as e.s.u.; the c.g.s. electromagnetic system referred to as e.m.u.; and the practical system.

In the c.g.s. electrostatic system the dielectric coefficient K (inductivity) of air at 0° Centigrade and 760 mm of mercury pressure is arbitrarily chosen as unity. For example, the inductivity of sea water of Table 1 would be referred to as 81, e.s.u.

In the c.g.s. electromagnetic system the magnetic permeability of air under the same standard conditions, as expressed in the preceding paragraph, is arbitrarily chosen as unity.

In the practical system the basic units are those conventionally used for resistance, current, and voltage; that is, the ohm, the ampere, and the volt respectively.

In order that electrical values may be expressed in terms that are immediately apparent but which will clearly indicate the system of unit used, the prefixes stat and ab are used in designating units of e.s.u. and e.m.u. respectively. For example, in the practical system the unit of capacity is the farad; in the electrostatic system the unit of capacity is the statfarad and in the electromagnetic system the unit of capacity is the abfarad. However, in practice, rather than use the somewhat awkward expression for the electromagnetic unit of capacity it is customary to refer to 1 abfarad as 1 e.m.u. In a similar manner in the electrostatic system 8×10^{18} statfarads might be written as 8×10^{18} e.s.u. These more simple designations clearly indicate that the value in question is expressed in electromagnetic or electrostatic units; the engineer, of course, knowing whether he is dealing with volts, amperes, coulombs, farads or whatever the values may be.

The relation between the electromagnetic and the electrostatic system is that

1 abfarad (e.m.u.) = 9 x 10^{20} statfarads (e.s.u.)

1 abcoulomb (e.m.u.) = 3 x 10^{10} statcoulombs (e.s.u.)

The fundamental relation between the c.g.s. electromagnetic system and the practical system is

1 abcoulomb (e.m.u.) = 10 coulombs (practical)

1 erg = 10^{-7} watt-seconds or joules.

The erg is the unit of energy in the c.g.s. electromagnetic system and the joule or watt-second is the unit of energy in the practical system. Also in the practical system one coulomb = 1 ampere-second.

Table 2 shows a comparison between units.

TABLE 2

Practical		e.m.u.		e.s.u.
1 ampere	=	.1 abampere	=	3 x 10^{9} statamperes
1 volt	=	10^{8} abvolts	=	1/300 statvolts
1 ohm	=	10^{9} abohms	=	1/9 x 10^{-11} statohms
1 coulomb	=	.1 abcoulomb	=	3 x 10^{9} statcoulombs
1 farad	=	10^{-9} abfarads	=	9 x 10^{11} statfarads
1 henry	=	10^{9} abhenries	=	1/9 x 10^{-11} stathenries

Particularly observe the very great difference between the amplitude of the units in the three systems. For example, 1 ohm = 10^{9} abohms = $1/(9 \times 10^{-11})$ statohms. It is apparent that one must clearly designate the unit in which a value is expressed if, in the range of calculations, more than one system of units are to be used. Two examples using values given in F.C.C. Table 1 for conductivity will be shown.

In Table 1 the conductivity of seawater is given as 4.64 x 10^{-11} e.m.u. (It should be stated at this point that in the c.g.s. system conductivity is expressed in terms of units/centimeter cube). Thus,

Conductivity = 4.64 x 10^{-11} e.m.u.

Transferring to mhos (practical units. See Table 2)

$$\text{Conductivity} = \frac{4.64 \times 10^{-11}}{10^{-9}} = 4.64 \times 10^{-2} = .0464 \text{ mho.}$$

$$\text{Resistance (R)} = \frac{1}{.0464} \mp 21.5 \text{ ohms/cm cube.}$$

In Table 1 the average conductivity for pastoral, medium hills and forestation, typical of Md., Pa., N. Y., exclusive of mountainous territory and sea coasts is given as 6×10^{-14} e.m.u.

Transferring to practical units,

$$\text{Conductivity} = \frac{.6 \times 10^{-14}}{10^{-9}} = 6 \times 10^{-5} \text{ mho.}$$

$$R = \frac{10^{5}}{6} = 17 \times 10^{3} \text{ ohms/cm cube.}$$

It is interesting to note the wide difference in conductivity or resistance between sea water and average soil. The calculations above show that the average resistance of sea water per cm cube is about 21.5 ohms, while for a typical average soil as taken from Table 1 the resistance may be approximately 17,000 ohms per cm cube. It may be of interest to point out at this time that assumed values are only approximations and that considerable difference in the magnitude of these approximations will be found in various authoritative sources. For example, based on Table 1 the resistance per cm cube of sea water is approximately 21.5 ohms per cm cube. Keen in his book "Wireless Direction Finding" lists as an average value for the resistance of sea water 10 ohms per cm cube. Other assumptions made by different authorities on measurements taken under different conditions may be expected to differ equally as much. This further emphasizes the fact that tabulated data, while helpful in arriving at typical or tentative values, must not be used as conclusive evidence of results to be expected in an actual installation.

Measurements and calculations of antenna fields, ground conductivity and inductivity are normally subject to certain quite large errors. It is often difficult to take field intensity measurements at locations sufficiently free from distorting influences (buildings, telephone and power wires, etc.). This is particularly true when measurements must be made within the area of a large city and in such cases every effort should be made to obtain authority to make the measurements in public parks, cemeteries, or other places where extraneous field distorting conditions will be at minimum. Also the conductivity and inductivity of soil will change with changes of weather, degrees of dampness, seasons, etc. To average out these variations measurements should be extended over a number of days and a large number of measurements taken. While such measurements can represent only average conditions, the greater the number of measurements taken the better should be the average accuracy. In this connection it should be remembered that the broadcast transmitter must deliver service under all types of conditions of weather and seasonal changes so that the transmitter performance really should be expressed in terms of average conditions.

MEASUREMENTS AND CALCULATIONS TO DETERMINE GROUND CONDUCTIVITY AND INDUCTIVITY

Over the years a number of empirical formulas have been developed for calculating the propagation of a radio wave. The most commonly used of these up until about 1930 was the Austin-Cohen formula. This formula was simple but was found to be inaccurate at considerable distances from the antenna, particularly at the higher frequencies and over poor soil. In 1909 Professor A. Sommerfeld published a paper on the attenuation of radio waves taking into consideration the conductivity and inductivity of the earth. The calculations involved were such as to render the formula of little practical use to the practicing engineer.

In March 1930 Bruno Rolf in a paper in the Proceedings of the Institute of Radio Engineers introduced confirmation of Sommerfeld's formula and devised a set of curves which reduced the formula to practical graphical form. The practical application of Rolf's graphs of Sommerfeld's formula to field strength measurements and attenuation calculation was further substantiated by K. A. Norton in a paper published in October, 1936 issue of the Proceedings of the I.R.E. Mr. Norton illustrated graphically the relation between ground field intensity and distance for three selected values of conductivity and inductivity over the frequency band of 150 KC/s to 5000 KC/s as compared with the graph for the inverse distance law without attenuation. Norton's graphs are based on Sommerfeld's formula corrected for earth curvature. (At broadcast frequencies the curvature of the earth is not important at distances less than about ten miles. At greater distances the correction factor must be employed). It has become recognized standard procedure to use these formulas and graphs in propagation problems.

Graphs or calculations involving conductivity and inductivity of the earth are used for three basic purposes:

1. To determine the average conductivity of the earth between a measuring point and a transmitter when the transmitter signal field intensity at one mile in that direction is known.

2. With a given signal intensity at one mile, to determine the signal to be expected at any distance from a proposed transmitter.

3. To determine the actual inverse signal--and hence the antenna efficiency--from a measured group of signals which include attenuation.

It is impossible within the scope of this discussion to present sufficient curves and graphs to completely solve problems involving conductivity and inductivity. The engineer desiring to do this work must have access to, by calculation or purchase, graphs with which to determine the attenuation constant over wide ranges of conditions encountered in practice. (The Engineering Handbook of the National Association of Broadcasters contains such curves and instructions for their use). The attenuation factor is a function of several variables--earth conductivity σ, the earth inductivity ε, and frequency. The relation between the various factors is not simple and there is no simple equation form in which the attenuation factor may be expressed. The basic equations are shown below:

If e is the field strength at a given distance from the antenna, then

$$e = \frac{\text{mv/meter at 1 mile}}{\text{d (miles)}} \times \text{attenuation factor} \times \text{earth curvature correction factor.}$$

At distances less than approximately 10 miles in the broadcast band of frequencies,

$$\text{mv/meter at 1 mile} = \frac{ed}{\text{attenuation factor}}$$

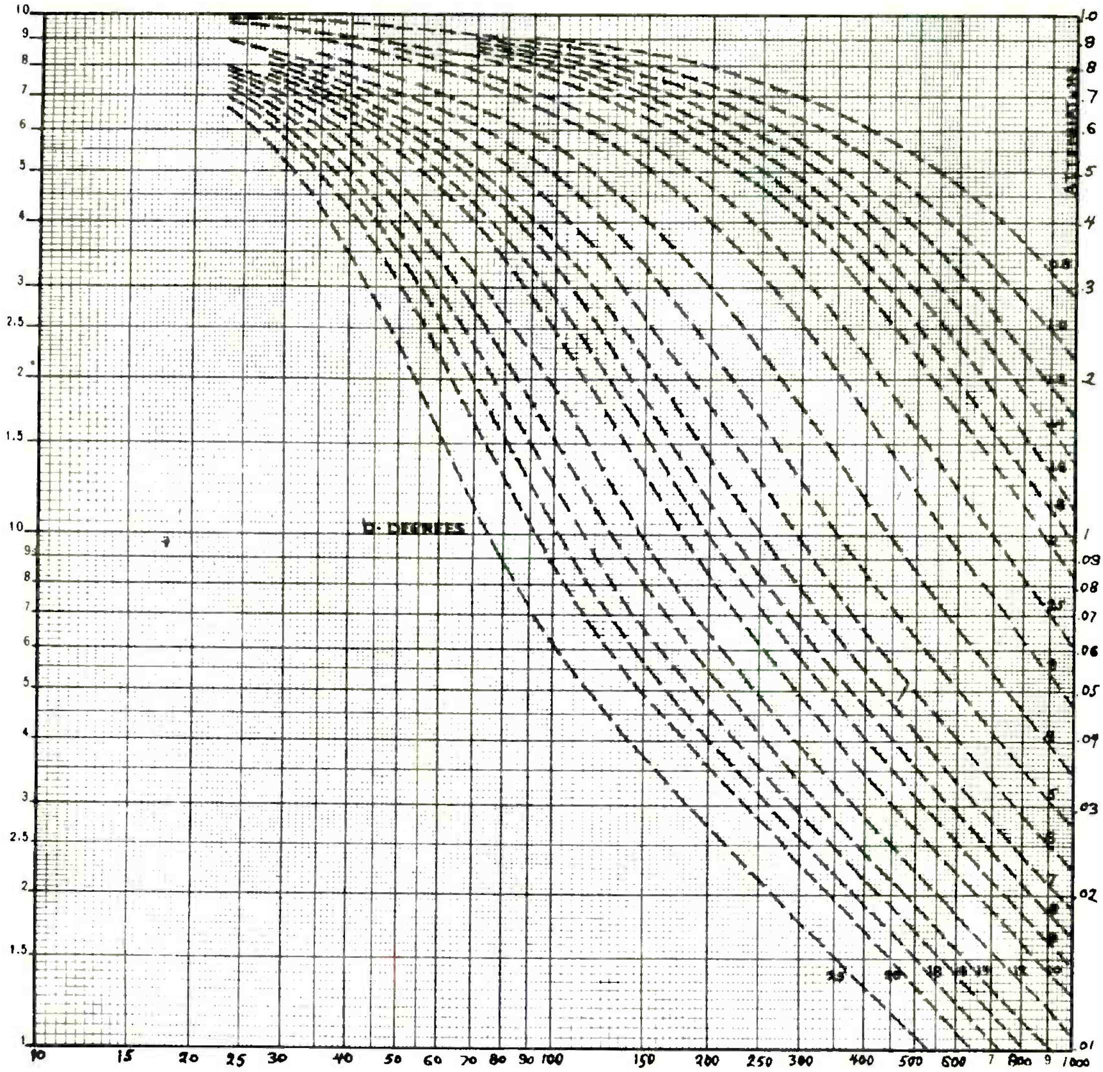
For the attenuation factor one must resort to curves.

Figure 19 shows a typical set of curves of "attenuation factor" vs. "distance in wavelengths" for $\varepsilon = 13$, the various curves being plotted for various values of "b". (A different set of curves will be required for each value of ε). b is determined as follows:

$$\text{Tan } b = \frac{\varepsilon + 1}{6\lambda\sigma 10^{15}}$$

Where

σ = conductivity, e.m.u.



Distance--wavelengths

Attenuation vs distance for various degrees of b. (From the Engineering Handbook of the National Association of Broadcasters.)

Fig. 19.

$\mathcal{E}$ = inductivity, e.s.u.

λ = wavelength in kilometers

1, 6 and 10^{15} are constants

$$b \text{ (degrees)} = \text{Tan}^{-1} \frac{\mathcal{E} + 1}{6\lambda\sigma 10^{15}}$$

For example:

Assume F = 1260 KC/s (= .238 Km)

$\sigma = 85 \times 10^{-15}$

$\mathcal{E} = 13$

$$\text{Tan } b = \frac{13 + 1}{6 \times .238 \times 85 \times 10^{-15} \times 10^{15}} = .115$$

$$b = \text{Tan}^{-1} .115 = 6^\circ 34'$$

If the measured signal at 1 mile is 225 mv/m, to determine the signal at 10 miles.

$$10 \text{ miles} = \frac{10}{.62137 \times .238} = 67\ \lambda$$

(.62137 is used in converting distance from miles to wavelengths. 1 Km = .62137 mile).

From the curves of Figure 19 it is found that at a distance of 67 wavelengths for b = $6^\circ 34'$ the attenuation factor is approximately .55. Neglecting the earth curvature correction factor which at this frequency and distance is found to be, from other curves, approximately .988, the signal at 10 miles is,

$$e = \frac{225}{10} \times .55 = 12.4 \text{ mv/m.}$$

Under the inverse distance law without attenuation the signal at 10 miles would have been 22.5 mv/m.

To show the effect of ground inductivity, assume that the ground conductivity is unchanged but $\mathcal{E}$ is increased from 13 to 20. Then

$$\text{Tan } b = \frac{20 + 1}{6 \times .238 \times 85 \times 10^{-15} \times 10^{15}} = .173$$

$$b = \text{Tan}^{-1} .173 = 9^\circ 49'$$

From another set of curves for $\mathcal{E}$ = 20, the attenuation factor is found to be .58 and the signal at 10 miles with the same 1 mile signal is

$$e = \frac{225}{10} \times .58 = 13 \text{ mv/m}$$

It will be noted that the increase in signal intensity due to increased inductivity from 13 to 20 is approximately 5 per cent. It should also be noted from Table 1 that increased inductivity is usually--*but not always*--accompanied by increased conductivity, so that the actual attenuation factor is a quite complex function.

It is important to use the earth curvature correction factor if the distance is more than a few miles. The correction factor is a function of both distance and frequency. For example, the curve of correction factor .98 extended over a frequency range of from 500 KC/s to 1700 KC/s extends over a distance of from 13.3 miles at 1700 KC/s to 20 miles at 500 KC/s. At 40 miles if F = 1450 KC/s, the correction factor is .91 while at 600 KC/s the correction factor is .94 for the same distance. Thus the effect of earth curvature increases with frequency.

It has been shown that the attenuation factor is a function of frequency, ground conductivity and ground inductivity. Thus for every different combination of F, σ, and ε a different curve of field intensity versus distance will result. The practicing engineer will require a number of such curves plotted from calculated data to cover the broadcast frequency range (for example, a curve for every 100 KC/s from 550 to 1600 KC/s), a separate set of such curves for numerous values of ε from 1 to 20 and for a number of values of σ over the range from 10^{-13} to 10^{-15} e.m.u., and of course a set of curves for sea water conditions. (A typical set of curves is shown in Figure 20 as published by the Federal Communications Commission).

Consider an actual problem. Assume that a transmitter has been installed and is operating at a frequency of 1000 KC/s. The power output is 1 KW. It is required to calculate the 1 mv/m field pattern and to do this it is necessary to know the ground characteristics in all directions from the antenna.

The first step is to take a series of measurements along a number of equally spaced radials around the antenna as previously explained under "Antenna Efficiency". From these measurements a separate curve for each radial should be plotted on log-log coordinate paper (see Figure 21). From Figure 21 it is seen that radial number

3 produced a curve based on approximately 20 measurements from less than .3 mile to 11 miles from the antenna.

After all the radial measurements have been taken and an individual curve is plotted for each radial as shown in Figure 21, the next step is to compare these curves with calculated data for earth conductivity and inductivity in order to determine the earth characteristic along each radial and the inverse field (unattenuated field at one mile) for each radial.

The calculations for each radial are a separate problem. Consider radial number 3 as shown in Figure 21. Estimate the ground inductivity and approximate conductivity from inspection of the plotted curve and select from the files the probable correct set of graphs, one of which is shown in Figure 20. From this set of graphs replot several of the curves for conductivity around the estimated range on log-log coordinate paper exactly as used for the radial curve of Figure 21. Such a set of plotted curves is shown in Figure 22. These curves are taken from the data of Figure 20 and converted to inverse signal of 1000 millivolts per meter instead of 100 millivolts per meter as shown on Figure 20.

The next step must be done very carefully. Place one sheet directly over the other and, keeping the sides coincident, slide one sheet up and down over the other in an attempt to match the measured curve of Figure 21 with one of the calculated curves of Figure 22. The student should actually perform this operation with the curves of Figures 21 and 22 which will enable him easily to see the solution.

The measured curve ordinarily will not match any calculated curve over its entire range, a discrepancy usually occurring in the range at short distances from the antenna. Thus the curves should be matched in the range of distances from about 3 to 7 miles. In this particular case it is found that a match is obtained between the measured curve and the calculated curve for $\sigma = 15 \times 10^{-14}$. This calculated curve has been plotted and drawn in dotted lines in Figure 21 over the measured curve.

With the curves coinciding, trace the inverse distance curve of Figure 22 onto Figure 21. It is seen that the inverse distance curve which is, of course a straight line, when drawn in on Figure 21 in-

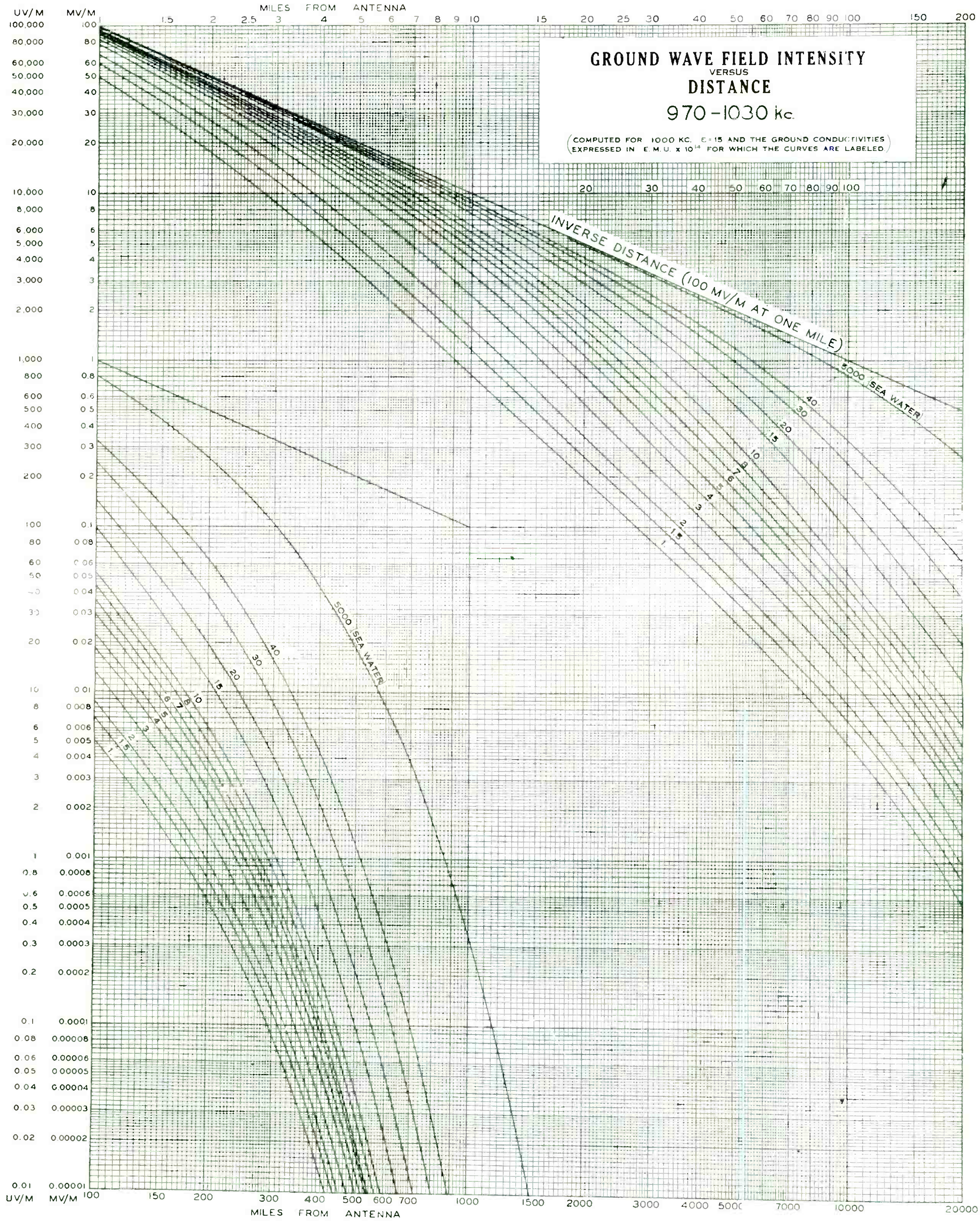

GROUND WAVE FIELD INTENSITY
VERSUS
DISTANCE
970-1030 kc.
(COMPUTED FOR 1000 KC. ε=15 AND THE GROUND CONDUCTIVITIES EXPRESSED IN E.M.U. x 10^14 FOR WHICH THE CURVES ARE LABELED)
MILES FROM ANTENNA
UV/M
MV/M
INVERSE DISTANCE (100 MV/M AT ONE MILE)
5000 (SEA WATER)
F.C.C.
MARCH-1938

Fig. 20.

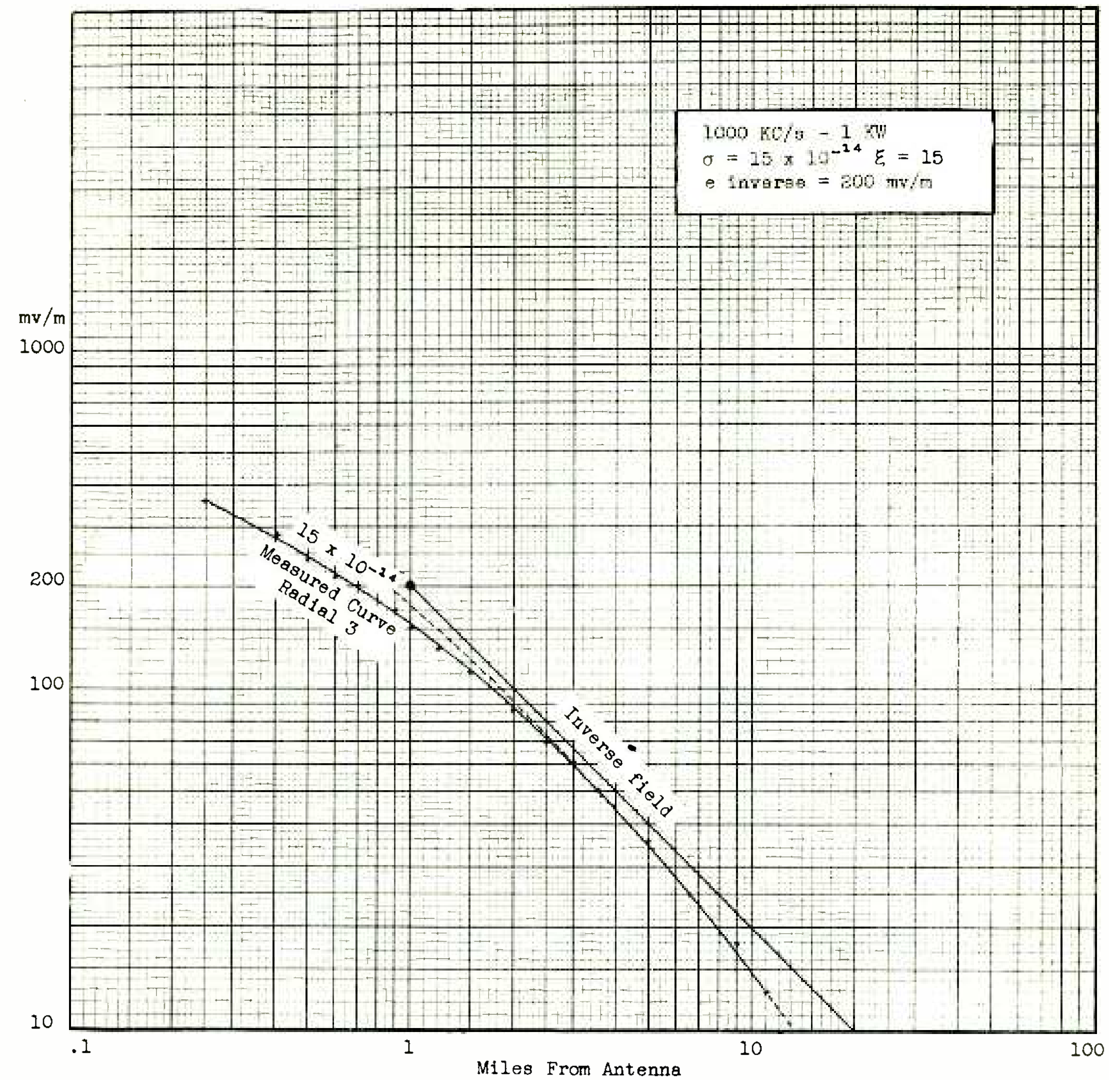
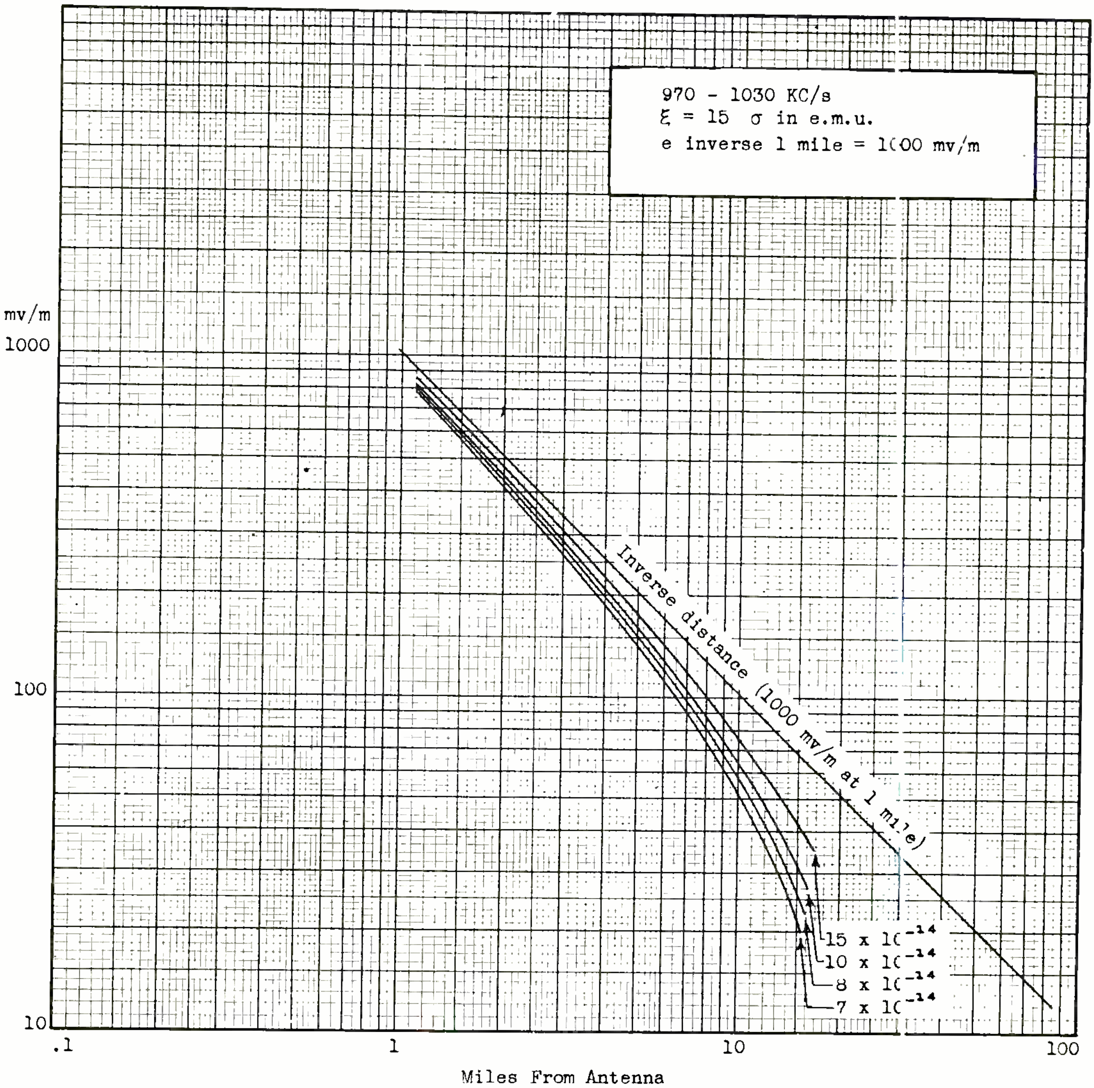

1000 KC/s - 1 KW
σ = 15 x 10^-14 ξ = 15
e inverse = 200 mv/m
mv/m
1000
200
100
10
.1
1
10
100
Miles From Antenna
15 x 10^-14
Measured Curve
Radial 3
Inverse field

Fig. 21.



970 - 1030 KC/s
ξ = 15 σ in e.m.u.
e inverse 1 mile = 1000 mv/m
mv/m
1000
100
10
.1
1
10
100
Miles From Antenna
Inverse distance (1000 mv/m at 1 mile)
15 x 10^-14
10 x 10^-14
8 x 10^-14
7 x 10^-14

Fig. 22.

tersects the 1 mile abscissa at the 200 millivolt per meter point. This is the inverse or unattenuated field for radial number 3.

From the preceding measurements and comparison of curves the following facts have been obtained: The ground inductivity along the direction of radial number 3 is 15; the conductivity is 15 x 10^{-14}; the unattenuated field at 1 mile from the antenna is 200 millivolts per meter. The above procedure seems quite simple and has been made especially so by drawing in a curve of assumed measurements that exactly coincides with one of the curves taken from data which is included in this discussion as typical of graphs which must be available to the engineer doing this type of work. In practice, of course, such an exact match is not always obtained and it may be necessary to plot in several sets of calculated curves before a close agreement is found. Although an exact match with a plotted curve may not be found, no difficulty should be encountered in obtaining a match which is sufficiently close for all practical purposes.

After this procedure has been followed with a measured curve for each radial, a set of curves similar to that of Figure 21 and equal in number to the radials will be on hand. If eight radials were used the engineer will know the average ground conductivity in eight equally spaced directions from the antenna and he will know the 1 mile unattenuated field in each of these directions.

As explained under "Antenna Efficiency" the RMS value of all the inverse fields will give the effective field to be used in calculation of antenna efficiency.

Knowing the inverse field at one mile and the ground characteristics in all directions from the antenna the engineer can, by means of calculations shown above, determine the actual field strength to be expected at any distance from the antenna along any radial. He may then extend the field intensity curve for each radial to any desired distance, for example to 50 or 60 miles. If he desires to find from this the ten millivolt contour he simply selects from his individual radial curves the ten millivolt points, accurately plots them on a map of the area surrounding his station and connects the points with a smooth curve.

A typical set of field intensity contours is shown in Figure 23 which is reproduced by courtesy of R.C.A. Review.

A most important use for ground conductivity and inductivity measurements is in predicting the performance of a broadcast transmitter in various sites prior to the final selection of the transmitter location. The early part of this lesson discussed a number of factors which must be taken into consideration in the selection of a location for a broadcast transmitter. Very important among those factors is the propagation characteristic in all directions from the proposed site. There are two ways in which the propagation characteristics, which depend mostly on the ground conductivity, may be determined. The first method is by means of a portable low power transmitter which can be set up in each of the several proposed locations and a group of measurements taken as explained above. From these measurements with the inverse field corrected to suit the type of antenna and power output of the transmitter to be used, the performance of the transmitter can be quite accurately predicted. (The approximate 1 K.W. inverse field for the type of antenna under consideration can be taken from Figure 18. For other than 1 K.W. power output, multiply that field by $\sqrt{P}$ as e varies as the square root of power output).

The second plan involves measurements on the attenuation of the fields of other broadcast transmitters in various directions from the proposed transmitter site instead of direct measurements on a low power portable transmitter. By this method measurements should be made along radials extending from the proposed transmitter site in the direction of the several broadcast transmitters whose field intensities are to be measured. The field intensity measurements along each radial should be plotted just as in Figure 21, and as explained for the use of curves in Figure 21 and 22 the ground conductivity along each radial is determined. With the proposed power output and type of antenna known the approximate inverse field can be determined by calculation. With the approximate inverse field and the ground conductivity along each radial known, the radial field intensity may be calculated and the field intensity contours plotted on a map.

It may seem that the above procedure in determining the performance of a broadcast station is quite complex. However, the entire problem is somewhat involved due to a number of reasons which have been explained and no simple means has yet been discovered to accurately determine or predict the performance of a broadcast station.

There are several sources of possible errors which must be considered in making a field intensity survey. Among the errors are: 1. Errors in determining the exact distance of the measuring

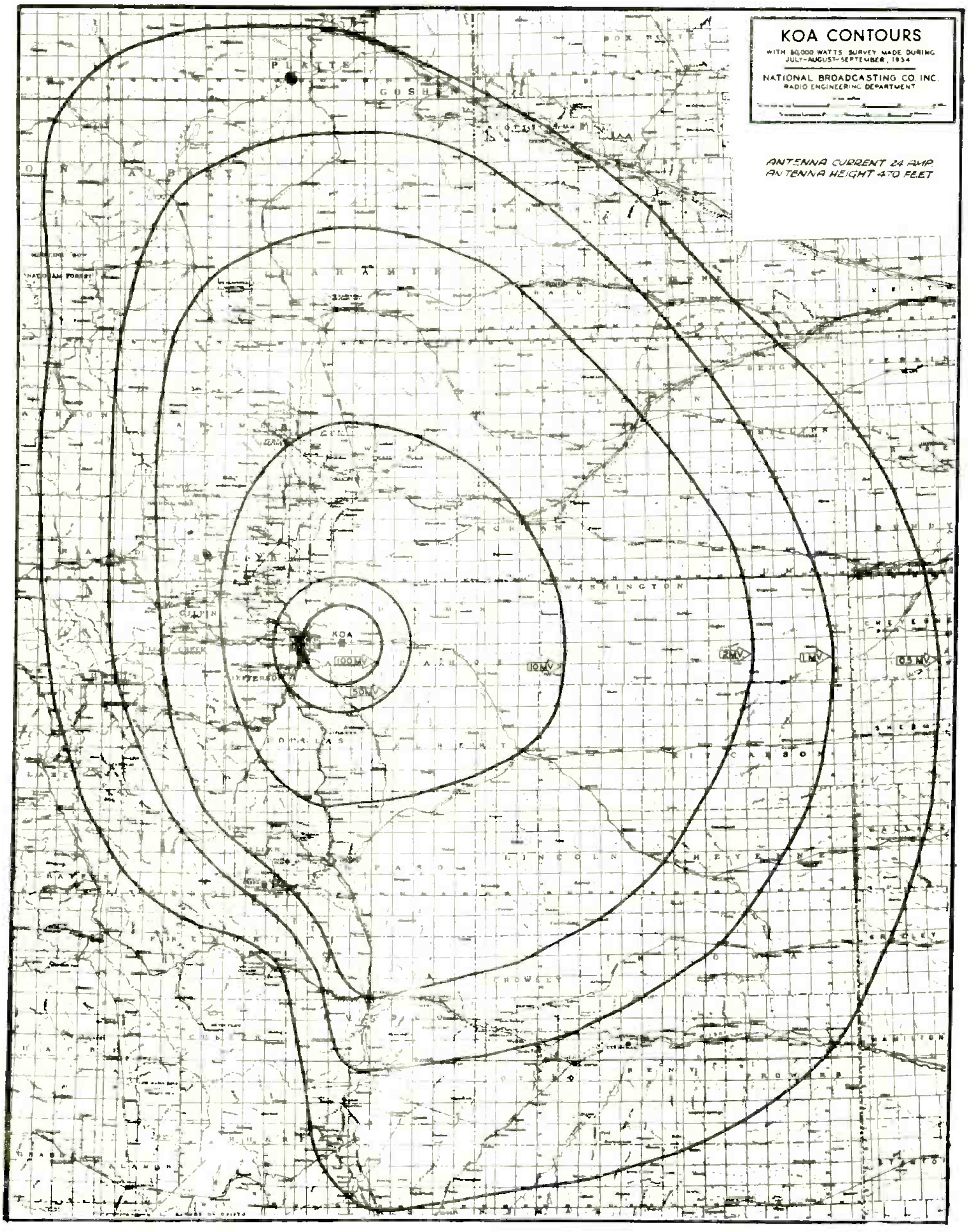


Fig. 23. Field-intensity contours of KOA.

point from the antenna. 2. The possibility that the value of signal intensity at that particular measuring point is not representative but is influenced by uneven terrain, proximity of overhead wires, and in some cases underground conductors. 3. Inherent inaccuracy of the field intensity meter plus the inaccuracy caused by the observer in the operation of the equipment. 4. Inaccuracies arising from an insufficient number of measurements about the antenna to show all the irregularities in the signal intensity that may occur in the different directions.

Each of these possible errors must be minimized if the results are to have any great value. Error 1 is minimized by the use of a large scale map which has been checked for accuracy and on which the distances from the antenna to the measuring point can be quite accurately determined. The second error is minimized as explained in an earlier section by selecting the measuring points that are as far as possible from all influencing objects. Experienced field engineers have had many unique experiences in attempting to locate and to get to suitable measuring sites. Such experiences involve taking cars and measuring equipment into muddy fields, etc. Error 3 is minimized by careful and regular checks on the calibration of the instruments and by having only thoroughly experienced engineers make the measurements. Error 4 is minimized by making a large number of measurements along a large number of radials.

The discussion involving the number of radials has stressed a minimum of eight. This number is probably sufficient where the transmitter is to be located in an inland city around which the terrain and soil are fairly uniform. However, in the case of a location involving radical changes of conductivity in the various directions, such as in the case of a high power transmitter located adjacent to a coastal city where part of the transmission is over salt water and where part may be over sandy soil of low conductivity, it is particularly important to take measurements over a sufficient number of radials and for sufficient distances that field intensity irregularities which may be large in amplitude but extend over only a few degrees will be shown on a contour map.

It should be emphasized that while the various procedures of measurements and calculations, as outlined in this lesson, are individually not too difficult, they do require that the engineer make use of high-grade accurate measuring equipment; that he have access to adequate and accurate data with which to interpret his measurements; that the engineer exercise a high degree of skill in the making of measurements and in the plotting of the many curves involved; and most important, that the engineer have a sufficient background of training and experience to accurately interpret and make use of the data obtained by measurement and calculation. This latter is particularly important in view of the many factors which must be taken into consideration in the selection of an antenna site, as explained earlier in this assignment, and which usually necessitate many compromises in the final solution of the problem at hand.

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<u>Illustrations used from above references.</u>

Figures 5, 6, 7, 8, 9. Reference 6.
Figures 14, 16, 17. Redrawn from illustrations in Reference 8.
Figures 11, 20. Reference 3.
Figure 19. Reference 9.
Figure 23. Reference 5.

DISCUSSION OF 8,9,10 of 314D

8. Field strength measurements are made at various distances along eight radials from a 250 watt broadcast transmitter operating on a frequency of 970 KC/s as follows:

Distance Miles	Field Strength Millivolts per Meter							
...	N	NE	E	SE	S	SW	W	NW
0.8	100	100	85	98	95	92	89	99
0.9	89	96	77	88	85	82	80	85
1.0	80	85	70	80	77	75	72	77
1.1	72	78	65	72	65	68	65	69
1.2	67	68	58	67	60	62	59	63
1.3	62	63	54	61	58	57	55	58
1.4	56	60	50	57	55	53	50	56
1.5	--	55	46	53	51	50	47	51
1.6	50	52	43	50	48	46	44	48
1.7	--	49	41	46	--	--	41	45
1.8	44	46	38	44	42	41	39	--
2.0	40	42	34	39	--	36	35	38
2.5	32	34	27	31	30	28	28	30
3.0	26	28	--	--	24	23	23	24
3.5	22	--	19	22	--	--	19	--
4.0	19	20	--	--	17.5	16	17	18
4.5	--	--	13.5	16	15	14.5	14	15
5.0	14.5	15	12	14	13.5	12.5	--	13
5.5	13.5	14	10.5	--	12	11	11	12
6.0	---	13	9.5	11.5	11	10	10	11
7.0	9.5	11	7.5	---	8.5	--	8.5	9
8.0	8.3	8.7	6.3	8	7.4	6.8	7.0	--
10.0	6.3	6.7	4.6	5.7	5.4	4.9	5.0	5.4
12.0	5.2	5.5	3.4	4.5	4.0	4.0	3.7	4.0
14.0	4.0	4.0	2.4	3.0	3.0	2.6	--	3.0
16.0	3.0	3.2	--	2.5	2.2	--	2.0	2.0

(a) What is the primary service area (within 10 MV/M contour) of the station?

The observed signal strengths in MV/M along each radial should be plotted as a function of the distance im miles, using log log paper in the manner suggested by Fig. 21 of the lesson. A smooth curve should be drawn through the best average cf the plotted points all of which do not lie exactly on the curve. One curve is drawn for each radial, using separate sheets of log log paper. Label the scales and curves clearly to avoid confusion.

8. (a) The distances along each radial to a field strength of 10 MV/M are read directly from the above mentioned curves of field strength as a function of distance.

Eight radials may be drawn from the center of an ordinary sheet of linear cross section paper at equal angles of 45° with respect to each other to simulate the radials that would be drawn from the transmitter site on a large scale map in actual practice. The radials may be numbered, or they may be labelled N, NE, E, etc. to indicate their actual direction from the transmitter. Distances are marked off on each radial in proportion to the distance from the transmitter to the 10 MV/M point along that radial, as read from the curves of measured field strength vs distance. A smooth curve is drawn through the points marked off on the radials and represents the 10 MV/M contour of the transmitter.

The area within the 10 MV/M contour may be measured with the aid of a planimeter if this instrument is available. The area may also be estimated to a close approximation by calculating the area of an equivalent circle whose radius is the root mean square of the distance along the radials from the station to the 10 MV/M contour:

A third or graphical method involves division of the area into parallel vertical strips, the strips being terminated at top and bottom by horizontal lines positioned by eye to give an area in the resulting rectangles equal to the area of the strips if they were terminated by the contour. This procedure facilitates computation of the area within the contour.

(b) Assuming that ground inductivity is approximately 14, what is the average ground conductivity along each radial?

Curves showing the calculated field strength as a function of distance and ground conductivity, for various values of ground inductivity and frequency are available in the N.A.B. Handbook and in other sources such as the F.C.C. curves of Fig. 20 of the lesson. Fig. 20 shows the field intensity at various distances and ground conductivities for frequencies between 970 and 1030 KC/s when the ground inductivity is 15.

As pointed out in the lesson (Page 39) the field intensity is only slightly affected by variations in ground inductivity within reasonable limits. The curves of Fig. 20 will therefore be used to illustrate the solution of the present example, although it should be understood that, in actual practice, curves for various inductivities will be available and the inductivity as well as the conductivity can be found from the curves.

The computed curves of Fig. 20 are replotted on log log paper of the same type as was used in plotting the measured field intensity along the radials. If exactly the same type of cross-section paper is employed for plotting the radials as appears in Figure 21 of the lesson then the replotted curves will be identical with Figure 22 of the lesson and the Figure 22 may be used in performing the following operation to find the ground conductivity.

The sheet on which the measured intensity along one radial is plotted should be placed over the sheet on which the computed curves are plotted. The sheets are held up to the light and the upper sheet is moved in a vertical direction over the lower until a point is reached where the measured curve most nearly coincides with one of the computed curves over the critical range of 3 to 7 miles of distance. Especial care must be taken to keep the distance scales coincident while one sheet is being moved vertically with respect to the other as no lateral movement is permissible. When the computed curve is found which provides the best match with the measured curve, the ground conductivity is read from the label of the computed curve. At the same time the intersection of the inverse distance line with the 1 mile distance line is noted and the unattenuated field at one mile is read from the field strength scale on the upper sheet.

9. (a) What is the unattenuated field intensity at one mile along each radial, expressed in Millivolts/Kilowatt/Meter?

Since field strength varies as the square root of the power in the antenna, if the power is increased from 250 to 1000 watts or 4 times the field strength will be increased by $\sqrt{4}$ or two times.

(b) What is the antenna efficiency?

The effective inverse field at one mile may be found by plotting a pattern on polar coordinate paper of the intensity of the inverse field at one mile along all the radials, from the data in Question No. 3. The radius of a circle, the area of which is equal to the area bounded by the pattern, will indicate the effective field.

The effective field may also be found to a close approximation by calculating the root mean square of the inverse fields along all the radials:

10. The following values are taken from the curve for the earth curvature correction factor at 1000 KC/s:

Miles	Correction Factor
16	.98
26	.96
34.5	.94
42	.92
49	.90

Calculate and show the position of the 50, 10, 2, 1, and .5 MV/M contours:

The distances along each radial to the 50 and 10 MV/M contours may be read directly from the curves of the measured field strength along each radial as in problem No. 1.

Lacking actual measurements of field intensities at greater distance than 16 miles, the distance to the contours may be calculated on the assumption that the average conductivity along each radial beyond 16 miles from the station will be approximately that noted along the same radial in the vicinity of the station. The attenuation depends upon the distance and the phase of constant b. The parameter b is a function of the frequency, the ground conductivity and the ground inductivity:

$$\text{Tan } b = \frac{E_r + 1}{6\lambda \, \sigma \, 10^{18}}$$

E_r is ground inductivity, e.s.u.
σ is ground inductivity, e.m.
λ is wavelength in kilometers

For example, along the North radial the conductivity is 15×10^{-14} e.m.u. and the inductivity is taken as 14. The wavelength corresponding to a frequency of 970 KC/s is 309.3 meters, or .3093 km. Thus:

$$\text{Tan } b = \frac{14 + 1}{6 \times .3093 \times 15 \times 10^{-14} \times 10^{18}} = \frac{15}{1.856 \times 150} = .0539$$

$$b = 3.1^{\circ}$$

The value of b may be similarly calculated for other radials and the results tabulated for further use.

The value of the attenuation factor is read from the curves of Fig. 19 for inductivity of 13, using the parameter b and the distance in wavelengths as arguments.

$$\text{Distance in wavelengths} = \frac{d_{miles}}{.62137\lambda_{km}} = \frac{d_{miles}}{.62137 \times .3093}$$
$$= 5.203\ d_{miles}$$

For example, to find the attenuation factor at 30 miles where $b = 3.1^{o}$.

Distance in wavelengths = 5.203 x 30 = 156.1 λ

From 156λ on the Distance scale move vertically to the point for $b = 3.1^{o}$ which is found by interpolating between the $b = 3^{o}$ and $b = 4^{o}$ curves. Then move horizontally to the right and read attenuation factor on the vertical scale as .49. The factor at other values of distance and of parameter b is found in similar manner:

Distance Miles	λ	Attenuation Factor $b = 3.1^{o}$	$b = 4.6^{o}$	$b = 5.8^{o}$
20	104	.61	.5	.44
30	156	.48	.35	.26
40	208	.375	.24	.175
50	260	.29	.175	.125

The earth curvature correction factor at the various distances may be found by plotting the given points and drawing a smooth curve through them.

The field strength along each radial is then computed by the use of the formula:

$$e = \frac{\text{mv/meter at 1 mile}}{d_{miles}} \times \text{attenuation factor} \times \text{earth curvature correction factor.}$$

Field strength versus distance may be plotted for each of the above radials. A smooth curve is drawn through the plotted points and the distances to the 2. 1. and .5 MV contours can be read off the curves.

BROADCAST ANTENNA SYSTEMS PART I

EXAMINATION

1. What factors must be considered in the selection of a suitable location for a broadcast transmitter? Explain.

2. (a) What is meant by "Mode of Operation" of a broadcast antenna?

   (b) How is the height of a tower radiator usually expressed?

3. (a) Describe a suitable antenna and ground system for use with a 250 watt transmitter.

   (b) What changes in the system, if any, would be indicated if the power were to be increased to 50 KW?

4. (a) What is meant by ground inductivity? Ground conductivity? How do these ground characteristics effect the signal strength at any given distance from the antenna?

   (b) What is meant by the "Inverse Field" of a transmitting antenna?

5. Upon what basis is the efficiency of a broadcast transmitting antenna rated? Explain.

6. What precautions must be observed in making field strength measurements? Explain.

7. A .582 λ radiator having a height of 498 feet employs shunt excitation. The impedance at the base of the inclined line is measured on a bridge and found to be 80 + j100 ohms. What value of series capacity should be used at the base of the inclined line to properly terminate a concentric transmission line having a surge impedance of 80 ohms?

8. Field strength measurements are made at various distances along eight radials from a 250 watt broadcast transmitter operating on a frequency of 970 KC/s as given in Table 1:

   (a) What is the primary service area (within 10MV/M contour) of the station?

   (b) Assuming that ground inductivity is approximately 14, what is the average ground conductivity along each radial?

TABLE I

Distance Miles	Field Strength Millivolts per Meter							
	N	NE	E	SE	S	SW	W	NW
0.8	100	100	85	98	95	92	98	99
0.9	89	96	77	88	85	82	80	85
1.0	80	85	70	80	77	75	72	77
1.1	72	78	65	72	65	68	65	69
1.2	67	68	58	67	60	62	59	63
1.3	62	63	54	61	58	57	55	58
1.4	56	60	50	57	55	53	50	56
1.5	--	55	46	53	51	50	47	51
1.6	50	52	43	50	48	46	44	48
1.7	--	49	41	46	--	--	41	45
1.8	44	46	38	44	42	41	39	--
2.0	40	42	34	39	--	36	35	38
2.5	32	34	27	31	30	28	28	30
3.0	26	28	--	--	24	23	23	24
3.5	22	--	19	22	--	--	19	--
4.0	19	20	--	--	17.5	16	17	18
4.5	--	--	13.5	16	15	14.5	14	15
5.0	14.5	15	12	14	13.5	12.5	--	13
5.5	13.5	14	10.5	--	12	11	11	12
6.0	--	13	9.5	11.5	11	10	10	11
7.0	9.5	11	7.5	--	8.5	--	8.5	9
8.0	8.3	8.7	6.3	8	7.4	6.8	7.0	--
10.0	6.3	6.7	4.6	5.7	5.4	4.9	5.0	5.4
12.0	5.2	5.5	3.4	4.5	4.0	4.0	3.7	4.0
14.0	4.0	4.0	2.4	3.0	3.0	2.6	--	3.0
16.0	3.0	3.2	--	2.5	2.2	--	2.0	2.0

9. (a) Reference Problem 8. What is the unattenuated field intensity at one mile along each radial, expressed in millivolts per kilowatt per meter?

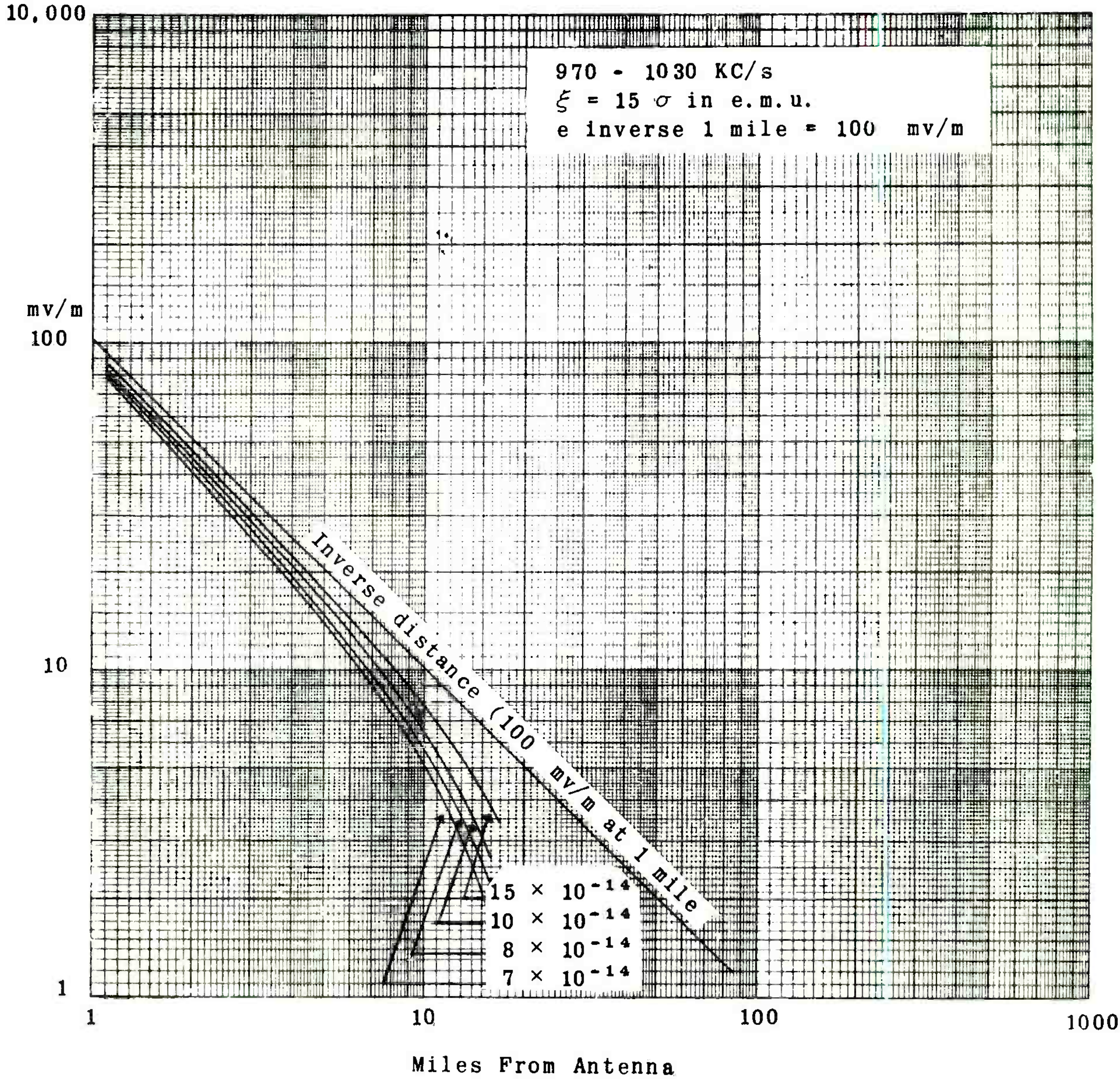
(b) What is the efficiency of the radiator?

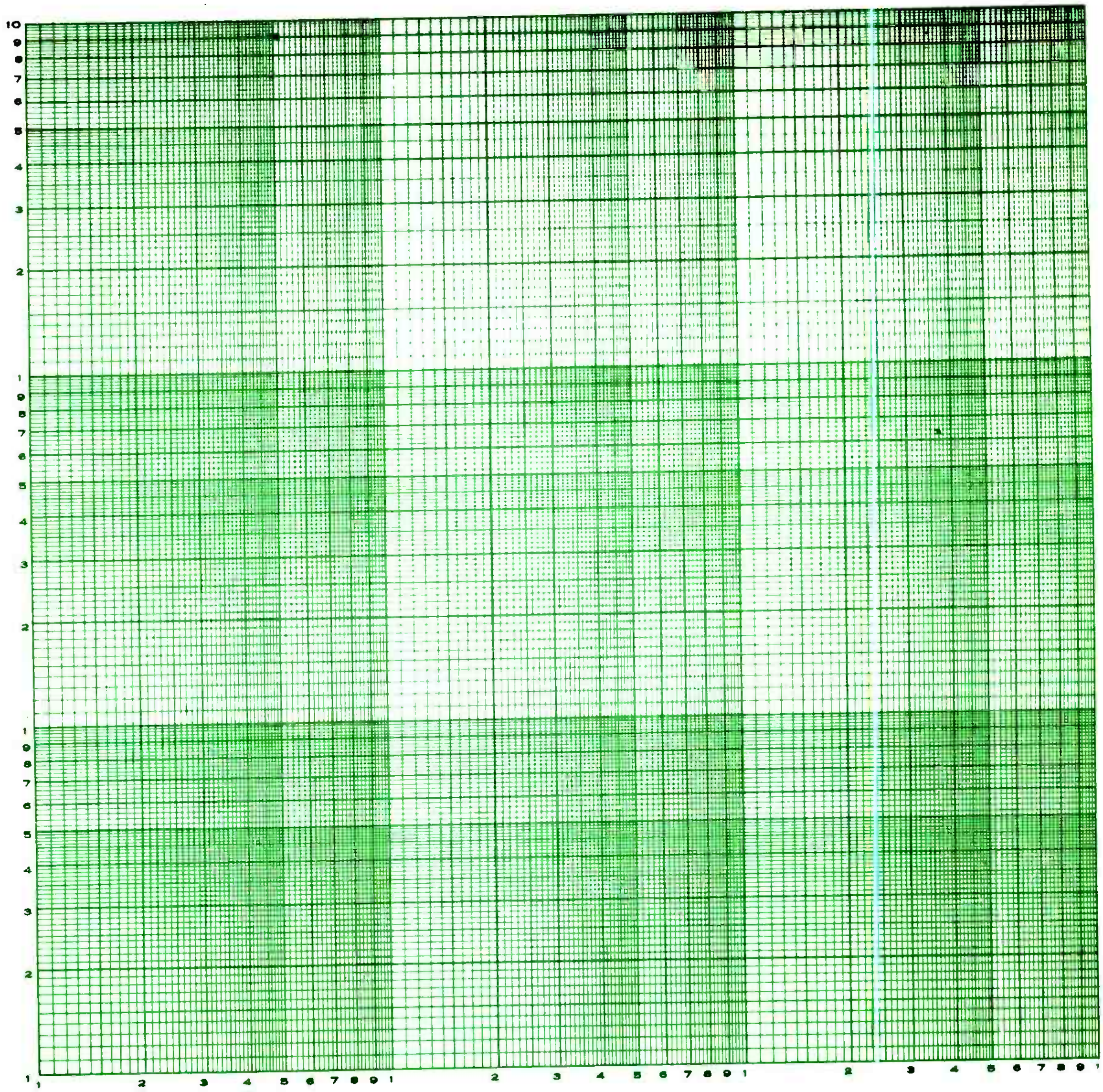
10. The following values are taken from the curves for the earth curvature correction factor at 1000 KC/s.

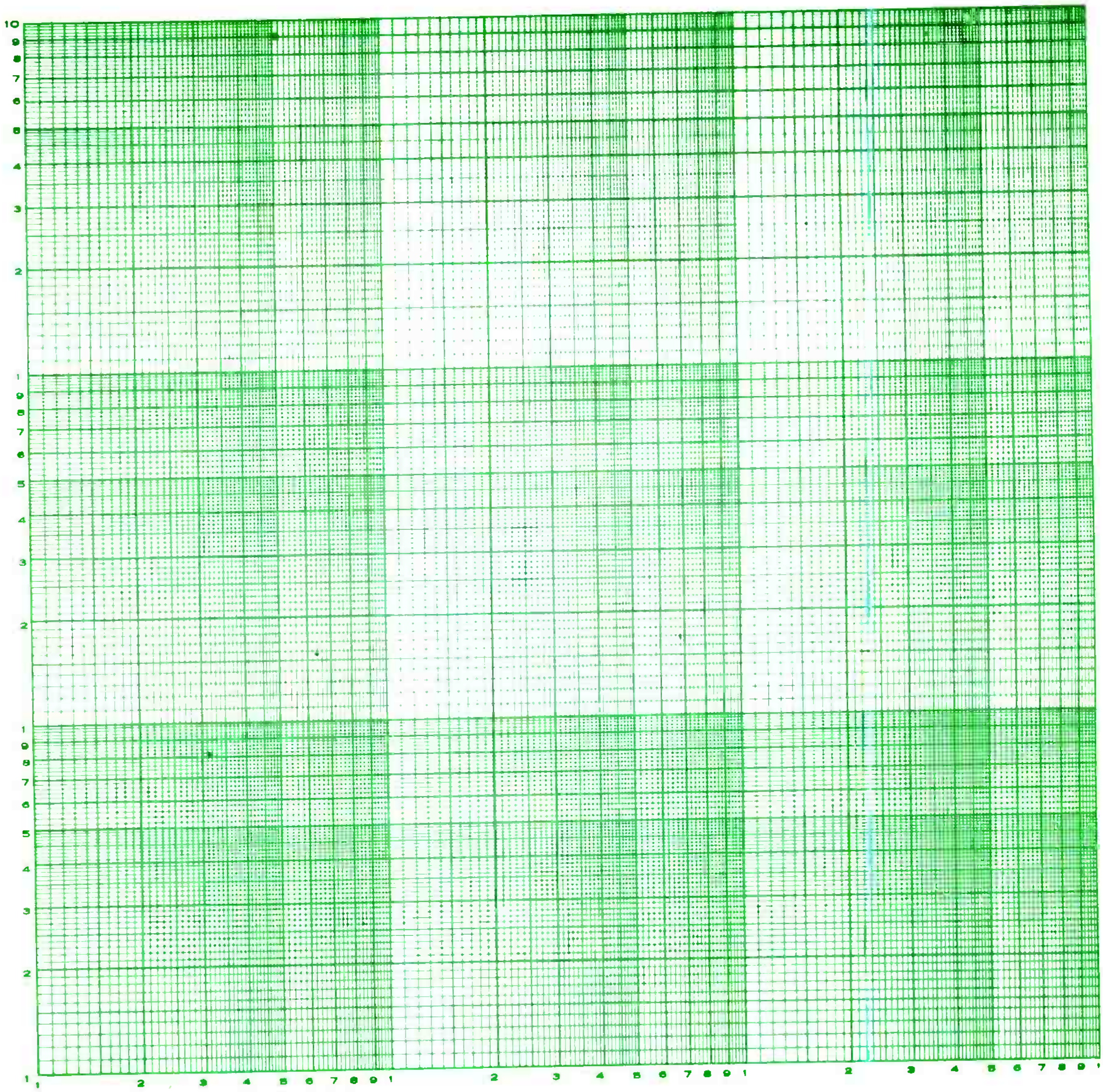
Miles	E.C.C. Factor
16	.98
26	.96
34.5	.94
42	.92
49	.90

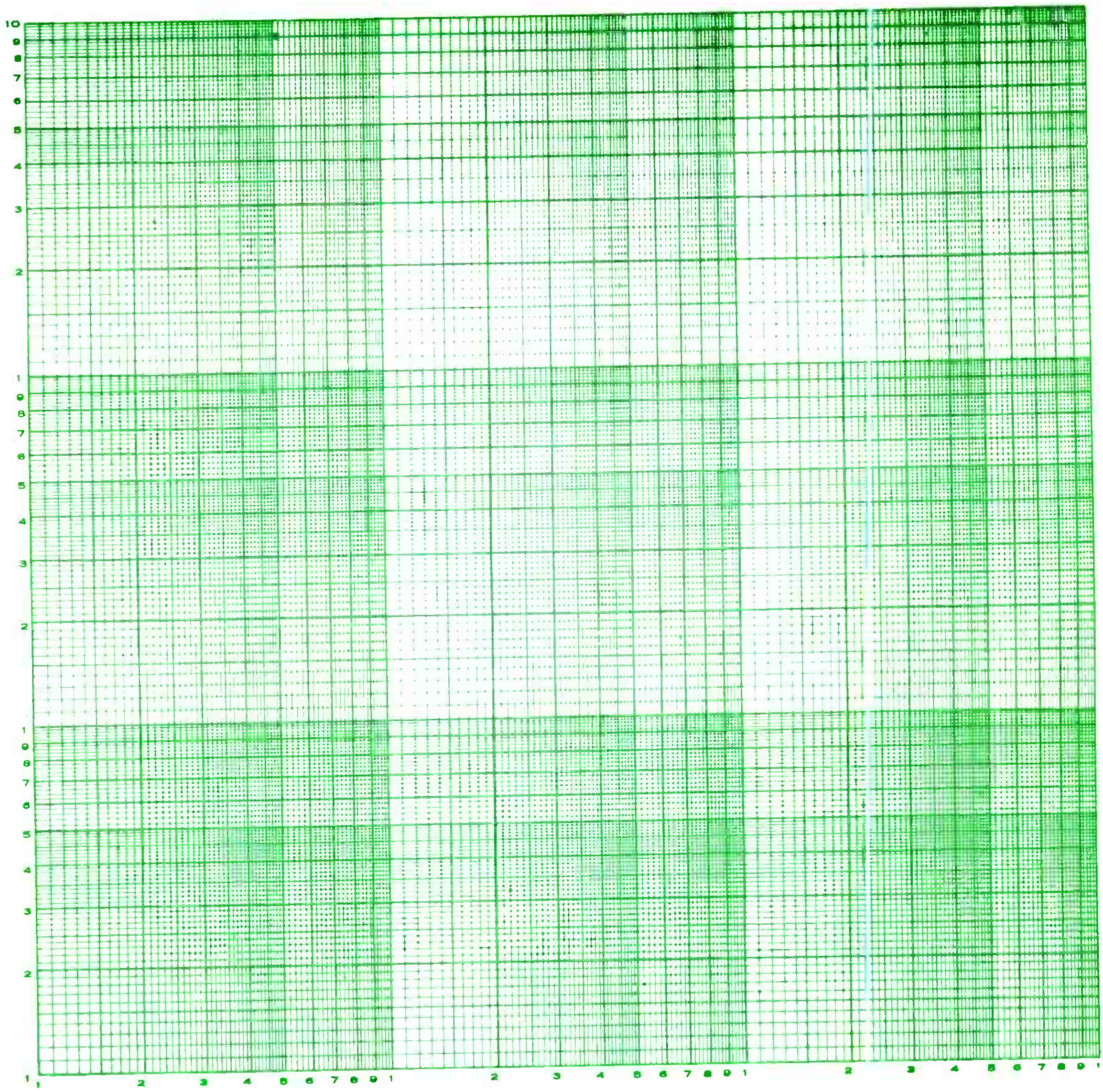
Calculate and show the position of the 50, 10, 2, 1, and .5 MV/M contours.

EXAMINATION, page 5





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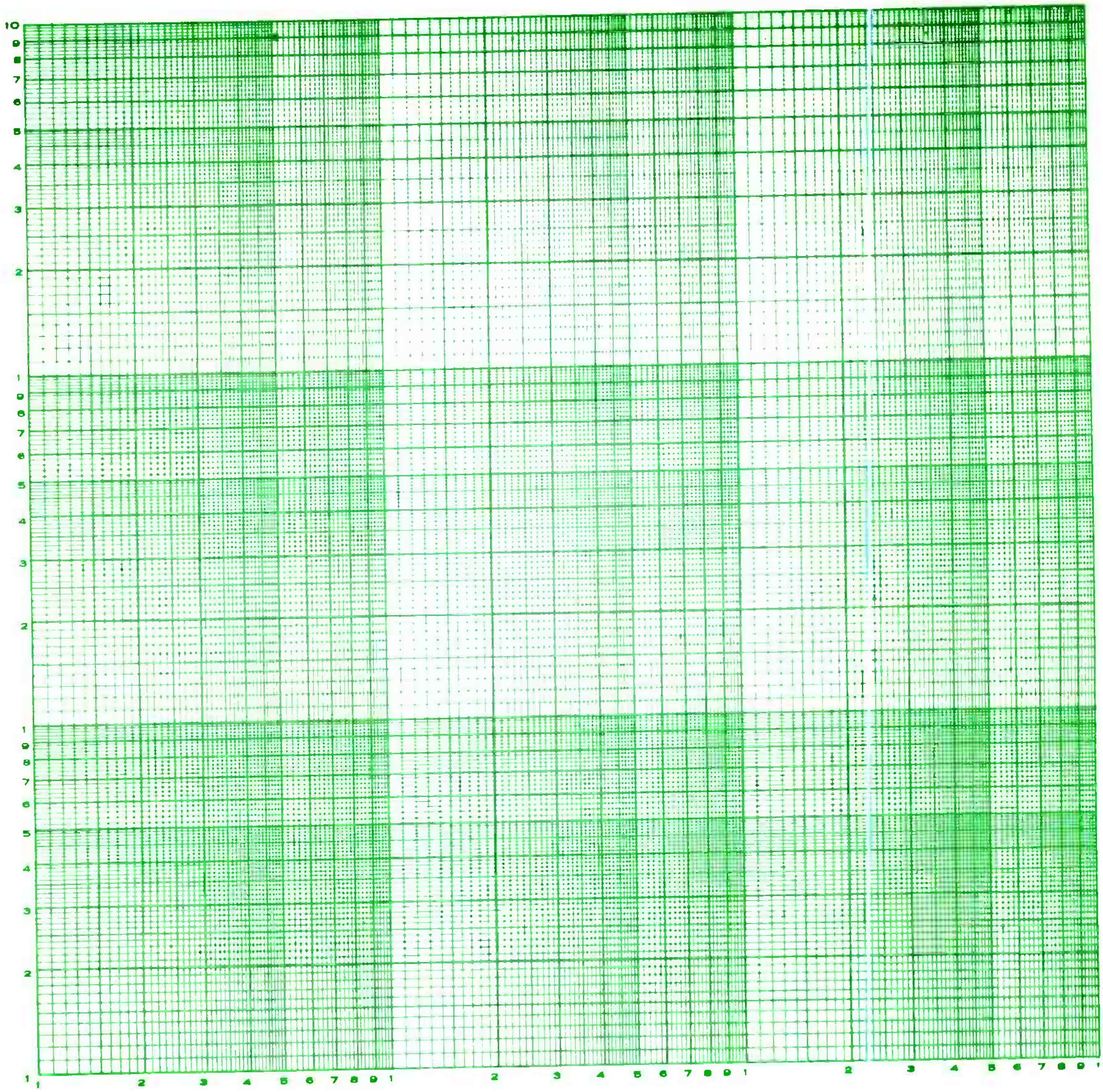

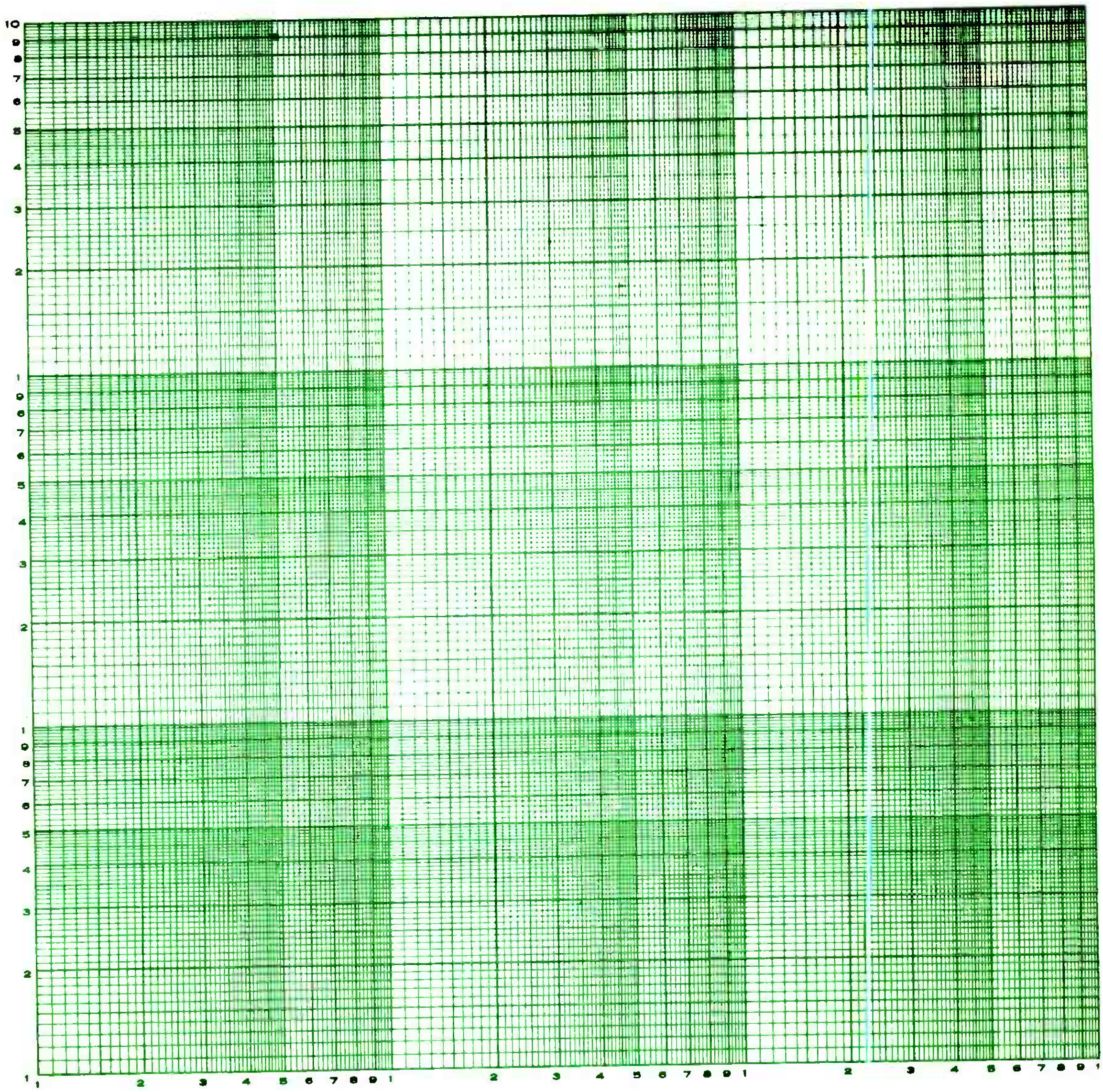
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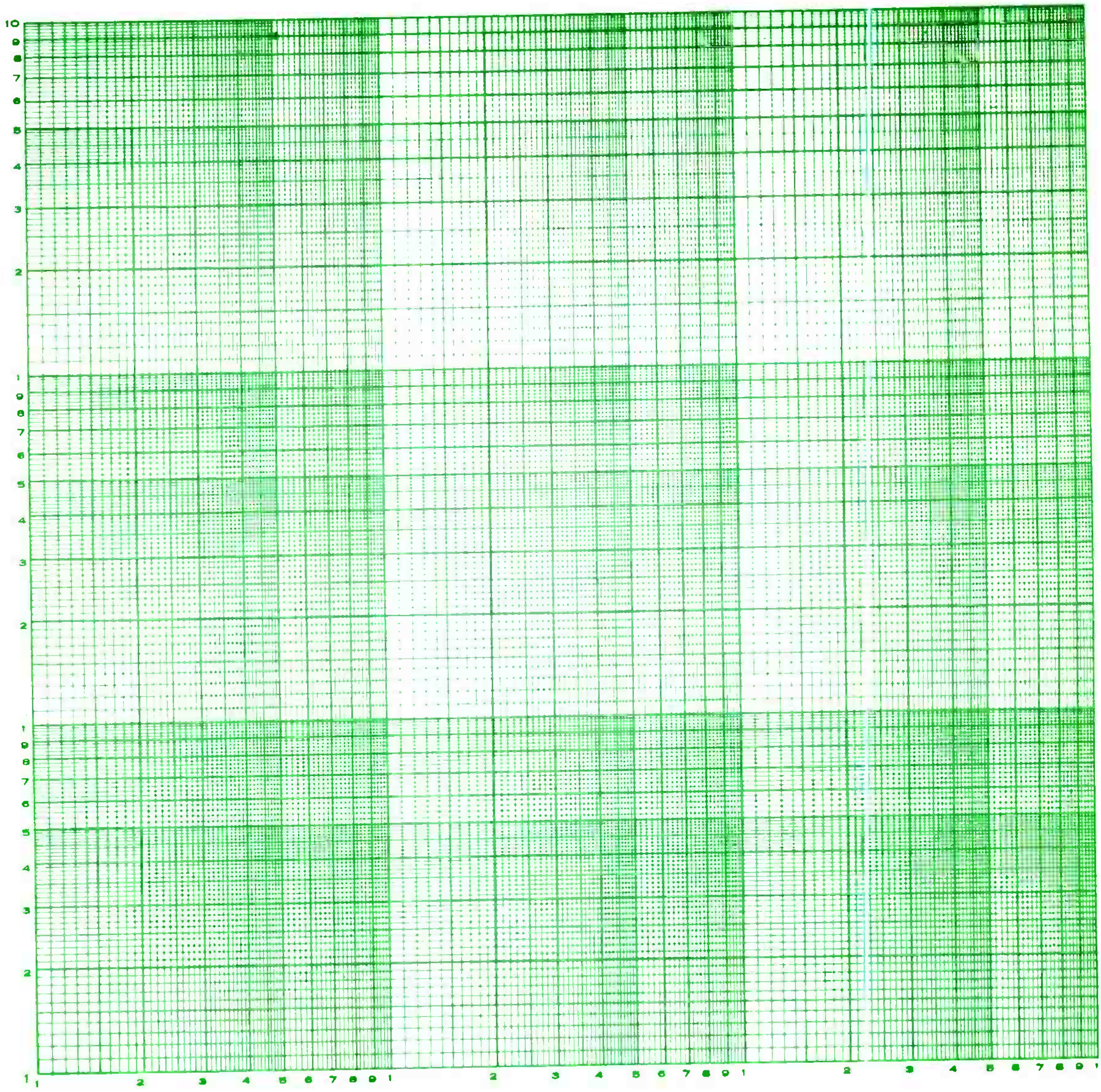

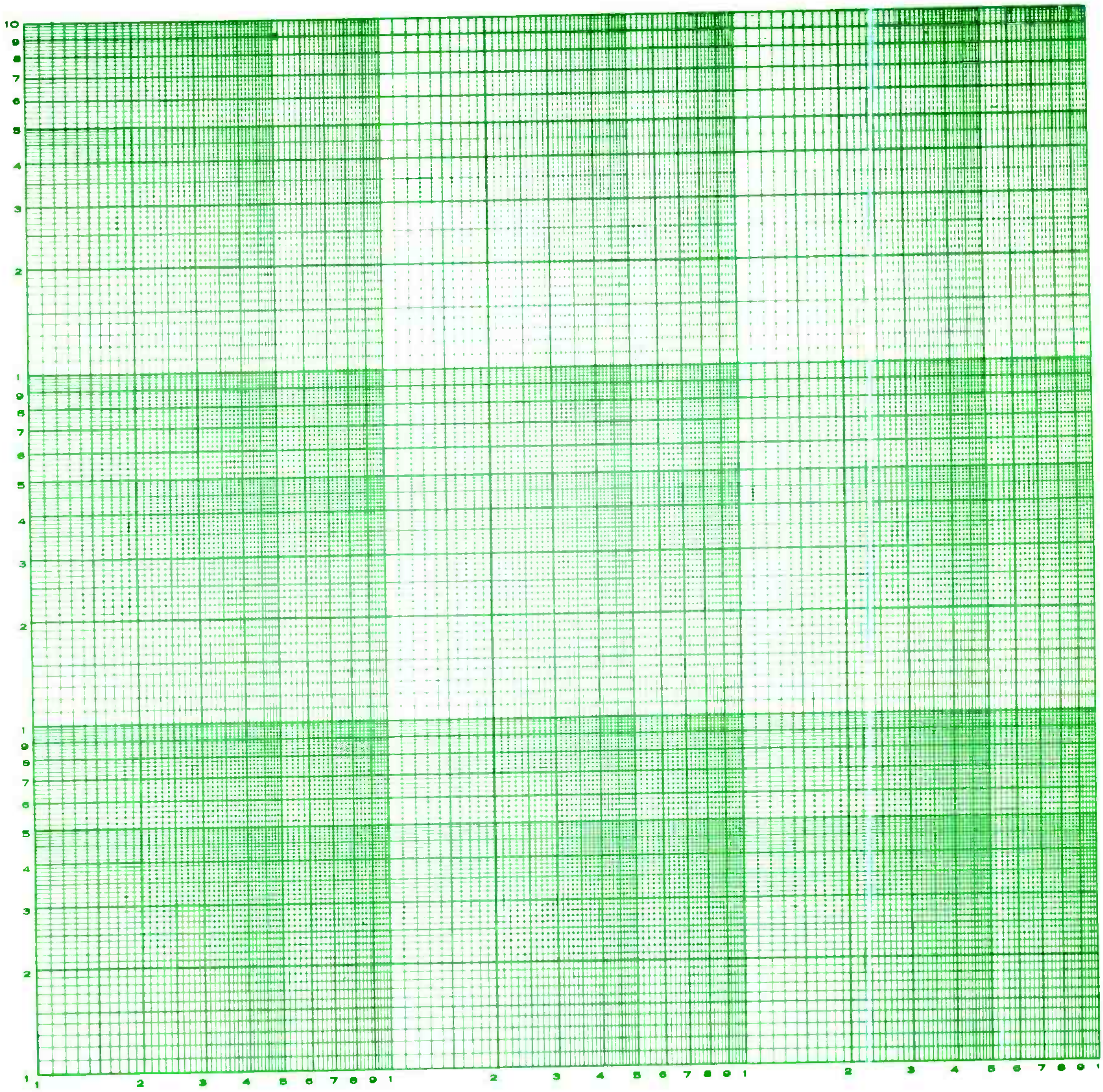

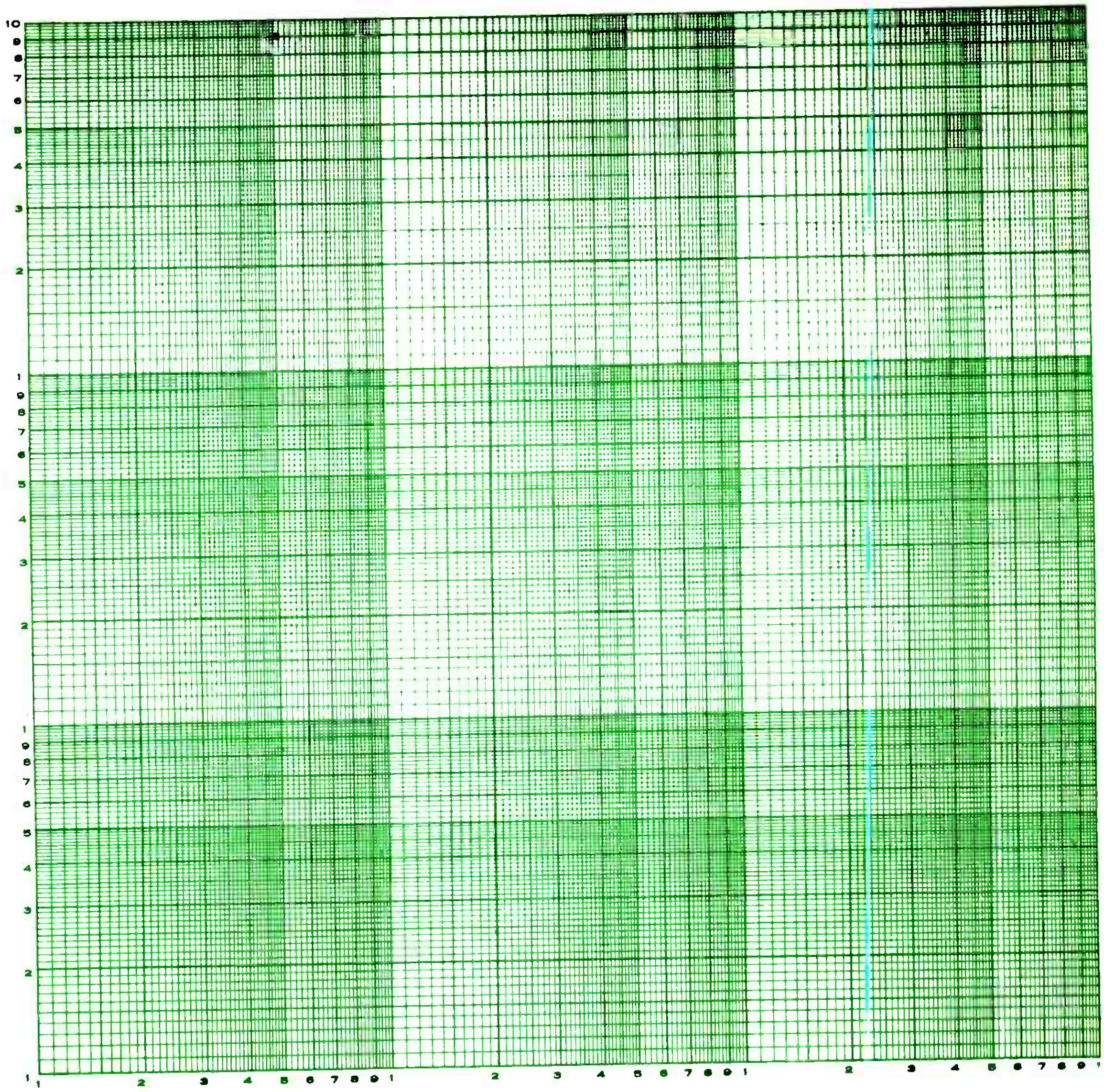
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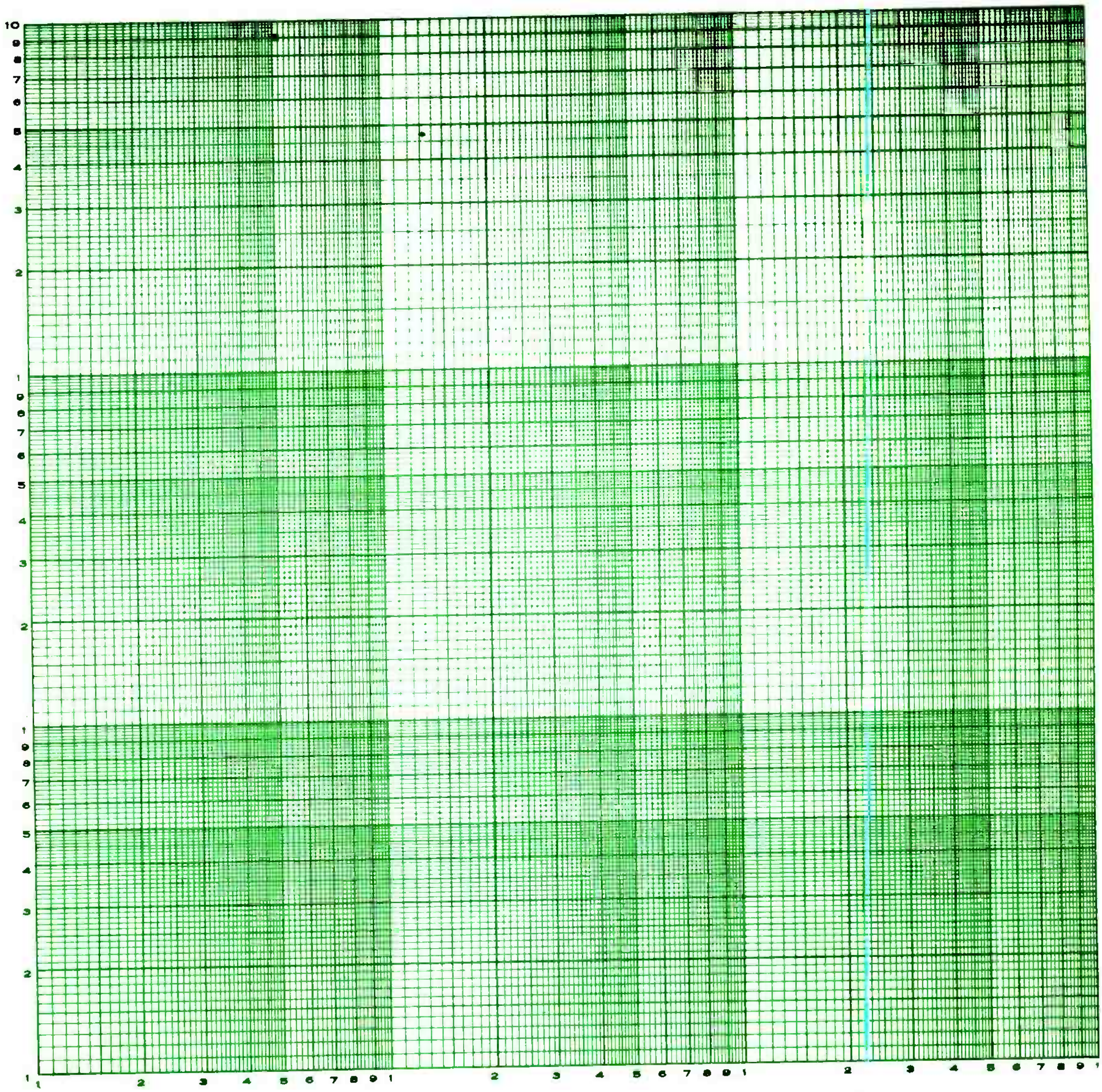

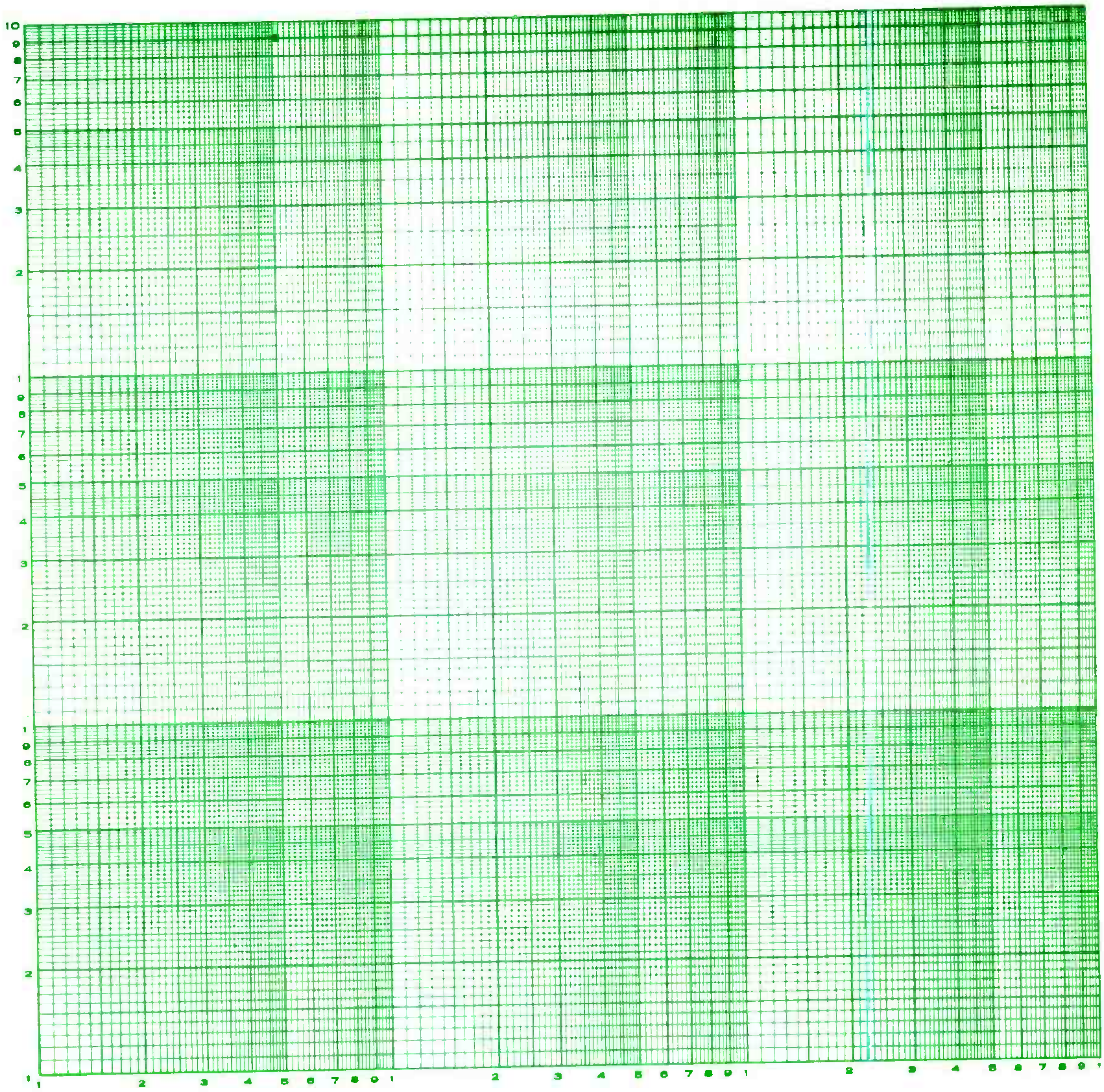

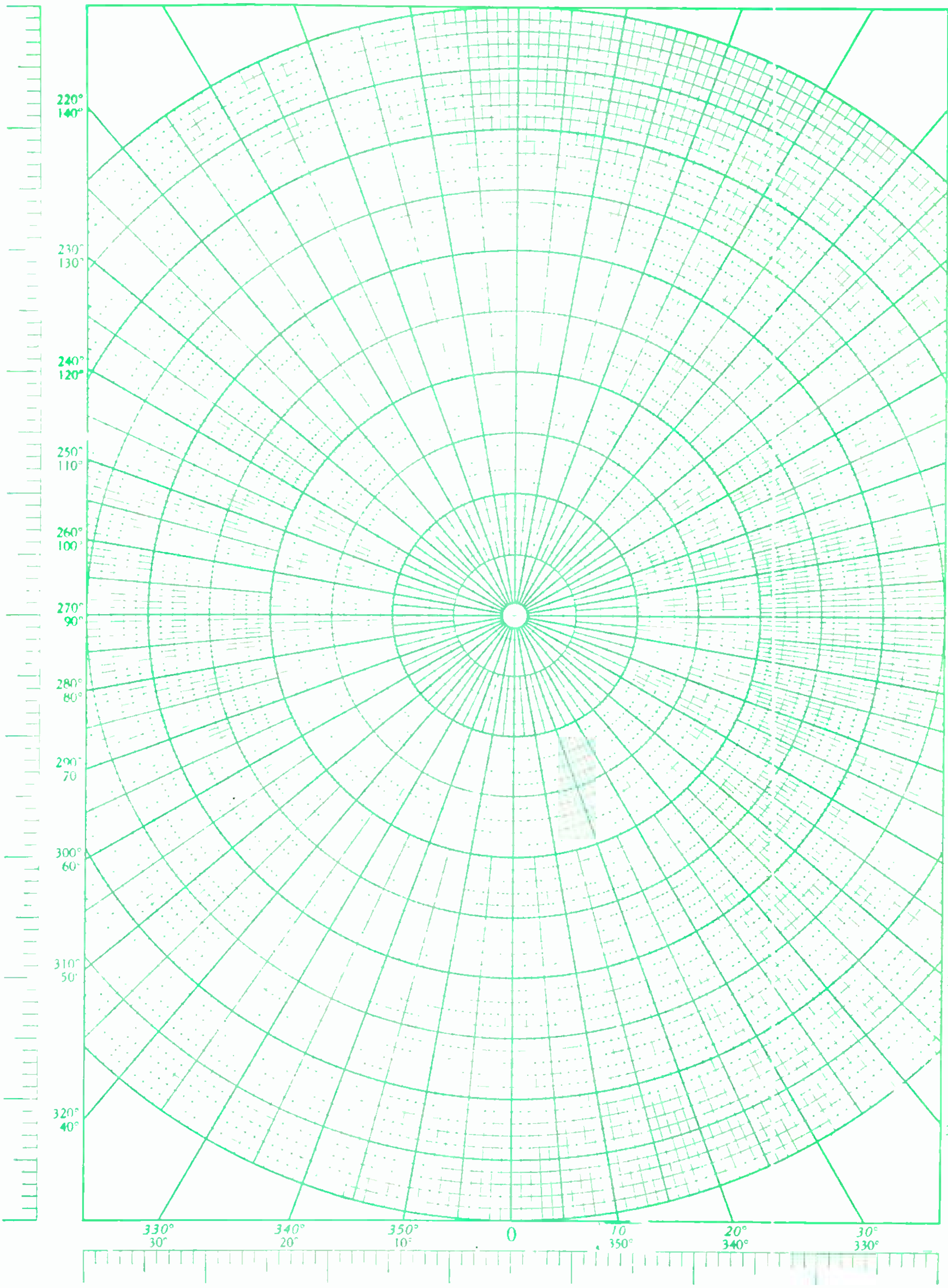
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240° 120°
250° 110°
260° 100°
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280° 80°
290° 70
300° 60°
310° 50°
320° 40°
140° 220°
130° 230°
120° 240°
110° 250°
100° 260°
90° 270°
80° 280°
70° 290°
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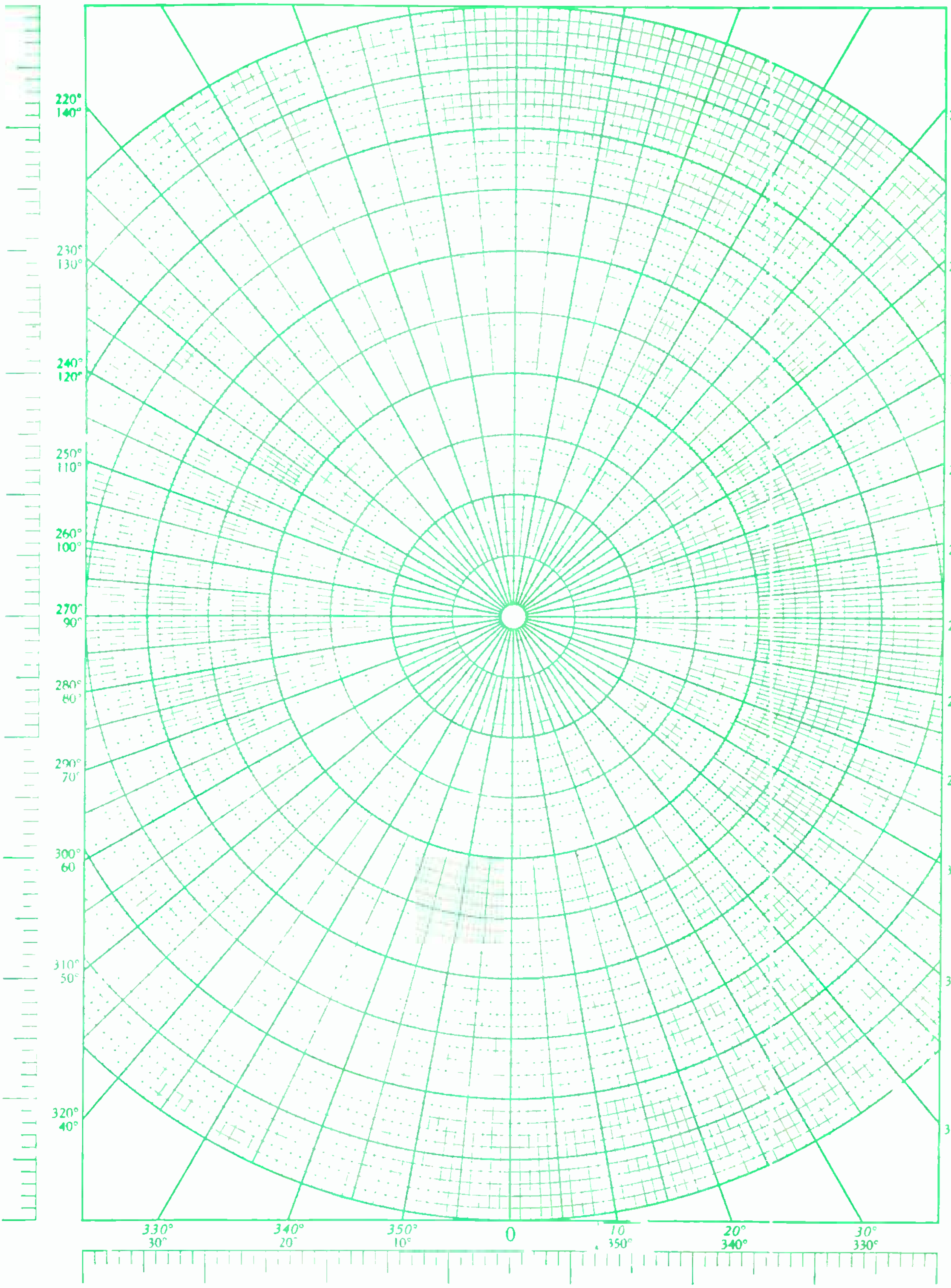
0
10 350°
20° 340°
30° 330°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50° 310°
40° 320°
330° 30°
340° 20°
350° 10°
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20° 340°
30° 330°