NORD LF ANTENNA COURSE

MULTRONICS, INC.

NORD

LF

ANTENNA

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NORD L.F. ANTENNA COURSE

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PREFACE

This book has been written as a supplement to an eight hour course on NORD L.F. antennas. The authors assume that the reader has a basic background in antenna theory and operation. The book has been divided into six sections for ease of presentation. It would not have been possible without the help of the entire engineering and clerical staff of Multronics, Inc.

The Authors

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

NORD L.F. ANTENNA COURSE

I. DISCUSSION:

The purpose of this course is to furnish supplementary data to a lecture series of eight one-hour lectures on L.F. antennas. (For our purpose 50-200 KC.)

This text is not meant to be a complete course in L.F. antennas, but rather a refresher in basic antenna theory applicable to L.F. and an introduction to the theory and operation of NORD antenna systems.

The text is divided into six sections for ease of presentation.

SECTION 1

II. GENERAL:

The purpose of this section is to review some important factors pertaining to electrically short vertical antennas operating in the L.F. region.

III. DISCUSSION:

(1) General Technical Considerations for Short Vertical Antennas:

A. Antenna Resistance:

The transmitting antenna system is the component of a radio frequency transmission system which serves to couple the power developed in the final stage of a transmitter into the impedance of free space. The power which is radiated into space is regarded as having been absorbed by a component of the antenna impedance called the radiation resistance. For an antenna arranged vertically on the surface of the earth, and having a height of less than a quarter wavelength, (always our case), the radiation resistance R_r may be approximately calculated by one of the following formulas:

$$R_r = 520\left(\frac{\ell}{\lambda}\right)^2 \qquad (1)^{(a)}$$

Where:

ℓ/λ = height of antenna in wavelength.

$$R_r = 10\, G_o^{\,2} \qquad (2)^{(b)}$$

G_o = electrical height of antenna in radians

or:

$$R_b = \frac{G^2}{312} \qquad (3)^{(c)}$$

Where:

R_b = base resistance in ohms

G = electrical height of antenna in degrees. (When G does not exceed approximately 40^o.)

The antenna resistance measured at the base of a vertical antenna will closely approximate those values determined from equations (1) through (3) and will only be altered because of ground system losses.

B. Antenna Reactance:

So far in our discussion, we have not treated the reactive component of the antenna, but have concentrated our presentation on the radiation resistance and the expected base resistance for a short antenna. The reactance for a short series fed antenna (referring to an antenna under 45^o) can be expressed as:

$$X_A = -j\,(Z_o \operatorname{Cot} \theta) \qquad (4)^{(d)}$$

Where:

X_A = antenna input reactance in ohms

$Z_c = 138.2 \log_{10} \lambda/d + 23.2$

θ = electrical length in degrees

The above formula assumes that the antenna is working against a perfect ground system, and sinusoidal distribution of current exists on the antenna. In most cases, none of these conditions hold. Therefore, equation (4) can be off by as much as 2:1 when consideration is given to short L.F. antennas. It is clear from a study of equation (4) that the ℓ/d ratio (length to diameter) materially affects the expected base reactance.

C. Length to Diameter Ratio:

It is well known that the physical height versus the electrical height in degrees for a given antenna are not identical except for a wire of such small diameter as to make the ℓ/d ratio a very large number. Some refer to this as the end effect. As the diameter increases for a given length, the electrical length becomes progressively greater than the physical length. Therefore an antenna will go through first resonances (point where reactive component is zero or antenna equal to one quarter wavelength) at a height slightly less than 90^{o} or one quarter wavelength.

It can be stated that for a given antenna height where the antenna cross section is small, close agreement exists between the calculated and measured reactance.

D. Top Loading:

At low radio frequencies, due to economic reasons, vertical radiators are very short in terms of the wavelength in use. At 100 kilocycles where a wavelength is 9843 feet an antenna of one quarter wavelength height (the usual height in the standard broadcast band, 540-1600 kilocycles) would tower nearly 2500 feet above the ground. Such a radiator would be extremely expensive.

In practice at the 100 kilocycles frequency antennas whose physical height is approximately 300 feet are employed. Electrically such antennas are very small structures. Their height is but 3% of the operating wavelength. Techniques may be employed to improve the situation of the electrically short radiator. Obviously the improvement must involve a means of increasing the electrical height of the antenna while leaving its physical height unchanged. This technique is aptly named top loading since by its application the antenna operates as if it were in fact a taller structure.

In a typical vertical antenna of 90° or less, the current is maximum at the base and zero at the top. If this condition could be reversed, that is the current at the base reduced to zero and the current at the top made maximum, this in turn would make a short antenna look closer to a 180°, or a halfwave antenna. This would result in lower base losses (I^2 reduced), and higher base and loop resistances. Unfortunately, however, it is not possible with top loading to achieve such a radical change in current distribution. Top loading increases the capacitance of the top of the vertical antenna to earth. Ideally since the earth represents one plate of the capacitor the other plate attached to the tower top should be parallel to earth and have the largest possible area. Unfortunately this would require masts equal in height to the antenna tower for support of the top loading structure. At this point economics raises its head and the expense of the most desirable solution renders it unacceptable.

Commencing during World War II and following through the post war period, considerable effort has been expended in studying the matter of top loading. For economic reasons guy wire or umbrella top loading is now employed in L.F. antenna systems. Umbrella top loading takes the form of using the top three sets of guys (sometimes use as many as fourteen guy loading wires) as the loading elements. These guys are electrically connected to the top of the tower and their length adjusted by insertion of guy insulators at the desired point in the guy.

Belrose[e] describes a number of experiments in top loading geometry and reports on their results in terms of efficiency.

These experimental investigations were made using a 70 foot vertical radiator and 8 umbrella wires. Figure A is a profile view of the experimental structure.

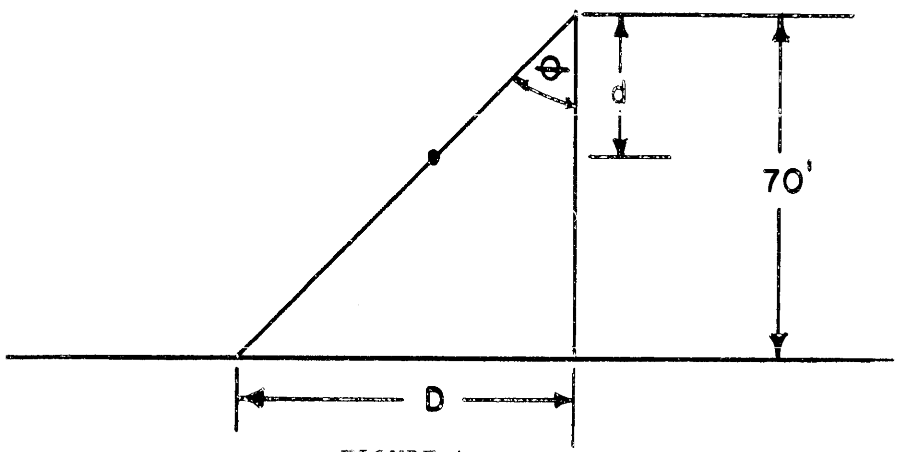

FIGURE A

The 70 foot height of the radiator was constant in all tests. Parameters D, the spacing from the radiator to the top loading guy anchors, and d, the vertical distance from the top of the radiator to the location of guy breakup insulators, were varied. The smallest dimension used for D was 70 feet which is equal to the tower height and which makes θ equal to 45°. The maximum value of D was 200 feet and this interval θ became 70.7°. Parameter d was varied over the range of 5 feet to 70 feet.

The antenna radiation resistance progressively increased as D was increased from the 70 foot minimum value to the 200 foot maximum figure. With d as the variable, radiation resistance maximized when d was approximately equal to 3h/7 or 30 feet. Increasing d beyond this point dropped the radiation resistance and increased bandwidth.

The results of the experimental work was checked on two vertical radiators 250 feet in height. The interval D for both installations was 350 feet. This dimension was dictated by property limitations. Dimension d was made 107 feet or slightly greater than 3h/7 for one antenna and 179 feet, approximately 5h/7 for the other antenna.

In the case of very short radiators the effect of "optimum" top loading is most pronounced in its reduction of antenna reactance with resulting improvement in bandwidth.

For a given antenna structure of height = G at the operating frequency with or without umbrella type of top loading bandwidth and efficiency are directly related to system losses.

The following approximation can be used for determining the effective top loading (three wire) that can be obtained by use of umbrella top loading on short antennas.

It is

$$G_{eff} = TL_p \times 0.705 + G_{t} \qquad (5)$$

Where

G_{eff} = effective height of antenna in degrees

TL_p = physical length of each top loading guy wire, in degrees, to first breakup insulator. The length of top loading guy shall not exceed 50% of the tower height.

G_{t} = physical height of tower, degrees, without top loading.

Equation (5) is based on assuming that the angles of depression and elevation are 45° and the physical length of the top loading does not exceed the physical length of the tower.

It is apparent that even when using conventional top loading, only a limited degree of effectiveness can be achieved with extremely short antennas due to the large hat or umbrella size required in relation to the physical height of the tower. therefore it can be concluded that top loading on very short antennas finds its greatest use in helping to realize a higher feed point resistance rather than an appreciable increase in radiation efficiency.

E. Current Distribution

So far we have briefly discussed some factors concerned with short antenna theory, but we have not dwelled on the distribution of current on an antenna. This paragraph will discuss that subject.

The distribution of current in an antenna can be directly related to its radiation pattern and efficiency. Figure 1 illustrates the typical short series fed antenna.

FIGURE 1

SHORT SERIES FED ANTENNA

Referring to Figure 1, it will be noted that the feed point is marked A and the top of the antenna is indicated as B. It can be stated that the current between A and B flows only to charge the capacity of the antenna keeping in mind that a series fed antenna which is less than 90° in electrical height always looks like a capacitor with a resistance in series with it. This means that the effective value of the current at point A of the base of the antenna is maximum, and at B the top of the antenna zero, for the current at A represents electricity flowing through that point which goes to charge the rest of the antenna, while at point B no electricity flows since there is nothing to which it can flow.

Figure 1 can be modified to increase its effective height or efficiency if capacity loading is used.

SIDE VIEW

TOP VIEW

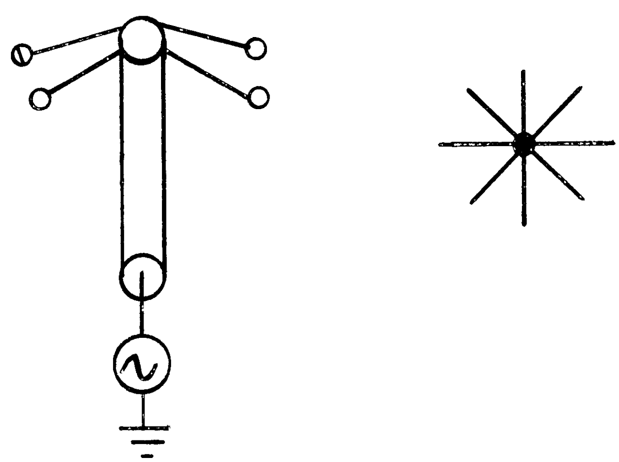

FIGURE 2

SHORT SERIES FED ANTENNA WITH GUY WIRE TOP LOADING

Referring to Figure 2 above, it will be noted that it illustrates a typical series fed vertical antenna where top loading is achieved by the use of the guy wires. As already discussed the number of guy wires used for top loading up to a point will determine the effectiveness of the top loading.

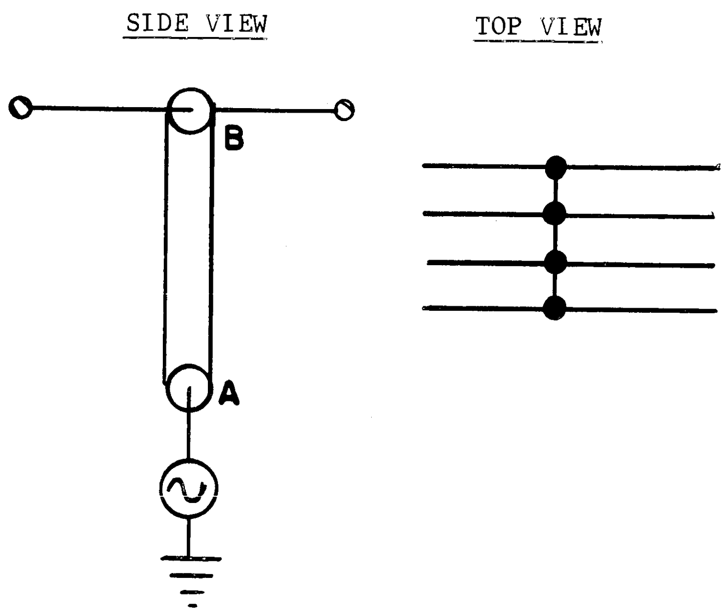

FIGURE 3

"T" TYPE SERIES FED ANTENNA WITH MULTI-WIRE TOP LOADING

Referring to Figure 3 it will be noted that a side and top view of a so-called vertical "T" antenna has been shown. This antenna has some of the characteristics of a series fed vertical antenna with guy wire top loading, but it has the advantage of obtaining a higher degree of top loading with less area due to the fact that the so-called top loading capacity is parallel to the ground plane of the antenna system.

Referring to Figures 2 and 3, in comparison to Figure 1, if the capacity loading has a large surface area in comparison to the base at the top of the antenna (A to B) the effective value of the current at B no longer will be zero, but rather a value almost equal to A at the base. This is due to the fact that the current at B must be such as to charge the large capacity of the loading wires. It therefore follows that for practical considerations that the effective current distribution change on a structure will be most effective when the top loading is in the form of a T and the current throughout the vertical portion of the antenna is uniform.

F. Antenna System Losses:

System losses are very important in low frequency antenna systems. In cases of short antennas the losses can be expected to be quite high inasmuch as the ground losses will be extremely high to begin with. (This subject is further discussed in Section 2.)

Another loss which is also appreciable is the AC ohmic heat loss of the loading coil (helix). The extent of the ground system and the Q of the loading coil will determine the loaded Q of the system, and this in turn will govern the overall circuit loss.

The following are additional losses associated with an antenna system which must be taken into consideration in determining efficiency.

These losses are due to the following factors:[f]

(a) Resistance of the ground system.

(b) Resistance of the antenna structure (ohmic).

(c) Eddy currents in neighboring conductors.

(d) Leakage paths.

(e) Poor dielectrics.

(f) Corona effect.

With respect to items (a) and (b), the losses involved are in the nature of Joulean heat effect, i.e., ordinary I^2R losses, where I is the antenna or ground current and R is the ohmic resistance of the antenna structure or ground system. For a given tower height, ground radial installation and power input, these losses are most likely to produce effects which are inversely proportional to the frequency, since the currents for a certain power will be greater at lower frequencies. In addition, ground radials of a certain length will be effective over a greater area for ground currents of high intensity when the frequency is increased. However, for installations involving an extremely high ratio of total loss resistance to radiation, these effects may be inverted because the currents for a certain power may become less instead of more at the lower frequencies. This is particularly true if an antenna is not galvanized. Experiments conducted by Dr. G. H. Brown of R.C.A.[g] indicate that for a 90° tower at 1000 KC a galvanized tower had a loss of 0.233 ohms whereas the same tower ungalvanized showed a loss of 1.11 ohms. He further shows if the galvanizing thickness is tripled, the loss is reduced to 0.075 ohms. Therefore at L.F., consideration must be given as to the type of the material used for the antenna.

Loss due to eddy currents will occur in neighboring conductors, particularly those within the induction field, and they depend upon the type of material in the conductor, size and shape, and distance from antenna, etc. The effective resistance representing the loss due to eddy currents increases with frequency, since the induced voltage causing the eddy currents is proportional to $-j\,2\pi f LI$.

Poor dielectrics represented in the base and strain insulators or in wooden materials, masonry, trees, etc., which may be located within the near vicinity of the antenna system will introduce losses because of dielectric hysteresis resulting from molecular friction within the material composing the dielectrics. The base insulator is of particular importance because its performance may be considered as analogous to that of a capacitor. In a perfect capacitor, with no energy loss, the current leads the impressed voltage by 90°. However, no capacitor is perfect and the power loss which may be experienced in a particular unit is expressed as follows:

$$\text{Power loss} = EI \sin \theta \qquad (6)$$

Where:

θ = Angle by which the current deviates from the quadrature current of a perfect capacitor.

The phase angle θ has a value in radians equal to the power factor of the capacitor, e.g., a power factor of 0.01 represents a phase angle of 0.573°. It is found that the power factor is essentially independent of frequency, the dielectric loss per cycle being almost unchanged by the number of cycles per second, with a nearly constant proportion of the energy supplied to the capacitor being dissipated as dielectric loss.

An imperfect capacitor may be represented as a perfect capacitor in series (or in shunt) with a resistance, which the value of the latter chosen so that the power factor of the combination is the same as for the imperfect capacitor.

The series resistance then has a value:

$$R = \frac{\text{Power Factor}}{2 \pi f C} \qquad (7)$$

It will be seen that the series resistance varies inversely with frequency (and this is also the case for a shunt resistance), so that dielectric loss is an inverse function of frequency.

Leakage paths may exist across the base and strain insulators of an antenna system and will be affected by weather conditions and chemical composition of the atmosphere. Power losses due to such paths are proportional to the square of the impressed voltage, which in turn may be expected to vary inversely with frequency for constant power input (except for conditions having a high ratio of total loss resistance to radiation resistance, as previously noted). Generally speaking, therefore, leakage path losses may be considered inversely proportional to the square of the frequency.

Corona effect is caused by high voltages, resulting in a partial ionization of air around a conductor. At certain voltages, pluming will occur, and a continuous current will be sustained, unless the voltage is lower or the ionized path is lengthened.

Corona is of importance in an antenna system usually for higher powers only, or in cases where the antennas operate at high elevations under conditions of reduced atmospheric density. The effect is somewhat frequency sensitive in that potentials at which pluming may occur are lowest for frequencies in the vicinity of 2 mc's.

It should be noted that the formation of corona and standing arcs or plumes cause very high losses and such phenomena can be very destructive. In order to determine the probability of corona or plumes forming, it is necessary to know the potential gradients to be expected for various parts of the antenna system. For antennas as short as we are discussing, one may assume that the maximum potential existing due to potential buildup will not exceed:

$$E_A = \frac{I_A X_A}{\text{Cos } G} \qquad (8)$$

Where:

E_A = maximum voltage on antenna.

I_A = antenna base current in amperes.

X_A = antenna base reactance in ohms.

G = antenna height in degrees.

The combined significance of the above factors contributing to the loss of energy in an antenna system is approximately illustrat on Figure 5.

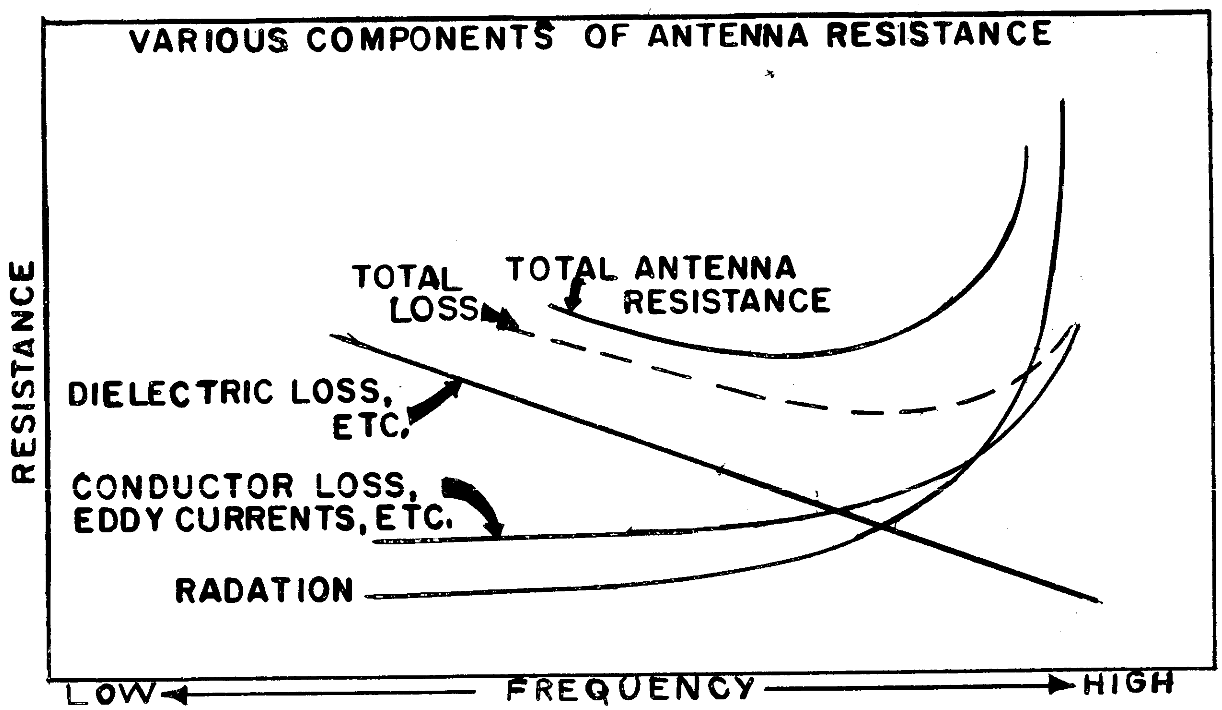

FIGURE 5

Figure 5 relates the various equivalent resistance components of the antenna to their variations with frequency. It will be noted that the net effect is to produce a total antenna resistance which does not vary directly with frequency, but rather starts with a certain value at low frequencies, decreases to a minimum and then rises consistently with frequency thereafter. Since the idealized curve would approach more nearly the curve for radiation resistance alone, it is obvious particularly at the lower frequencies, that all reasonable efforts should be made to keep the various loss resistance components as low as possible.

In addition to the factors mentioned above, which have to do with the efficiency of the antenna proper, it is also important to consider the effect of the feeding and coupling methods employed upon the overall efficiency of antenna systems. When dealing with antennas for which the resistance component of the feed point imepdance is quite low, (and this is almost invariably the situation for antennas employed at low frequencies) it is necessary to keep the resistance factor of the coupling device as low as possible. All inductors should have a high Q, contact resistance should be minimized, capacitors should have a low dissipation factor and the least number of components should be employed.

To illustrate how serious the coupling losses can be , let's consider a 300 foot series fed antenna with a 120 radial ground system at three different frequencies (50, 100, 200 KC) to determine the coupling losses we can expect from the helix coil alone.

We must first compute the base resistance and reactance of the antenna for each frequency so we can determine the value of reactance necessary to resonate the antenna.

To determine the base resistance for a 300 foot antenna at 50 through 200 KC, we will use equation (3) which states:

$$R_b = \frac{G^2}{312} \qquad (9)$$

Where:

R_b = base resistance in ohms.

G = electrical height of antenna in degrees.

Using approximation (9) for resistance we develop the following:

FREQ. (KC)	G^c	R_b (OHMS)
50	5.46	0.096
100	10.92	0.384
200	21.84	1.54

The reactance for each of the above conditions can be expressed as:

$$X_A = -j\ (Z_o\ \mathrm{Cot}\ \theta) \tag{10}$$

Where:

X_A = antenna input reactance in ohms.

Z_o = 138.2 $\log_{10}$ L/D + 23.2

θ = electrical length in degrees.

Assume an L/D of 60 for computation purposes.

The following table indicates the reactances computed for the three conditions under consideration:

FREQ. (KC)	G^c	X_A (OHMS)
50	5.46	-j2811
100	10.92	-j1394
200	21.84	-j671

It is apparent from the above that in order to resonate each of the conditions we will need positive reactances of the same magnitude for each case. Typical helix coils used today have Q's on the order of 500; therefore, using the expression:

$$Q = \frac{X_A}{R_H} \tag{11}$$

Where:

Q = 500 for each case.

X_A = inductive reactance in ohms.

R_H = apparent AC resistance of helix.

Solving for R_H for each condition results in:

G°	R_H (OHMS)
5.46	5.62
10.92	2.79
21.84	1.34

Let's now summarize all of our data for the three conditions:

FREQ. (KC)	G°	R_b (OHMS)	X_A (OHMS)	R_H (OHMS)
50	5.46	0.096	-j2811	5.62
100	10.92	0.384	-j1394	2.79
200	21.84	1.54	-j671	1.34

Examination of the above table indicates that the helix resistance is greater than the base resistance for G = 5.46° and 10.92°, and quite close to R_B for G = 21.84°; therefore the helix will consume most of the power before it even gets to the input of the antenna. This is clearly demonstrated by the following table which is based on assuming 1 KW output from a transmitter to the input of the helix coil, and the resulting power that reaches the antenna. Keep in mind that the transmitter or generator will see both R_b and R_H in series so that I_A for 1 KW will be developed by:

$$I_A = \sqrt{\frac{1000}{R_b + R_H}} \qquad (12)$$

Then:

FREQ. (KC)	G°	I_A	POWER LOSS IN HELIX (WATTS)	POWER AT INPUT OF ANTENNA (WATTS)
50	5.46	13.23	983.2	16.8
100	10.92	17.81	878.9	121.1
200	21.84	18.63	465.6	534.4

We could assume higher Q's for the helix coils which would reduce the loss but the Q must be at least doubled to really contribute a significant reduction.

It has been demonstrated that if losses are not to be completely prohibitive the antenna loading coil must have a very high figure of merit or Q. Since the antenna itself has a high ratio of $\frac{X\ ant}{R\ ant}$ or Q the high Q of the loading coil drastically limits the rate of application of power to the system. The large inductive reactance of the loading coil limits the buildup of current which is required to charge the capacitance of the antenna. Conversely the reactor will continue to release its stored energy for an appreciable time after transmitter power has been removed. The combination of these effects places a ceiling on keying speed which must be low enough to permit reasonable power flow into the system and its correspondent decay without distortion of following characters. Since the information rate is low the system described has narrow bandwidth. The matter of bandwidth and its effects on system losses will be further discussed in section 5 of this course.

SECTION 2

I. GENERAL.

This Section will discuss the number and length of ground radials and how to realistically determine antenna radiation efficiency.

II. DISCUSSION.

(1) Number of Ground Radials:

So far we have not discussed how many ground radials should be employed for an antenna system. A ground system of 113 to 120 radials evenly disposed around an antenna is generally considered adequate for most installations. In certain cases where the conductivity is quite low and base currents are quite high it is not uncommon to use 240 radials. In order to more fully understand the need for ground radials, let's briefly review the main purpose for a ground system.

A ground system serves a twofold purpose: first, it provides a good conducting path for earth currents so that they do not flow through a poorly conducting earth; and second, it acts as a good reflector for waves originating at various points on the antenna so that the vertical radiation pattern closely resembles an antenna located over a perfectly conducting earth. These two functions are synonymous. If the ground system is extensive and complete (at least two wavelengths long) so that there is no power lost in the earth, the reflection of each incident wave will be perfect.

The earth currents in the vicinity of an antenna are created in the following manner. Displacement currents leave the antenna, flow through space, and finally flow into the earth where they become conduction currents. As the current flows back to the antenna it is concentrated near the surface of the earth due to the

the skin effect. If there are ground radials present the earth current will be made up of that part which flows in the wires and that which flows through the earth. It is therefore of utmost importance then to maintain a large number of radials in order to have an efficient radiating system.

Dr. George H. Brown of R.C.A. is an authority on ground system losses. He has made extensive measurements on various types of ground systems.[h] Figure 6 is a graph taken from the Brown article which illustrates the unattenuated field intensity at one mile in mv/m for different height antennas with a 0.274 wavelength or a 99.5° ground system with varying number of radials.

The following table illustrates the efficiency for three different height antennas with a ground system of 15 and 113 radials 99.5° long.

HEIGHT OF ANTENNA G°	THEORETICAL EFFICIENCY FOR 1 KW INPUT	EFFICIENCY WITH 15 RADIALS	EFFICIENCY WITH 113 RADIALS
5	188 mv/m	30 mv/m	59 mv/m
10	189 mv/m	58 mv/m	90 mv/m
20	190 mv/m	102 mv/m	139 mv/m

It is quite evident from a study of the above table that at G = 5° the difference in field efficiency is approximately two to one, or four to one in power (field intensity varies as $\sqrt{P}$). At G = 20° the difference is not as pronounced but it is quite apparent that the 113 radial system is preferable.

It should be noted that Figure 6 is for a 99.5° long ground system, and in practice the average LF ground system length is closer to 500 feet; hence, the losses for typical ground systems are even higher.

(2) Radiation Efficiency:

Radiation efficiency can be expressed in terms of power in to power out, or unattenuated field intensity in millivolts per meter (mv/m) at one mile. The latter is referred to as field efficiency.

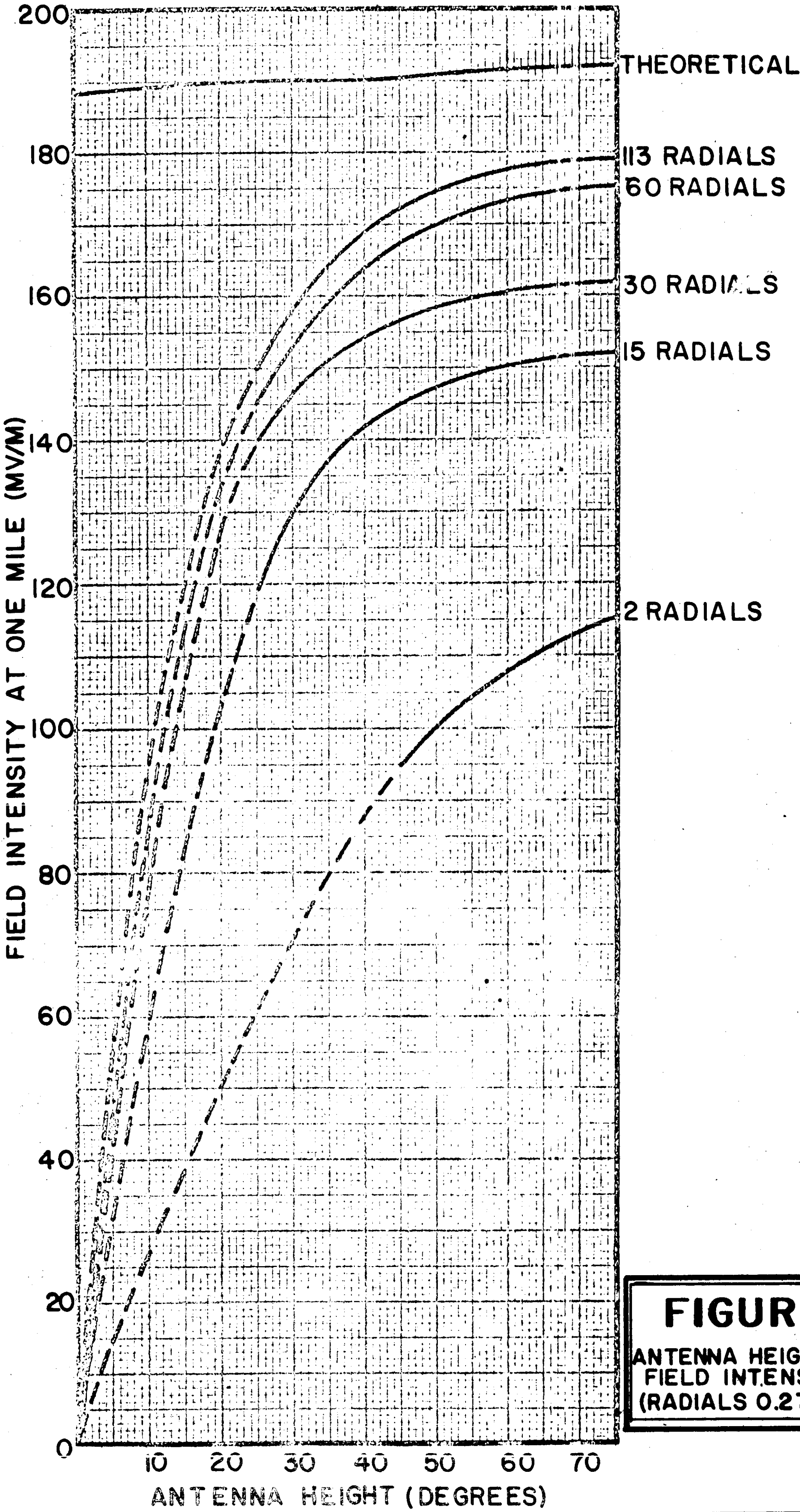

FIGURE 6

ANTENNA HEIGHT VS. FIELD INTENSITY (RADIALS 0.274 λ)

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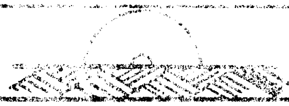
Unfortunately in ordinary antenna work most radiation efficiency is expressed as a percentage of power without stating that power is the reference, therefore, when comparisons between antennas are made some confusion can exist unless one states what reference is being used.

We believe that field efficiency is a more meaningful way of expressing radiation efficiency because it is the millivolts or microvolts that actuate the receiver terminals and [illegible] the [illegible] coverage of a station must be determined by the field [illegible] field strengths at different distances and thus make it easier [illegible].

During World War II [illegible] it became common practice to equate efficiency of [illegible] antennas by using an isotropic radiator as the primary reference.

In L.F. the vertical current element is considered a secondary standard; therefore, for our purposes, the vertical current element will be used as the reference.

The following table illustrates four types of antennas, their vertical patterns, and their field and power efficiencies.

TYPE OF ANT.	VERTICAL PATTERN	MV/M AT 1 MILE 1 KW	POWER GAIN	db GAIN
ISOTROPIC OR SPHERICAL		107.6	1	0
HEMISPHERICAL		152.1	2	3.01
VERTICAL CURRENT ELEMENT		186.3	3	4.771
1/4 λ VERTICAL		194.9	3.282	5.161

Inasmuch as L.F. antennas for our case will not exceed a length of 600 feet, the vertical current element is the proper reference for any short vertical antenna at L.F. (Note: There is one school of argument that states it is possible to obtain a hemispherical radiator at L.F. with antennas under 600 feet. Whether we accept this theory or not, we must keep in mind that from an efficiency standpoint this only states if such an antenna can be designed that its field efficiency compared to a vertical current element will be 18.4% less.)

The unattenuated field strength at the surface of the earth one mile from the antenna can be expressed in equation form as:

$$E_o = 37.25\, I_o \frac{1-\text{Cos } G}{\text{Sin } G} \qquad (13)$$

Where:

E_o = mv/m unattenuated field intensity at one mile.

37.25 = a factor from basic radiation formula.

I_o = antenna base current in amperes.

G = antenna height in electrical degrees.

Equation (13) can be expressed in the following manner if we assume a constant radiated power:

$$E_o = 37.25\left[\frac{P}{R_r\ (\text{Base})}\right]^{\frac{1}{2}}\left[\frac{1-\text{Cos } G}{\text{Sin } G}\right] \qquad (14)$$

Where:

P = Power input at the base of the antenna.

We have already shown that the unattenuated field intensity at one mile for a 90° (one quarter wavelength) antenna is 194.9 mv/m for 1 KW input. This can be verified by using equation (14).

By use of equation (14) it can be demonstrated that as an antenna becomes shorter than a quarter wavelength for all practical purposes, the field strength remains constant. (This assumes no loss.) For instance, the following series expansion demonstrates this fact if we assume that the height of the antenna G is extremely small.

$\text{Sin } G \cong G$

$\text{Cos } G \cong 1 - G^2/2$

$1 - \text{Cos } G \cong G^2/2$

Using the above relations together with equation (2) for an input power of 1000 watts at the base of the antenna, the following is obtained:

$$E_o = 37.25 \left[\frac{1000}{10\ G^2} \right]^{\frac{1}{2}} \left[\frac{0.5\ G^2}{G} \right] = 186.3 \text{ mv/m} \qquad (15)$$

It therefore can be seen by the above expansion that an antenna of infinitesmal length, assuming no losses, will yield a field which is only 4.25% less than the field of a quarter wavelength antenna using the same considerations.

Unfortunately, however, the determination of the unattenuated field as set forth in equation (14) is based on a "no loss" system. This condition will not exist in actual practice, particularly for short antennas. We therefore have to determine the total loss of the antenna to obtain the actual radiation efficiency.

So far we have briefly discussed factors which control antenna system losses. The most prominent controlable variable loss is the type of ground system. We therefore will now go to some detail to demonstrate the effects of ground system length versus antenna height. For our purposes we will always use a ground system of 120 radials. The length will at least be the tower height.

(3) Examples of How to Compute Radiation Efficiency:

In order to develop a method for determining antenna radiation efficiency, use will be made of Dr. Brown's article already referenced, published data of the Federal Communications Commission, Mutual Broadcasting System and studies made by Multronics, Inc. on short antennas. It should be noted that during the last thirty years appreciable information concerning antenna efficiencies have been filed with the Federal Communications Commission in the form of field intensity measurements made on commercial broadcast antennas. The Commission as part of its technical rules has published a theoretical and averaged measured curve for a simple omnidirectional vertical antenna with a ground system of at least 120 radials one quarter wavelength long for antennas varying in length from 0.05 0.68 wavelengths. (18° to 244°).

Figure 7 is a curve which illustrates the effective field at one mile for one kilowatt input for antennas having a height varying between 0.0152 to 0.2 wavelengths. Figure 7 assumes the ground system is 120 radials one quarter wavelength long. It is based on using data from all of the sources referenced.

Figure 8 is a correction factor curve for Figure 7 to determine the additional loss factor that must be used for a ground system less than one quarter wavelength.

In view of the fact that we are concerned with short antennas between 50-200 KC, we will analyze a series of problems for a 300 foot vertical antenna with ground systems as noted. (Note: This technique can be used for any height L.F. antenna to determine radiation efficiency.)

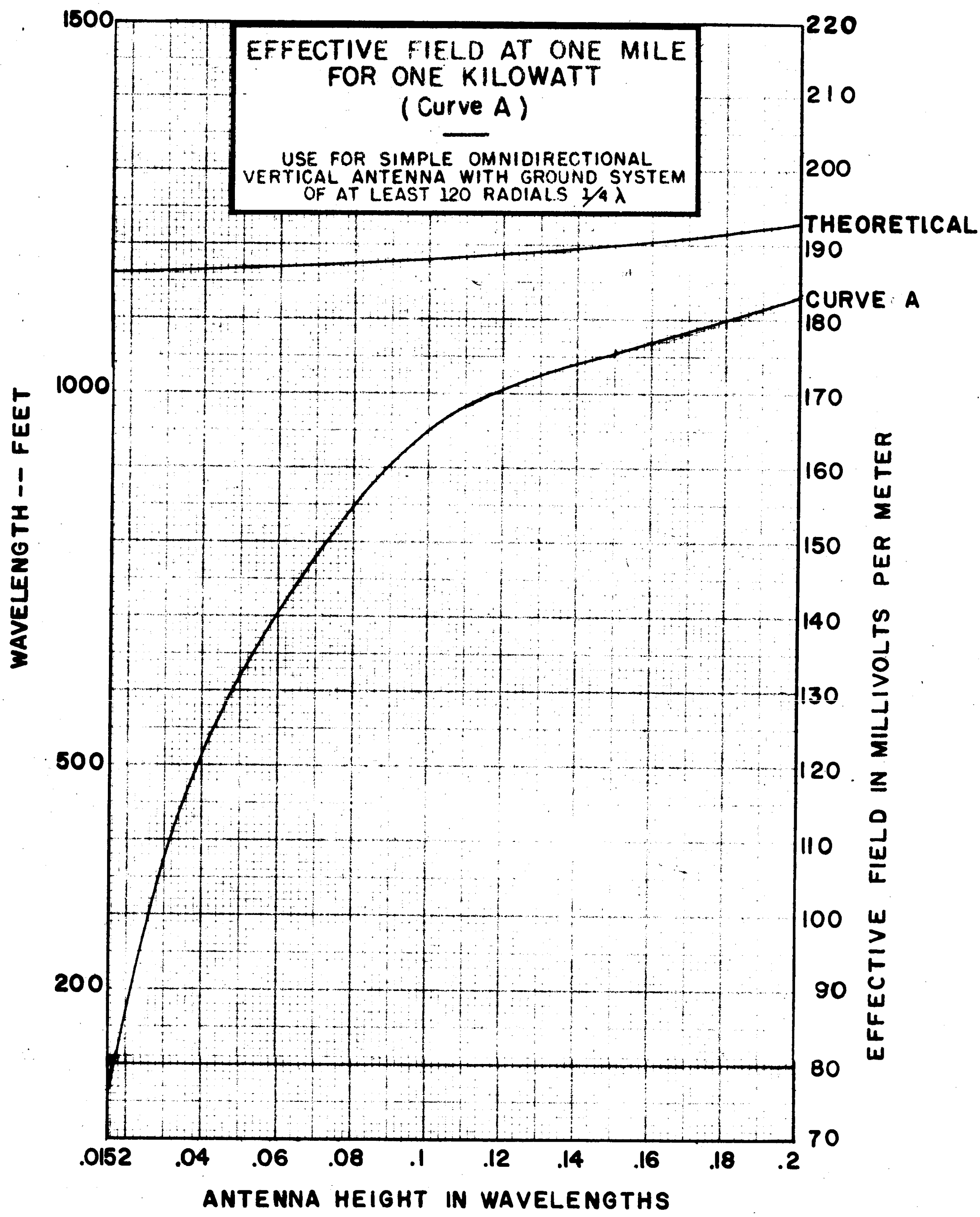


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FIGURE 7

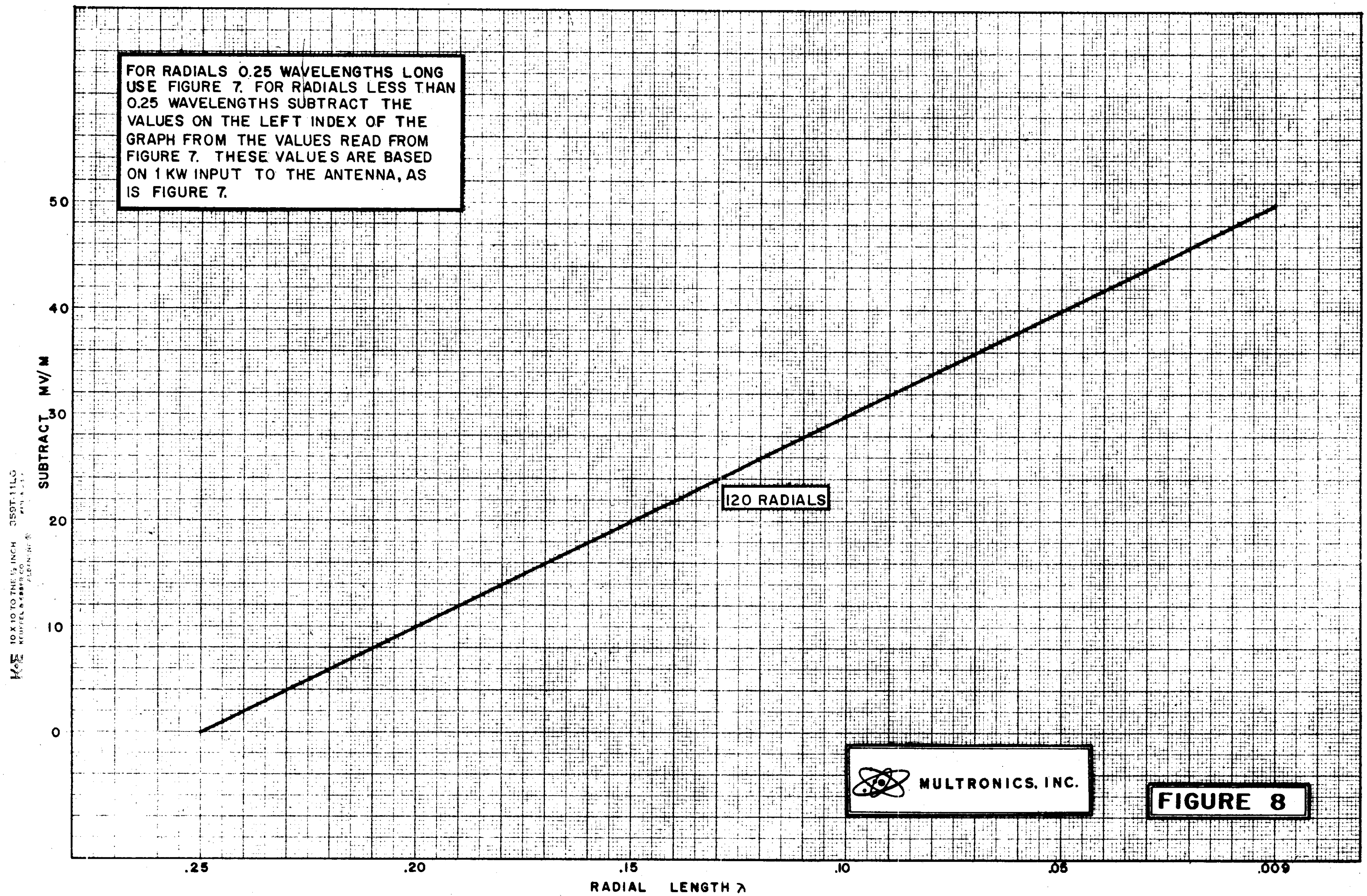

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FIGURE 8

Case #1:

Given: 300 foot series fed vertical antenna with a ground system consisting of 120 radials 0.0152 wavelength long, operating at a frequency of 50 KC.

Determine: The power and field efficiency.

Solution: A 300 foot antenna at 50 KC is 0.0152 wavelengths or 5.46^{o} high. At 50 KC a 0.0203 wavelength ground system is 7.3^{o} long or 400 feet.

To determine the efficiency first refer to Figure 7 and look up the unattenuated field for a 0.0152 wavelength antenna which is 77 mv/m. Next look up the loss factor for a 0.0203 wavelength ground system on Figure 8 which is 46 mv/m. The resultant field efficiency is 31 mv/m (77-46 = 31). The radiated field efficiency is 16.6% (31/186.3 = .166). The radiated power efficiency is 2.74%.

Case #2:

Given: 300 foot series fed vertical antenna with a ground system consisting of 120 radials 400 feet or 0.0406 wavelengths long. Operating frequency 100 KC.

Determine: The field and power efficiencies.

Solution: A 300 foot antenna at 100 KC is 10.92^{o} high or 0.0304 wavelengths. A 0.0406 wavelength ground system is 14.6^{o} or 400 feet long.

Figure 7 indicates the antenna field is 109 mv/m(Curve A). The loss factor from Figure 8 is 42 mv/m; hence, the net field is 67 mv/m. This is equivalent to a field efficiency of 26% or a power efficiency of 12.8%.

The frequency can be increased to 150 and 200 KC's and keeping the antenna at 300 feet with a 120 radial ground system 400 feet long the following efficiency results:

Frequency (KC)	E (Field Efficiency %)	P Power Efficiency %)
150	47.5	22.4
200	57.2	32.8

We can now summarize radiation efficiency for a 300 foot antenna with 120 radials 400 feet long for the following frequencies:

Frequency (KC)	E(Field Efficiency %)	P(Power Efficiency %)
50	16.6	2.74
100	36	12.8
150	47.5	22.4
200	57.2	32.8

The above efficiencies are materially lower than those assumed by many engineers who have not made detailed studies of how much field and power efficiency can be obtained with any type of a vertical antenna (series fed, NORD, UG's or Pan Polars) with a 300 foot height and a limited ground system.

It should now be apparent that regardless of what type of vertical antenna is used, if the height is 300 feet between 50-200 KC (7^{o} to 22^{o}) with a ground system consisting of 120 radials 400 feet long, the maximum expected field efficiency will not exceed approximately 57% and the power efficiency would be on the order of 33%. (This also assumes a limited bandwidth.) The only way to increase the antenna's efficiency for a given antenna height would be to materially increase the ground system length. Based on existing crowded conditions at most military installations, this does not appear to be a realizable goal.

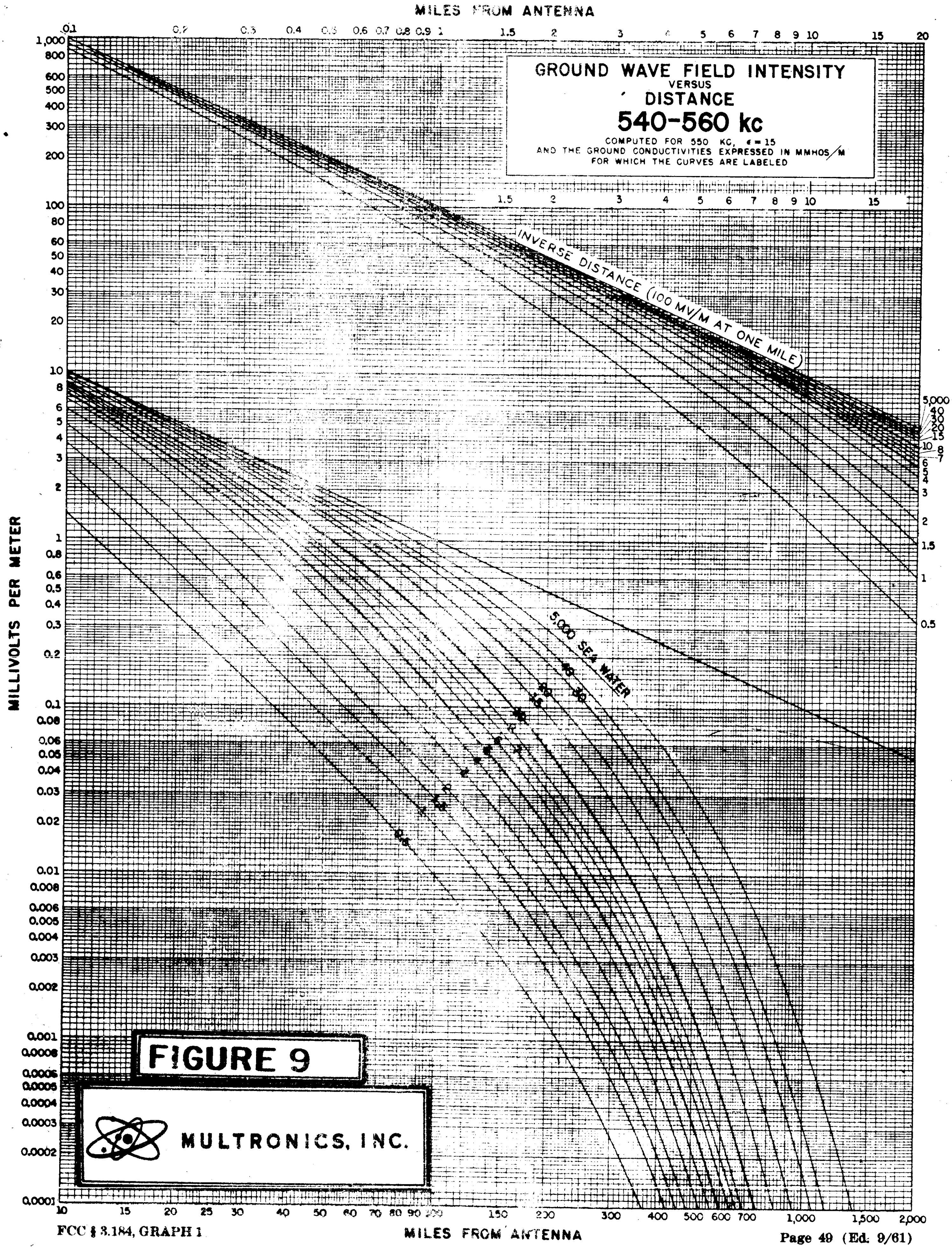
(4) Inverse Distance Field and Attenuation:

The radiation field from an antenna, assuming no absorption or attenuation, is inversely proportional to the distance from the antenna. In other words if we assume a vertical current element with an input power of 1 KW at one mile, we would expect to measure 186.3 mv/m, at two miles the field would be 93.15 mv/m, and continue to reduce as an inverse proportion with distance. This assumes the earth is a perfect conductor. When a signal follows this inverse relationship we say it is following the inverse distance law and the field intensity at one mile is called the unattenuated or inverse distances field.

We know that the most important type of ground wave is a vertically polarized wave which is radiated from a vertical antenna over an assumed perfect conducting earth. In vertically polarized waves, the electrostatic lines of force are normal to the surface of the perfect conducting earth, therefore, they are not absorbed or reflected. Such a wave has associated with it a charge density which travels along above in parallel to the surface of the earth. The surface of the earth, therefore, is the guiding conductor just as in the case of progagating energy along a transmission line but instead of having a uniform conduction for propagation, we have the vertically polarized field diminishing in magnitude inversely with the distance from the transmitting antenna. Because we are dealing with an imperfect earth, we have to keep in mind that the electrostatic field has a slight forward tilt which results in a downward component of energy to supply earth losses. Therefore because the earth is not a perfect conductor, it absorbs or attenuates some of the signal and depending upon the conductivity of the path over which the signal travels will determine the amount of absorption or attenuation. Norton[i] has published data on attenuation that is universally used.

Figure 9 is an example of a series of attenuation curves for a frequency range of 540-560 KC's published by the Federal Communications Commission. It will be noted that sixteen different attenuation curves are shown. The values shown represent ground conductivities expressed in millimhos per meter (mm/m), assuming a dielectric constant of 15.

Referring again to Figure 9 we note that the field intensity is plotted against distance for both inverse distance (perfect conductivity) and the actual signal we would measure if the effective conductivity was any one of the sixteen values shown.


MILES FROM ANTENNA
GROUND WAVE FIELD INTENSITY
VERSUS
DISTANCE
540-560 kc
COMPUTED FOR 550 KC, ε = 15
AND THE GROUND CONDUCTIVITIES EXPRESSED IN MMHOS/M
FOR WHICH THE CURVES ARE LABELED
INVERSE DISTANCE (100 MV/M AT ONE MILE)
5,000 SEA WATER
MILLIVOLTS PER METER
FIGURE 9
MULTRONICS, INC.
MILES FROM ANTENNA

The unattenuated field intensity is shown as 100 mv/m for convenience. If we are working with an antenna having an inverse field of 186.3 (current element with 1 KW), we still can use this curve by multiplying all readings by 1.863.

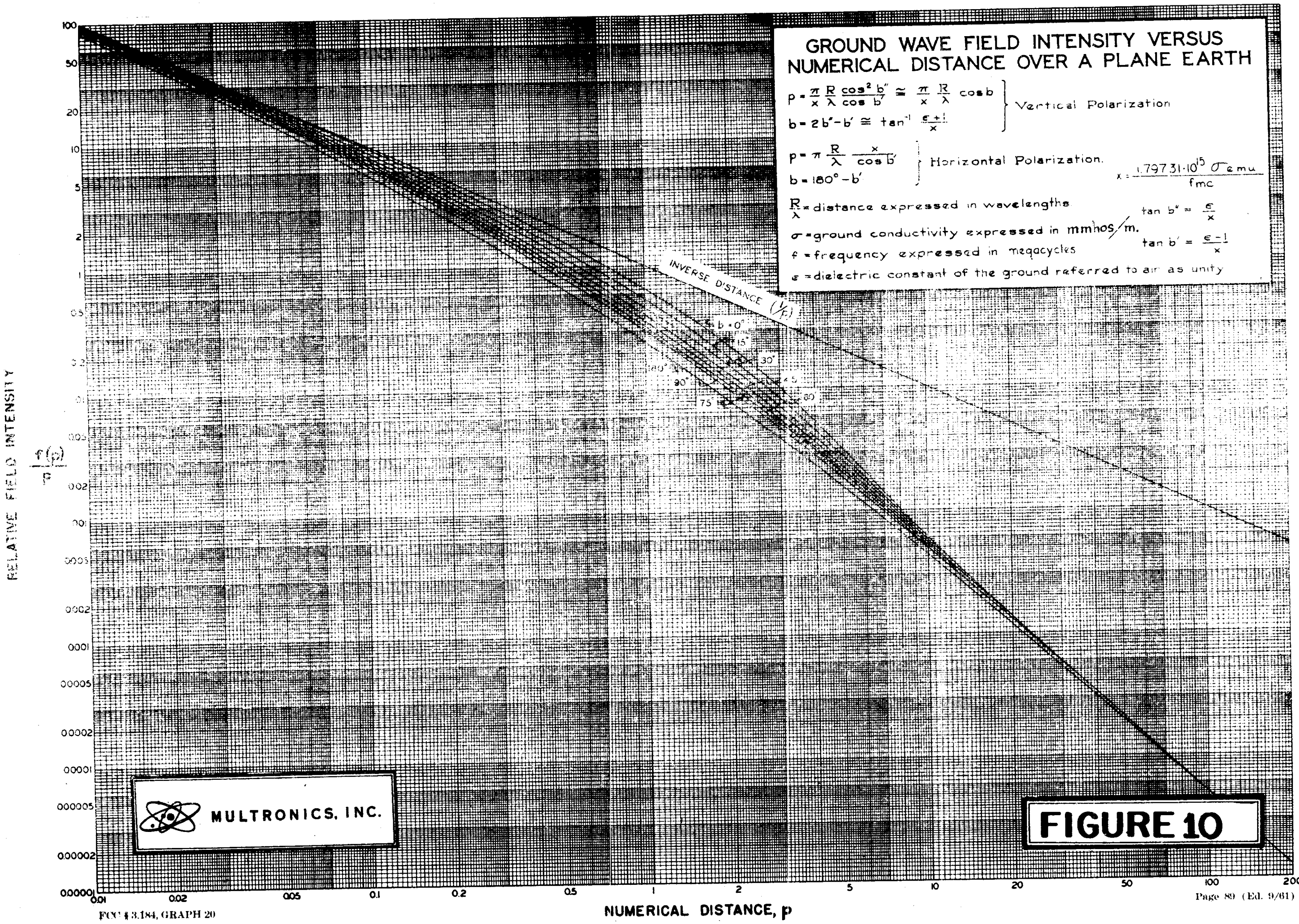
Going further we note that the inverse distance field at one mile is 100 mv/m. At two miles it is 50 mv/m. At ten miles it is 10 mv/m, and continues on down as the inverse distance law. For sea water (highest conductivity), we have a small amount of absorption but its real effect doesn't start to show up until the distance from the antenna is over 100 miles. In the case of a conductivity of 3 mm/m, the effects of absorption or attenuation is pronounced and can readily be noted from an examination of Figure 9. In the latter case note that at 10 miles from the antenna, the field using 3 mm/m is approximately 6 mv/m or 40% below the inverse distance value of 10 mv/m. At 50 miles from the antenna the field for a conductivity of 3 mm/m is 0.32 mv/m compared to 2 mv/m for inverse distance. Therefore it is quite apparent that attenuation must be considered before an accurate inverse distance field can be determined.

(5) Determination of Inverse Distances or Unattenuated Field Intensity By Analysis of Field Intensity Measurements:

A. Attenuation or Absorption:

Attenuation or absorption at L.F. is less than at broadcast frequencies, but it does exist. In order to make use of field intensity measurements and accurately determine the unattenuated field intensity, one must have a family of conductivity curves to compare measurements to for analysis purposes.

Figure 10 is a copy of Graph 20 in the F.C.C. Rules (Standards of Good Engineering) entitled "Ground Wave Field Intensity Versus Numerical Distance


GROUND WAVE FIELD INTENSITY VERSUS NUMERICAL DISTANCE OVER A PLANE EARTH
$p = \frac{\pi}{x}\frac{R}{\lambda}\frac{\cos^2 b''}{\cos b'} \cong \frac{\pi}{x}\frac{R}{\lambda}\cos b$
$b = 2b'' - b' \cong \tan^{-1}\frac{\epsilon+1}{x}$
Vertical Polarization
$p = \pi \frac{R}{\lambda}\frac{x}{\cos b'}$
$b = 180° - b'$
Horizontal Polarization.
$x = \frac{1.79731 \cdot 10^{15}\, \sigma_{emu}}{f_{mc}}$
$\tan b'' = \frac{\epsilon}{x}$
$\tan b' = \frac{\epsilon - 1}{x}$
$\frac{R}{\lambda}$ = distance expressed in wavelengths
σ = ground conductivity expressed in mmhos/m.
f = frequency expressed in megacycles
ϵ = dielectric constant of the ground referred to air as unity
INVERSE DISTANCE (1/p)
b = 0°
15°
30°
45°
60°
75°
90°
RELATIVE FIELD INTENSITY $\frac{f(p)}{p}$
NUMERICAL DISTANCE, p
MULTRONICS, INC.
FIGURE 10

Over a Plane Earth". It is based on the Norton article already referenced. It can be used to compute a family of conductivity curves for L.F.

Figures 11 through 13 are a family of conductivity curves for 149, 162, and 185 KC's, respectively. They were prepared by use of Figure 10. It should be noted that the highest conductivity computed is 4 mm/m. It will be noted that conductivities have been computed for 0.5, 0.75, 1, 1.5, 2, and 4 millimhos per meter. These curves have all been normalized for 100 mv/m unattenuated efficiency at one mile. Reference to these curves will show that as the distance increases from an antenna, the effects of the conductivity, particularly where low effective conductivity is encountered, is quite pronounced between 149 and 185 KC.

Figures 11 through 13 show that all conductivity lines tend to merge together and approach a value slightly under inverse distance between ten miles back to the antenna, but beyond 10 miles the effects of low conductivity are material.

There is one school of thought which states because the conductivity lines tend to merge into one curve just below inverse distance, one can assume for all low frequencies that the unattenuated field intensity varies inversely with distance and one can then determine unattenuated field by taking the measured field strength times distance (E x D). This technique in theory is correct, but in practice field intensity measurements cannot be so precisely taken between two to ten miles that the effects of conductivity, reradiation, reflections and instrumentation error can be ignored. Further because of wide variations at identical distances (different directions from antenna) in field intensity can be measured, it is imperative that a large number of measuring points on at least eight radials be measured.

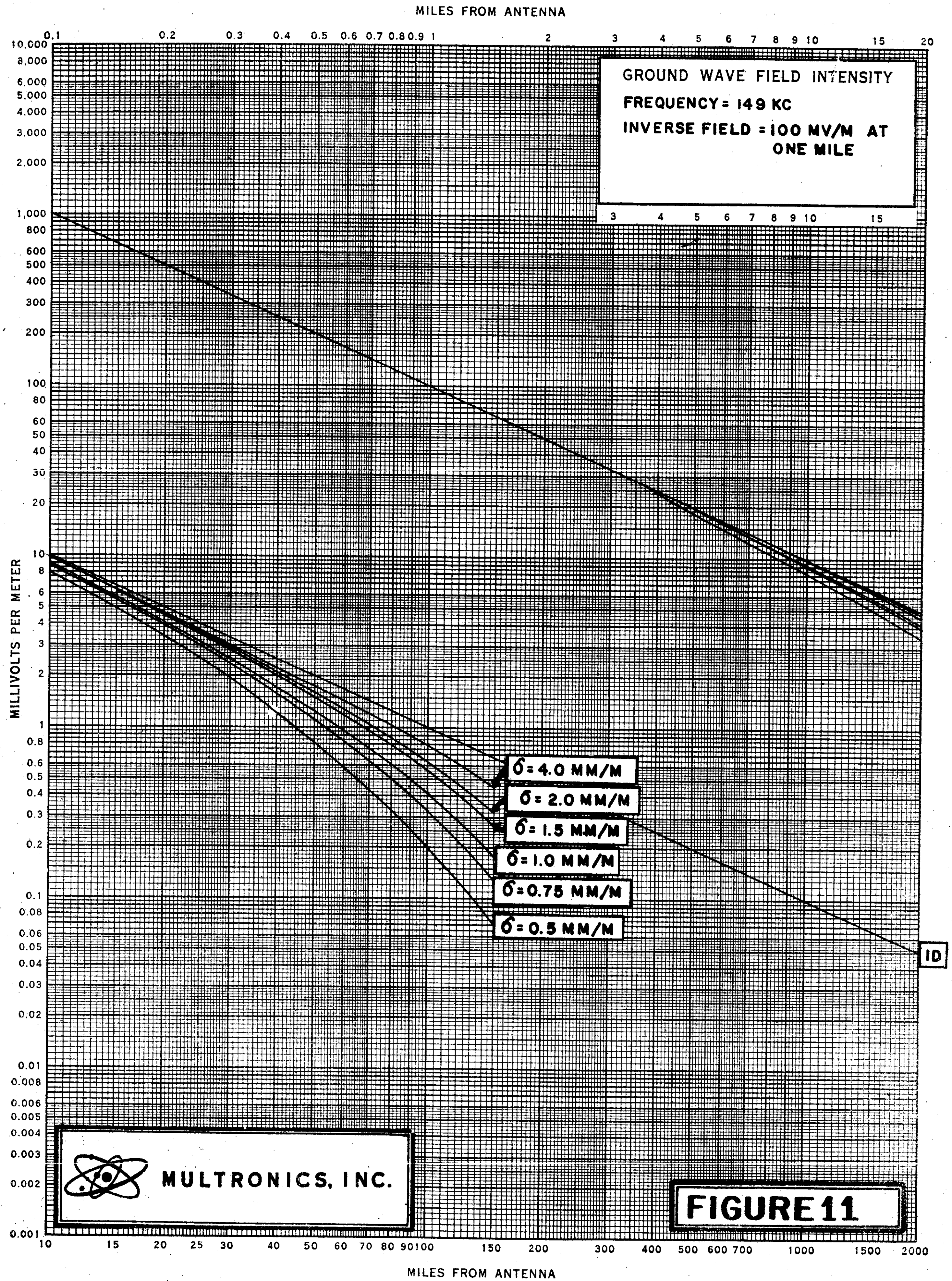

MILES FROM ANTENNA
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
3
4
5
6
7
8
9
10
15
20
GROUND WAVE FIELD INTENSITY
FREQUENCY = 149 KC
INVERSE FIELD = 100 MV/M AT ONE MILE
MILLIVOLTS PER METER
10,000
8,000
6,000
5,000
4,000
3,000
2,000
1,000
800
600
500
400
300
200
100
80
60
50
40
30
20
10
8
6
5
4
3
2
1
0.8
0.6
0.5
0.4
0.3
0.2
0.1
0.08
0.06
0.05
0.04
0.03
0.02
0.01
0.008
0.006
0.005
0.004
0.003
0.002
0.001
σ = 4.0 MM/M
σ = 2.0 MM/M
σ = 1.5 MM/M
σ = 1.0 MM/M
σ = 0.75 MM/M
σ = 0.5 MM/M
ID
MULTRONICS, INC.
10
15
20
25
30
40
50
60
70
80
90
100
150
200
300
400
500
600
700
1000
1500
2000
MILES FROM ANTENNA

FIGURE 11

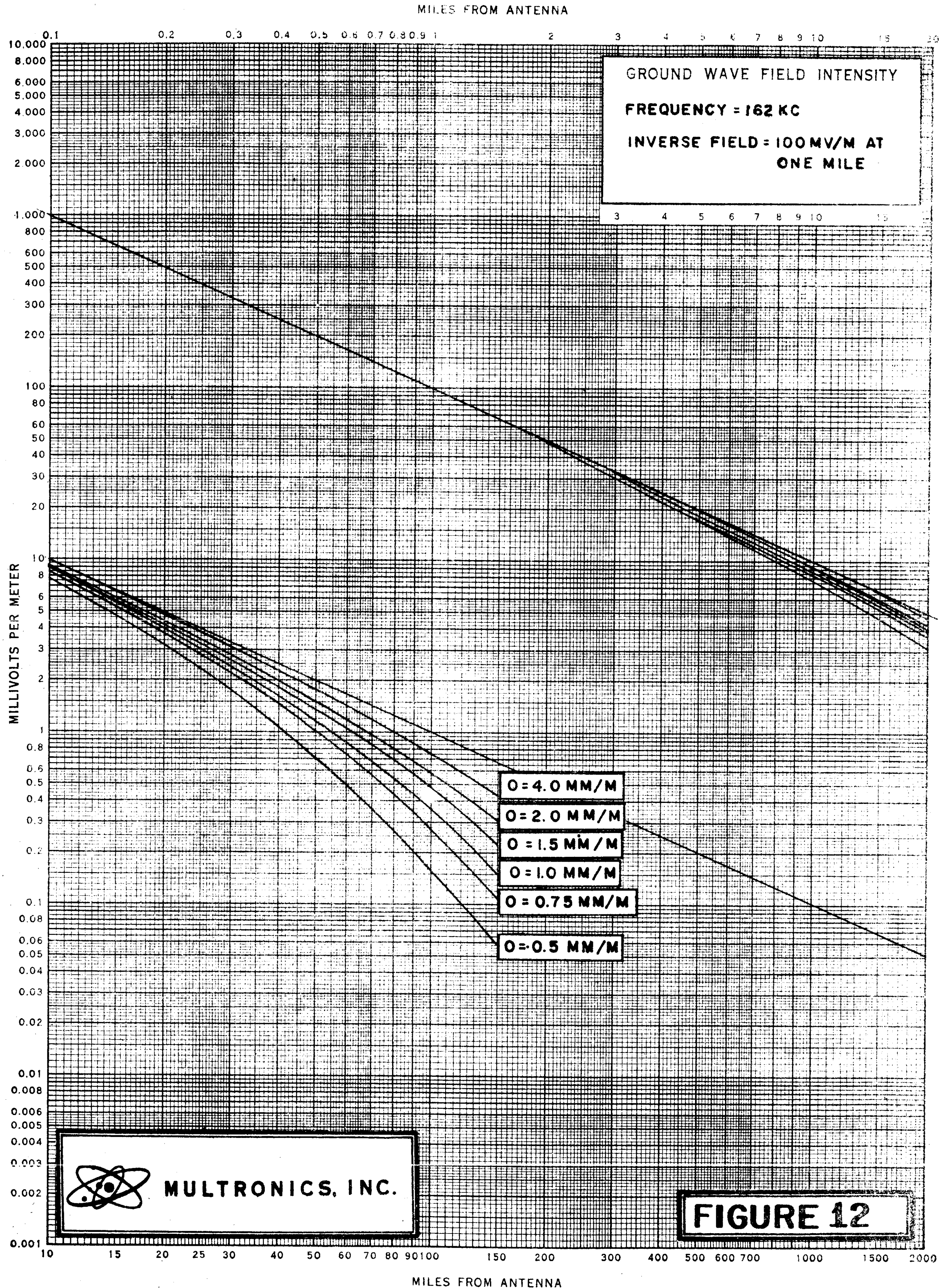

MILES FROM ANTENNA
GROUND WAVE FIELD INTENSITY
FREQUENCY = 162 KC
INVERSE FIELD = 100 MV/M AT ONE MILE
MILLIVOLTS PER METER
O = 4.0 MM/M
O = 2.0 MM/M
O = 1.5 MM/M
O = 1.0 MM/M
O = 0.75 MM/M
O = 0.5 MM/M
MULTRONICS, INC.
MILES FROM ANTENNA

FIGURE 12

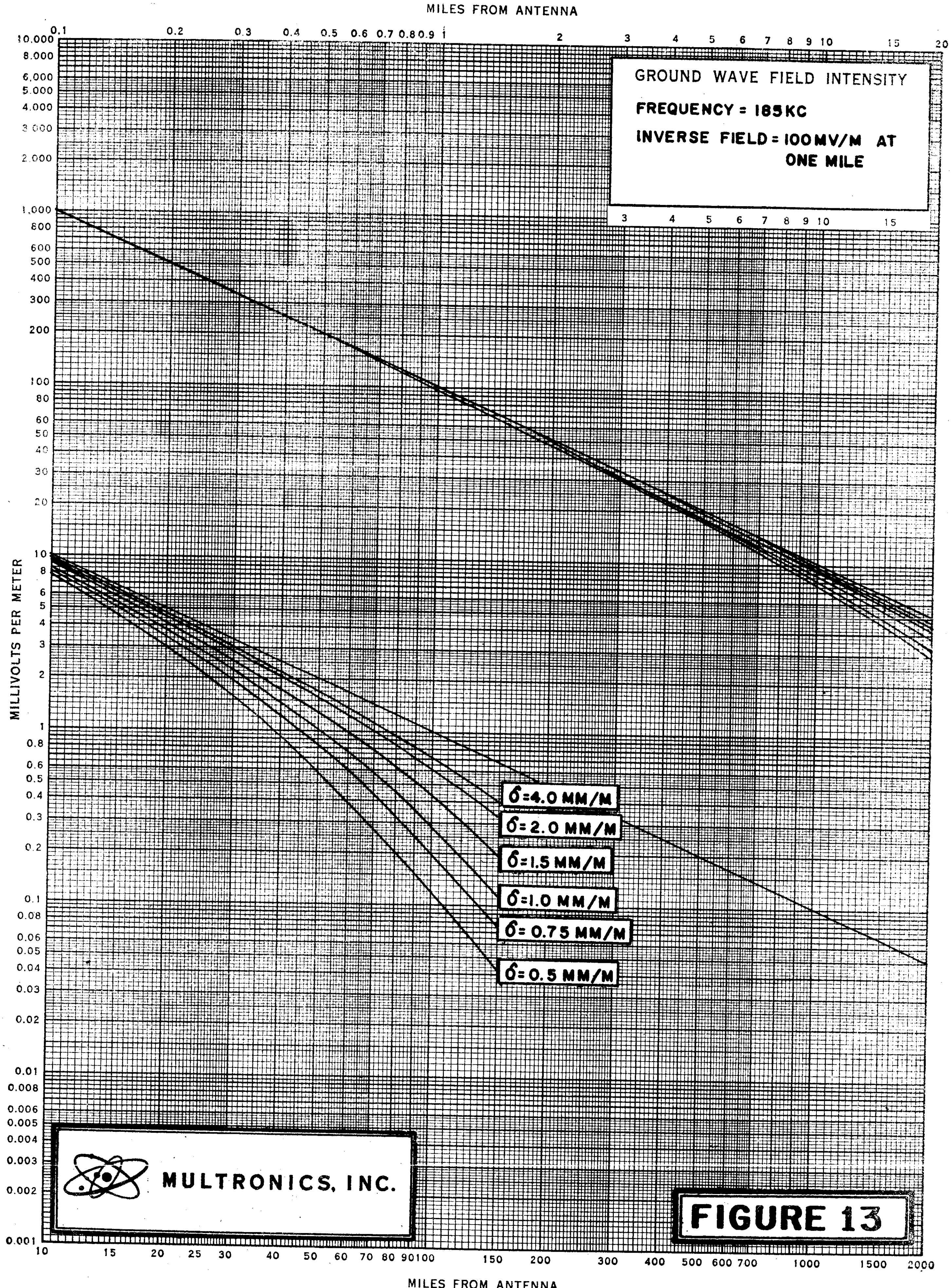

MILES FROM ANTENNA
GROUND WAVE FIELD INTENSITY
FREQUENCY = 185KC
INVERSE FIELD = 100MV/M AT ONE MILE
MILLIVOLTS PER METER
δ=4.0 MM/M
δ= 2.0 MM/M
δ=1.5 MM/M
δ=1.0 MM/M
δ= 0.75 MM/M
δ= 0.5 MM/M
MULTRONICS, INC.
MILES FROM ANTENNA

FIGURE 13

A good example of the futility of using one point for analysis is as follows:

Field intensity measurements were made on two antennas, one operating on 162 and the other operating on 185 KC. At a given location (appears excellent) which we will call Point A, the 162 KC measurement obtained a field of 1900 microvolts whereas the 185 KC operation obtained a field of 4500 microvolts per meter. This establishes a field ratio of 2.36 (E 185/E 162 = 2.36). It also establishes a power ratio of P 185/P 162 = 5.58. Now we continued on the same radial to Point B (also an excellent location) where we found that the field at 162 KC was 2200 microvolts and the field at 185 KC was 4000 microvolts. This, therefore, established a field ratio of 1.82 or a power ratio of 3.3. During these measurements the power was maintained constant for both the 162 and the 185 KC operations; therefore, if we were attempting to state the power relationship for either antenna based on using either Point A or Point B, we immediately have a power ratio of 3.3 to 5.8, depending upon which point was selected either A or B. This is an appreciable difference in efficiency. This difference in apparent efficiency based on using one or two points for an analysis most certainly points up the reason why a series of measurements at varying distances on the same path must be carefully analyzed to obtain the true efficiency of the antenna system.

Another example of why field intensity measurements must be made to determine the efficiency and conductivities along a given path is illustrated by the following example where we assume a frequency of 1000 KC and a 90° antenna and a 120 radial ground system 90° long.

For illustration purposes we will assume that we desire to determine the 0.2 mv/m (200 microvolts per meter) contour using three different conductivities and five different powers. The following table illustrates the differences in coverage based on using the Norton (i) technique.

GROUND WAVE DISTANCES TO THE 0.2 MV/M CONTOUR IN MILES:

Power Radiated (KW)	Conductivity 5 mm/m	Conductivity 30 mm/m	Conductivity 5000 mm/m(Sea Water)
1	55.0	150.0	300.0
5	78.5	200.0	392.0
10	91.0	222.0	432.0
25	110.0	253.0	489.0
100	141.0	302.0	570.00

The above table clearly shows that with 1 KW and a conductivity of 30 mm/m the 0.2 mv/m contour goes nine miles further than the like contour of a 100 KW station where the path conductivity is 5 mm/m.

It should be readily apparent that to obtain true efficiency from any antenna system the existence of effective conductivity along a path cannot be ignored, and the effective conductivity cannot be obtained without adequate data in the form of field intensity measurements.

B. Method For Making and Analyzing Field Intensity Measurements:

It has already been stated that we feel that in order to accurately determine the efficiency of a vertical antenna system, a large number of field intensity measurements should be made throughout a complete circle on radials to obtain the efficiency as well as the effective conductivity. The Federal Communications Commission for over thirty years have required a very precise method to be employed by engineers in the making of field intensity measurements to assure that the data obtained is accurate and it in turn can be analyzed to a reasonable efficiency and effective conductivity for the antenna system and the area under consideration. Section 73.186 of the Federal Communications Commission's Rules (Part III) sets forth a method for making and analyzing measurements. It is not the purpose of this section to give all of the details concerned with field intensity measurements but rather to point out that great care must be exercised in the taking and analyzing of field intensity measurements in order to obtain realistic efficiencies.

The following based on F.C.C. practices is a suggested procedure for taking and analyzing L.F. field intensity measurements:

(a) Beginning as near to the antenna as possible without including the induction field and to provide for the fact that an L.F. antenna not being a point source of radiation starting at points no closer to the antenna than one wavelength, measurements shall be made on eight or more radials, at intervals of approximately one-tenth mile up to two miles from the antenna, at intervals of approximately one-half mile from two to six miles from the antenna, at intervals of approximately two miles from six miles to forty miles from the antenna and a few additional measurements if needed at greater distances from the antenna. Where the antenna is rurally located and unobstructed measurements can be made, there shall be as many as sixty measurements on each radial. However where the antenna is located in an area where unobstructed measurements are difficult to make, measuremeans shall be made on each radial at as many unobstructed locations as possible, even though the intervals are considerably less than suggested above, particularly within 6 miles of the antenna. In cases where it is not possible to obtain accurate measurements at the closer distances (even out to 5 or 6 miles due to the character of the intervening terrain), the measurements at greater distances should be made at closer intervals. (It is suggested that "wave tilt" measurements may be made to determine and compare locations for taking field intensity measurements, particularly to determine that there are no abrupt changes in ground conductivity or that reflected waves are not causing abnormal intensities.)

(b) Next plot each individual radial's data on log-log coordinate paper with the field intensity as the ordinate and the distance as the abscissa.

(c) Prepare a family of conductivity curves for the frequency of interest. (Use Figure 10 for preparing curves similar to Figures 11 through 13.)

(d) Next place the sheet on which the actual points have been plotted over the curve prepared in step (c) above and adjust until the curve most closely matching the points is found. This curve should then be drawn on the sheet on which the points were plotted, together with the inverse distance curve corresponding to that curve. The field at 1 mile for the radial concerned shall be the ordinate on the inverse distance curve at one mile.

(e) When all radials have been analyzed in accordance with paragraph (d) above, a curve should be plotted on polar coordinate paper from the fields obtained, which gives the inverse distance field pattern at one mile. The radius of a circle, the area of which is equal to the area bounded by this pattern, is the effective field or E_{rms}. As a check of your analysis use Figures 7 and 8 to determine its reasonableness by checking the theoretical field for a given antenna system and power input.

SECTION 3

I. GENERAL:

The purpose of this section is to review some useful information pertaining to antenna L matching networks, particulary at L. F.

II. DISCUSSION:

(1) Network Efficiency:

Network efficiency is primarily determined by the components used in the network. In Section 2 it was shown how the Q of the helix coil affects the overall system losses. Antenna network efficiency can be expressed as:

$$\text{Efficiency (\%)} = \frac{Pin}{Pout} \times 100 = \frac{Pout}{Pout + Plost} \times 100 \quad (16)$$

Where:

Pin = power into network in watts.

Pout = power delivered to antenna in watts.

Plost = power lost in conponents in watts.

Exantly how to determin loss for a given network will be discussed in the following paragraphs.

(2) Networks General:

The purpose of an antenna matching network is to transform the antenna impedance to its line or generator impedance. Typical networks used in L.F. are the L, T, or π types. The T and π networks are an extension of the L network hence, we will only discuss L networks.

Matching networks operate on the principal that for any series circuit (a resistance in series with a reactance) there exists an equivalent parallel circuit (a resistance in parallel with a reactance) of the same impedance.

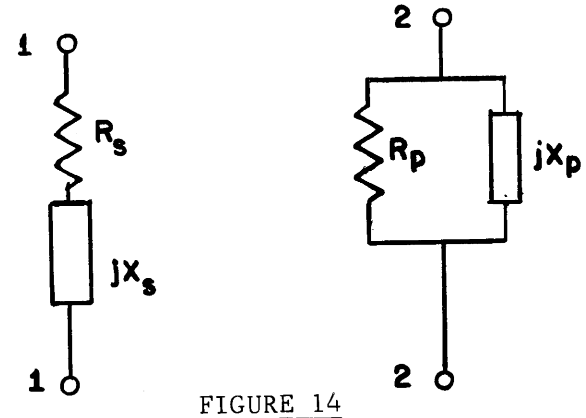


FIGURE 14

Figure 14 illustrates a series and parallel circuit having identical magnitude of impedance between terminals 1,1 and 2,2 where at the operating frequency:

$$R_p = R_s \left[1 + \frac{X_s^2}{R_s^2}\right] \text{ and } X_p = X_s \left[1 + \frac{R_s^2}{X_s^2}\right] \qquad (17)$$

Equation (17) can also be expressed as:

$$R_s = \frac{R_p}{1 + \frac{R_p^2}{X_p^2}} \qquad \text{and } X_s = \frac{X_p}{1 + \frac{X_p^2}{R_p^2}} \qquad (18)$$

It can be seen that any impedance can be balanced on the known side of a bridge, either by using two elements in parallel or by two other elements in series. Whichever arrangement is used, when balance is obtained, the values of the other arrangement which would give balance can be found from equations (17) or (18).

The impedance and Q for the series circuit of Figure 14 is:

$$Z_s = (R_s^2 + X_s^2)^{\frac{1}{2}} \qquad (19)$$

Where:

X_s = impedance in ohms for series circuit.

R_s = series resistance in ohms.

X_s = series reactance in ohms.

and

$$Q = \frac{X_s}{R_s} \quad \text{and } X_s = QR_s \tag{20}$$

The impedance for the equivalent parallel circuit of Figure 14 can be expressed as:

$$Z_p = \frac{R_p X_p}{(R_p^2 + X_p^2)^{\frac{1}{2}}} \tag{21}$$

Where:

Z_p = magnitude of parallel impedance in ohms.

The Q for the equivalent parallel circuit is:

$$Q = \frac{R_p}{X_p} \tag{22}$$

Now that we have the Q's for both the series and the equivalent parallel network, we can rearrange our equations to state:

$$\frac{R_p}{R_s} = Q^2 + 1 \tag{23}$$

Where:

Q = either series or parallel value.

We can accomplish a given transformation by selecting a value of either our series or parallel Q. For instance, assume we desire to match or transform a 50 ohm series load to a 1000 ohms generator. First we use equation (23) and substitute 50 ohms for R_s, the series R and 1000 ohms for the parallel R_p or $1000/50 = 20 = Q^2 + 1$ or $Q = 4.36$.

The series reactance is determined from equation (20) where substituting we have:

$$4.36 = \frac{X_s}{50} = 218 \text{ ohms.} \tag{24}$$

We can now say the series circuit consists of a 50 ohm resistance and a 220 ohm reactance. To find the equivalent parallel circuit we use equation (22) and substitute $Q = R_p / X_p = 4.36 = 1000 / X_p$, $X_p = 230$ ohms.

Note that the reactance can be either an inductance or a capacitor providing one side is positive and the other side negative.

Our example can be proved by use of equations (19) and (21). If we have worked the problem correctly, the magnitude determined by equation (19) we have:

$$Z_s = (50^2 + 218^2)^{\frac{1}{2}} = 225 \qquad (24)$$

Substituting in equation (21) we have:

$$Z_p = \frac{1000 \times 230}{(1000^2 + 230^2)^{\frac{1}{2}}} = 225 \qquad (25)$$

It therefore can be seen that for any series circuit of R and X there exists an equivalent parallel network having the same magnitude of impedance.

The above example, although we did not state it, is the theory of an L network. Now let's go further into the subject.

(3). <u>The L Network</u>:

The L network gets its name from its shape or the arrangement of components. An L network can be shown as:

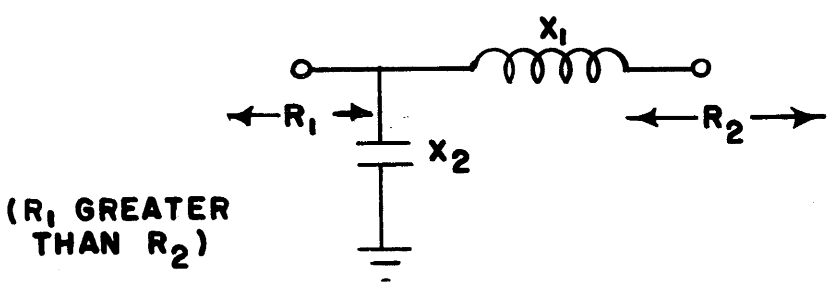


FIGURE 15

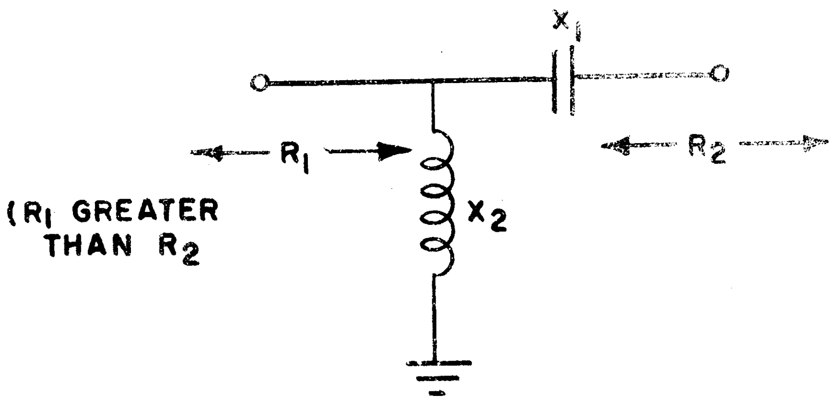


FIGURE 16

Equations (17) through (23) are used for determining the value of reactance for each element.

The following is a step by step method of calculating an L network using the above equations:

(a) With the two impedances to be matched by the L network known, the required value of Q can be calculated by using equation (23).

(b) The value of the series reactance can then be calculated by substituting the value of Q determined in step (a) in equation (20).

(c) The value of the shunt reactance, which must be of opposite sign from step (b), can then be calculated by substituting the value of Q determined in step (a) in equation (22).

(d) For either of the circuits shown in Figures 15 or 16, the value of the inductance and capacitance to be used can be determined from the equation

$$L = \frac{X_L}{2\pi f} \quad (24)$$

$$C = \frac{1}{2\pi f X_C} \quad (25)$$

Where:

L = inductance in henrys.

C = capacitance in farads.

X_L= reactance in ohms, calculated for the inductance.

X_C= reactance in ohms, calculated for the capacitance.

f = frequency in cycles per second.

It should be noted that we have not assumed the antenna or load having a reactance. Inasmuch as the antenna has reactance the output reactor of the L network will have to be equal to the value but opposite sign of the antenna reactance plus the value determined by equation (20).

We have already discussed network efficiency in general, however,it should be noted from an examination of equation (16) that it becomes increasingly difficult to achieve high efficiencies for low values of load resistance. The load resistance tends to become comparable to the coil r-f resistance in these cases. This is the problem commonly encountered when attempting to match a transmission line to antennas appreciably shorter than a quarter wavelength at L.F. The efficiency of an impedance-matching network for such an application is expressed by the

$$\% \text{ efficiency} = \frac{Q_L}{Q_A + Q_L} \qquad (28)$$

Where:

Q_L = ratio of coil reactance to coil resistance.

Q_A = ratio of antenna reactance to antenna resistance.

SECTION 4

I. GENERAL:

This section will discuss some factors pertaining to Folded Unipole antennas which is the first step to a NORD antenna system.

II. DISCUSSION:

(1) Folded Unipole Antenna:

In order to more readily understand the principal of the NORD antenna, it is first necessary to understand the theory of the folded unipole antenna, particularly operating at second resonance. So, let's take a quick look at some basic transmission line theory to explain its operation.

We know that a transmission line which is less than 90° in length and shorted at its far end will appear inductive at its input terminals. If this line is increased in length so that it equals a quarter wave, it will appear to be a parallel resonant circuit at its input. That is, it will appear to have very high impedance.

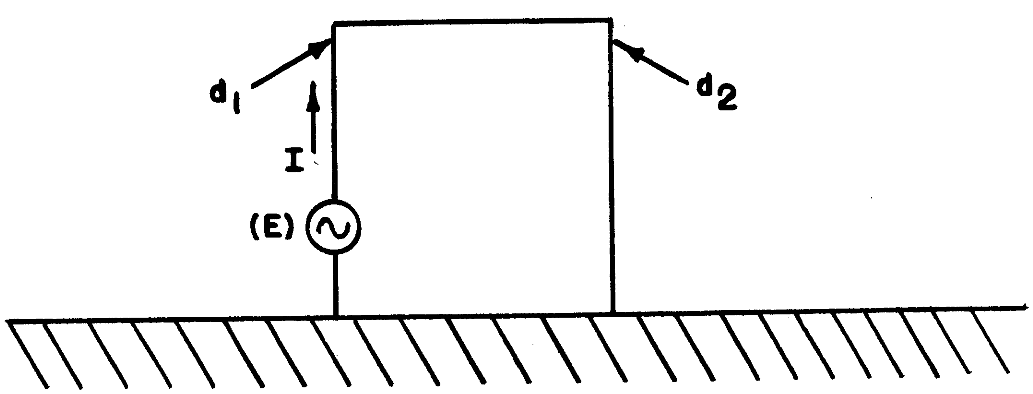


FIGURE 16

Figure 16 illustrates a one fold, folded unipole antenna. In order to determine its input impedance, let us assume a generator voltage (e) and then find the current (I) flowing in the lower end of element d_1 as illustrated in Figure 16. Roberts, (Input Impedance of a Folded Dipole, R.C.A. Review, Volume 8, No. 2, June 1947, W. Van B. Roberts) has outlined a method for analysis of a folded unipole antenna. Figure 16 then becomes:

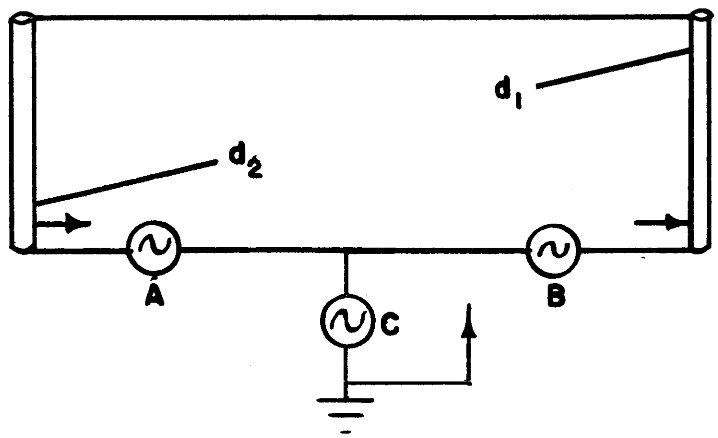


FIGURE 17

Referring to Figure 17, it should be noted that Generator A is opposing Generator C, with respect to the lower end of element d_2. Thus, element d_2 is grounded so far as any voltage in concerned.

Generators B and C impress a voltage, 2E, on the lower end of element d_1; therefore, Figure 17 is equivalent to Figure 16. Our reason for using three generators is that it is fairly easy to determine the current developed by each generator and then by the principal of superposition, add these currents to obtain the actual current in the lower end of element d_1.

Let's go a little further and first assume that there is no voltage (for the moment) in the lower generator. There is then only the voltage 2E acting between the lower ends of d_1 and d_2. Inasmuch as elements d_1 and d_2 form a 90^o transmission line, shorted at the far end, their resistance is very high; consequently, only a small current will flow into element d_1. Next, assume there is voltage only in Generator C. Then, since the lower ends of d_1 and d_2 are shorted together (by the zero internal impedance of A and B), the two elements act as a simple 90^o radiator made up of two elements connected in parallel. If R is the radiation resistance of this radiator, Generator C will supply a total current equal to E/R to this composite antenna, but by symmetry, this current divides equally between d_1 and d_2, so that the current entering element d_1 is:

$$I_1 = \frac{1/2E}{R} \tag{29}$$

Thus, if Generators A, B, and C are working at once, the voltage impressed on element d_1 is 2E, while the current entering it is 1/2E/R plus a very small amount produced by Generators A and B working above. The input resistance of element d_1, being the ratio of voltage impressed to resulting current flow, is therefore approximately 4R. If the two elements are close together, the value of resistance will be different from that of a single radiator, and the impedance multiplication due to folding is approximately four.

The impedance transformation can be expressed as follows:

$$\text{The impedance transformation} = \frac{Z_1}{Z_o} = (1 + n)^2 \tag{30}$$

Where:

Z_1 = input impedance of the folded unipole antenna.

Z_o = input impedance of a single antenna.

n = current ratio $\frac{I_2}{I_1} = 1$

Up to this point, we have discussed equal size conductors, that is, the diameter of the tower and the fold is the same. However, with the introduction of the transformation ratio, as noted in (30) above, we are now prepared to discuss the operation of a folded unipole antenna with unequal diameter conductors. Figure 18 illustrates the folded unipole antenna with unequal size conductors.

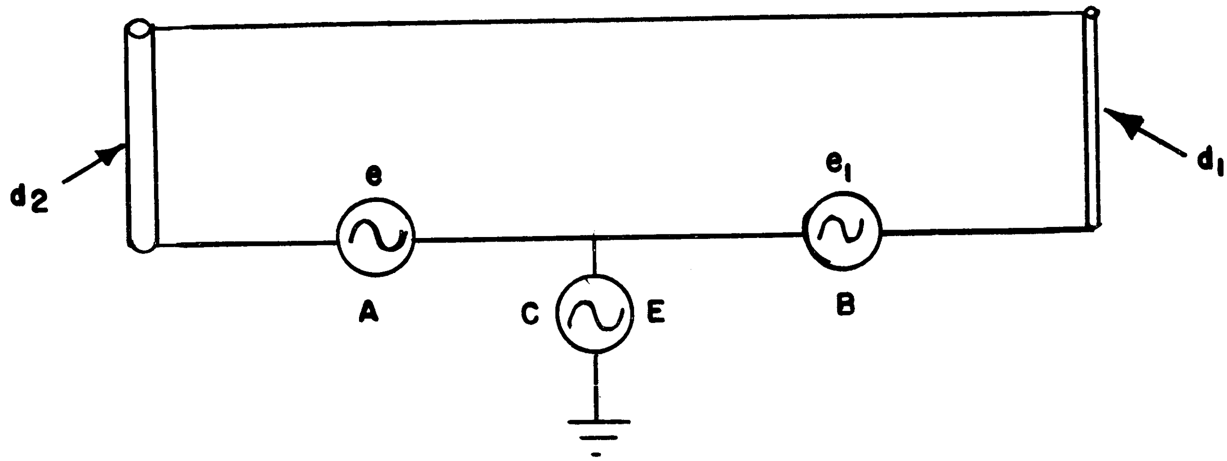


FIGURE 18

Generators A and C are alike in order to put zero voltage on element d_2, but Generator B must now be so chosen that no current will flow through Generator C when it is not producing voltage. The determination of this voltage (e_1) is one of the two essentials to the solution of the problem. The other is to determine how the current produced by Generator C, acting above, divides between elements d_1 and d_2. This problem becomes extremely complex because of the non-symmetry of the elements and there are several methods which can be used to solve the problems. (Guertler, Impedance Transformation in Folded-diopole, Proceedings of the IRE, September 1950) demonstrates a method for determining this voltage. Roberts has also demonstrated methods for determining this voltage. We will use the electro-static or capacitive method discussed by Roberts, since this method appears to offer the most promise for a simple solution. Briefly, this theory states that the current will divide directly as the ratio of the capacities of the elements, which the voltage ratio will be the inverse of the capacity ratio. To solve our problem then, we must assign undefined capacities c_1 and c_2 to elements d_1 and d_2. Then:

$$\frac{e}{e_1} = \frac{c1}{c2} \tag{31}$$

The current entering element d_1 is the total current produced by Generator C acting alone multiplied by:

$$c_1 \ / \ (c_1 + c_2) \tag{32}$$

Neglecting the very small current produced by Generator A and B acting alone, as already discussed for equal elements, the total current due to Generator C alone is:

$$\frac{e}{R} \tag{33}$$

Where:

R = radiation resistance of the two elements connected in parallel.

The driving point impedance of the antenna is:

$$\frac{(e + e_1)}{\text{the current entering } d_1} \tag{34}$$

Thus, it is readily proven that the driving point impedance is:

$$R \left(1 + \frac{c_2{}^2}{c_1}\right) \tag{35}$$

The above method of determination indicates that the impedance step up ratio depends upon the ratio of the elements' diameters, being inversely proportional to the diameter of the excited fold or element and directly proportional to the diameter of the grounded element. The spacing between the tower and fold is not extremely critical, but does determine, to some extent, the impedance transformation ratio.

Although this type of antenna has good bandwidth, its bandwidth characteristics will be decreased if a transformation ratio of greater than approximately ten is attempted by means of the spacing factor. It has been found that the best way to increase the bandwidth of the antenna is to increase the number of folds.

The electrostatic or capacitive method outlined by Roberts is primarily a physicist's approach to a solution of the folded unipole antenna. It can be shown that the impedance transformation ratio for a folded unipole antenna where unequal diameters are used is:

$$\text{Transformation ratio} = \left(1 + \frac{Z_1}{Z_2}\right)^2 \qquad (36)$$

Where:

Z_1 = the characteristic impedance of a transmission line made up of the smaller of the two conductor diameters spaced the center to center distance of the two conductors in the antenna.

Z_2 = the characteristic impedance of a transmission line made up of two conductors the size of the larger of the two.

The above equation assumes that the power will be fed to the smaller conductor (fold). This is, the feed line from the transmitter is connected in series with the fold (fold's diameter always assumed to be smaller than tower's) so that an impedance step-up of greater than four will be achieved.

The magnitudes for Z_1 and Z_2 of equation (36) for uniform cross-section conductors can be determined from standard transmission line formulas.

A folded unipole antenna can obtain a wide range of resonant radiation resistance by varying the ratio of the diameters to the folded conductors to the diameter of the tower. The radiation resistance varies as the square of the height and if the transformation ratio is raised enough, the height of the antenna can be reduced, the limit being the point where ground losses consume a prohibitive percentage of the power.

For practical operation a very short antenna should have a resistance of at least 25 ohms. Unfortunately short series fed antennas in the range of 5° to 30° do not approach this value (only 1 to 4 ohms); consequently, these types of antennas have excessive losses. In these ranges, the use of a top-loaded folded unipole antenna is extremely desirable, inasmuch as these antennas can be operated at first or second resonance. For second resonance, a top-loaded folded unipole has a length of approximately one half that of a folded unipole at first resonance.

It should be noted that a folded unipole antenna can go into first resonance at approximately a frequency equivalent to 60° of electrical length, therefore, this is the same as saying that if a folded unipole antenna goes into first resonance at an equivalent length of 60°, we would expect second resonance to occur at approximately one half this length, or 30°. The base impedance for a top-loaded folded unipole antenna at second resonance can be expressed as:[j]

$$R_{2r} = 1580\left[\frac{h_{2r}}{2r} \times \frac{\log 4S^2/d_1d_2}{\log 2S/d2}\right]^2 \qquad (37)$$

Where:

R_{2r} = resistance of folded unipole at second resonance in ohms.

h_{2r} = height at second resonance in degrees.

$2r$ = wavelength at second resonance (same units as h_{2r}).

S = spacing, center to center, of tower to fold.

d_1 = fold diameter.

d_2 = tower diameter.

S, d_1 and d_2 should be expressed in the same units.

It should be noted that "$\log_{10}$" or "$\log_e$" can be used, inasmuch as a ratio is expressed in equation (37).

A top-loaded folded unipole antenna at second resonance can be used to obtain a base resistance on the order of 12 to 15 ohms for antennas as short as 10°.

The current in the fold wires in the antenna of a folded unipole at second resonance are in phase just the same as if the antenna were operated at first resonance, hence there is no cancellation of field due to out of phase currents and the end effect is to increase the efficiency of the short antenna, which in turn appears as an increase in effective antenna height.

Folded unipole antennas are now widely used in standard broadcast antenna systems.

SECTION 5

I. GENERAL:

Low frequency antennas are invariably short in terms of their operating wavelength hence these systems have high values of Q and are extremely selective or narrow band.

In antenna systems the bandwidth controls the amount of intelligence that can be transmitted, therefore,this section will deal with a simple procedure for determination of bandwidth, and factors which control the usable bandwidth of an antenna.

II. DISCUSSION:

A. General:

The bandwidth of an antenna depends upon its base impedance and the rate with which its reactance and resistance change with frequency. The bandwidth is considered to be the frequency band within which the power is equal to or greater than one-half the power at resonance.

There are two types of bandwidth to be considered, one being the static condition which is the antenna reactance divided by the antenna radiation resistance (series equivalent of antenna circuit X_a/R_a), and the dynamic or loaded condition which is the net bandwidth after consideration is given to the antenna structure losses and the "tuning reactance" used to resonate the antenna.

B. Dynamic Conditions:

The loaded or dynamic bandwidth conditions can only be obtained by considering the coupling components used to resonate the antenna. If a series fed antenna less than 90^o in height is considered, we know that its equivalent circuit can be represented as a capacitor in series with a resistance. To resonate this antenna it is necessary to cancel out its negative reactance. This requires a positive reactance (helix coil) equal in magnitude to the antenna reactance. Coupling to the resistance of the antenna is then obtained either by a network (such as an L) or a coupling transformer. Conversely, if the antenna is a folded unipole or grounded type its measured reactance will be positive, therefore, a negative reactance of the same magnitude must be used to obtain resonance. Bandwidth for a simple series fed type of structure can be expressed in equation form as:

$$\Delta f = \frac{2R_a}{\frac{dx}{df}} \qquad (38)$$

Where:

Δf = bandwidth in kilocycles between half-power points.

R_a = measured antenna resitance in ohms.

$\frac{dx}{df}$ = slope of reactance curve at resonant frequency.

The effective bandwidth will be doubled when the generator is matched to the antenna circuit.

Equation (38) assumes that the resistance over the range of interest does not change appreciably. It therefore can be stated that for a series fed antenna whose resistance and reactance are symmetrical around the operating frequency that the half-power bandwidth condition is where R = X on either side of the operating frequency. ($\text{Tan}^{-1} \frac{X}{R} = 1 = 45^o$).

The bandwidth for a NORD antenna cannot be accurately determined by use of equation (38) because a NORD is designed to operate on one side of a resonant curve, hence, the resistance and reactance curves do not vary symmetrically but rather asymmetrically. Although a transfer function can be computed for any shape of curve, it is not within the scope of this course to demonstrate that technique. However, a simple method for determining bandwidth of a NORD antenna will be explained.

The bandwidth for any antenna system at the transmitter feed point can be readily obtained by the use of a VSWR meter which has a reference resistor equal to the magnitude of the characteristic impedance of the transmission line in use.

Absolute bandwidth of a system is the frequency separation between the low frequency and high frequency points where fifty percent of the applied power is delivered to the load which in this case is the antenna.

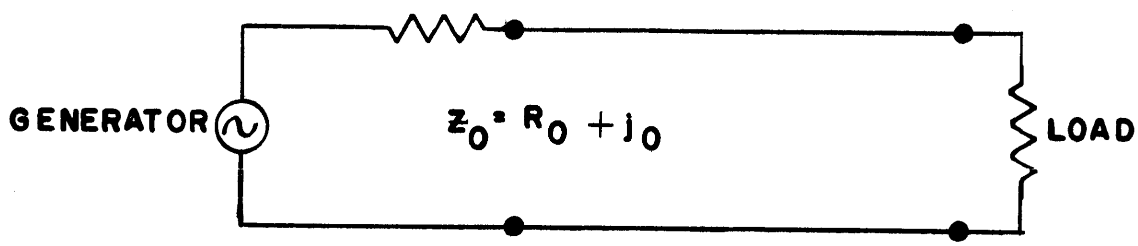


FIGURE 20

Figure 20 illustrates a transmission system in which the generator is matched to the line and the load is mismatched. The power loss may be expressed as:

$$\frac{P_m}{P} = \frac{1}{|p|^2} = \frac{(S + 1)^2}{4S} \qquad (39)$$

Where:

P = power delivered to the load.

P_m = power which would be delivered were system matched.

p = voltage reflection coefficient.

S = voltage standing wave ratio.

For the condition where one-half of the available power is delivered to the load p has a value of .707 and the VSWR is 5.83:1.0.

By connecting a signal generator to the VSWR meter and transmission line and varying the generator frequency above and below the operating frequency (frequency determined by frequency counter) of the antenna system until VSWR readings of 5.83: 1.0 are obtained the half power points are located and the bandwidth thus obtained.

C. Bandwidth Efficiency Product:

Figures 21 and 22 are bandwidth efficiency product curves. They can be used to determine the power efficiency or bandwidth when either parameter is known. In both figures the ordinate shows values of power efficiency in percent and the abscissa provides corresponding values of loss factor K. Operating bandwidth = K (Static Bandwidth). Static Bandwidth is the antenna bandwidth which would be obtained if the antenna system had no loss. Figures 21 and 22 cover ranges of power efficiency from 10 to 100 percent and 1 to 10 percent respectively.

In order to determinethe bandwidth efficiency for any antenna it is first necessary to determine the static Q, assuming the structure under consideration is a perfect radiator (no loss). This is determined by computing the radiation resistance by means of either formulas (1), (2), or (3). The base reactance is next determined by means of equation (4). The static Q of the antenna then becomes:

$$Q = X_a/R_o \qquad (40)$$

Where:

X_a = base reactance of the antenna in ohms.

R_o = radiation resistance in ohms assuming no loss.

We have already discussed how to determine the radiation efficiency of a vertical antenna but we did not point out the effect of bandwidth on radiation efficiency. The following example will illustrate a method for accurately determining the overall power efficiency that can be expected from a given antenna structure taking into

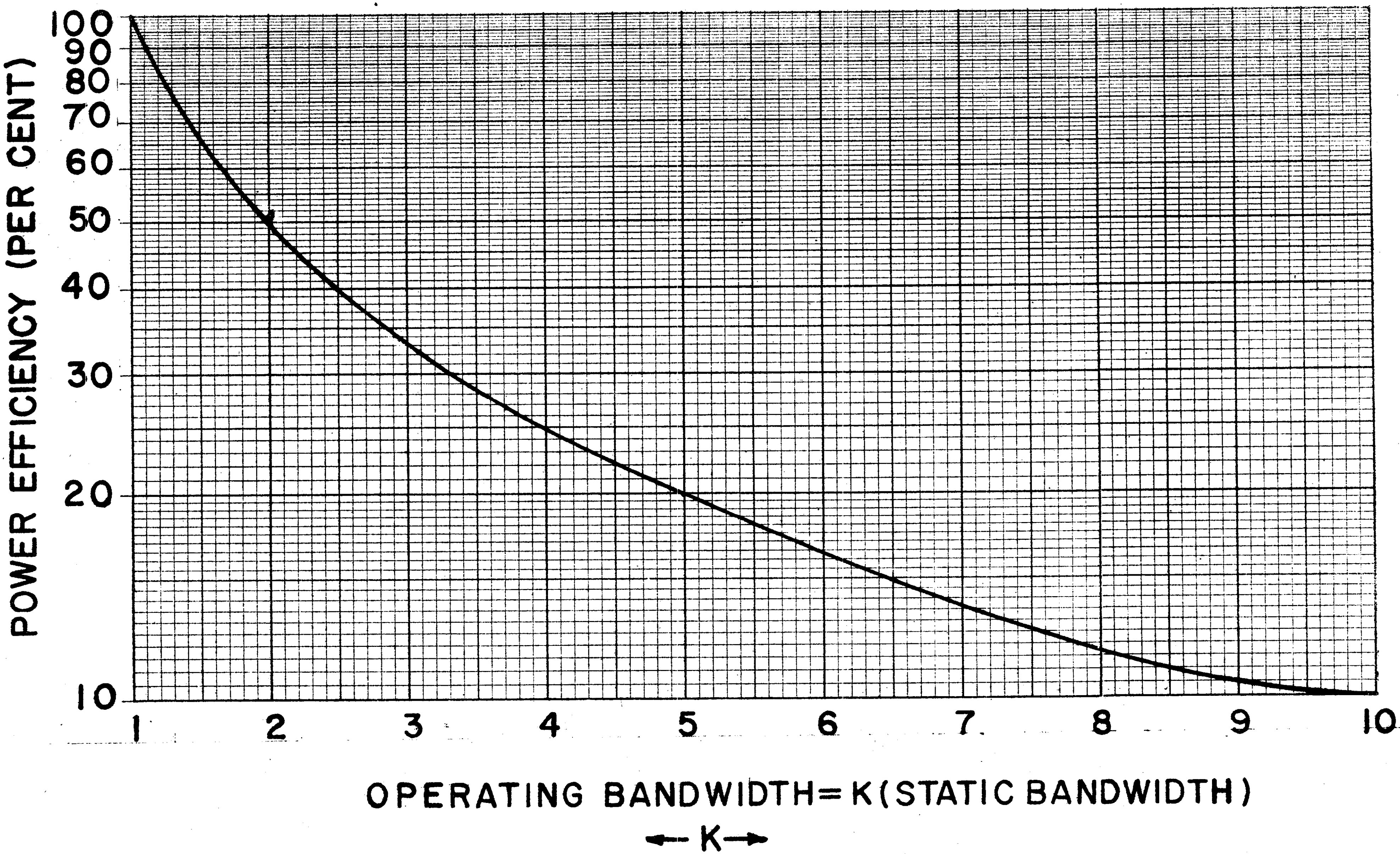


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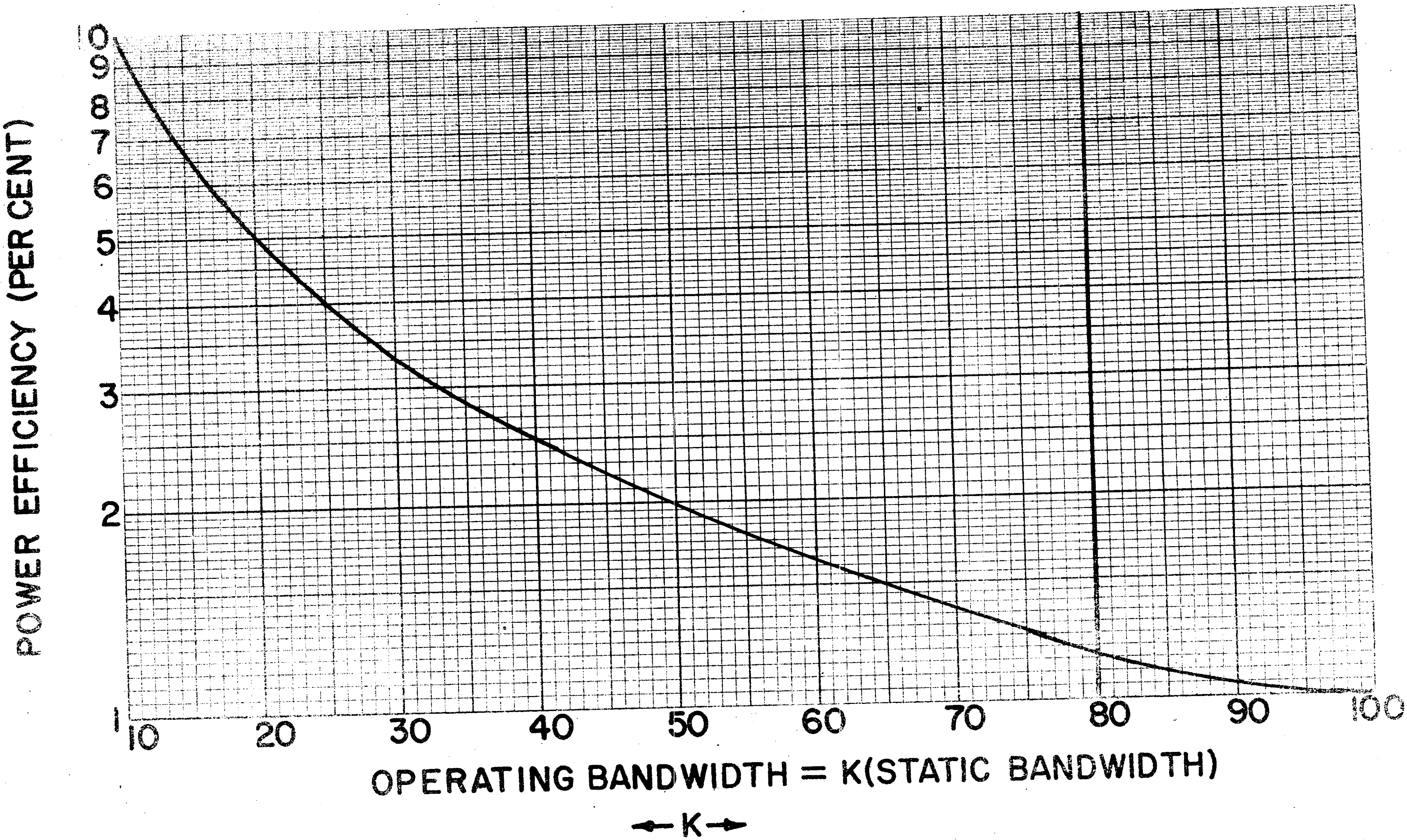
FIGURE 21



MULTRONICS, INC.

FIGURE 22

consideration its bandwidth efficiency product.

Assume a frequency of 80 KC's and an antenna 400 feet (.033 wavelengths) and a ground system consisting of 120 radials 500 feet long (.0406 wavelengths). Then determine the 100% bandwidth efficiency product for this antenna assuming no loss. This is accomplished by using equation (3) where we determine:

$$R_b = (11.78)^2 \ / \ 312 = 0.444 \text{ ohms} \tag{41}$$

and the base reactance is:

$$X_A = -j\ (Z_o \text{ Cot } \theta) \tag{42}$$

Where:

Z_o = characteristic impedance for an antenna height of 400 feet with a 3 foot side. (assumed effective radius = 1.35 feet, and L/D = 296).

θ = .033 wavelengths or 11.82^o.

Substituting in the above equation we determine that the capacitive reactance

$X_A = -j\ 1560$ ohms.

The static Q is:

$$Q = \frac{1560}{0.444} = 3514 \tag{43}$$

Knowing the static Q we can now determine the bandwidth by the expression:

$$\Delta F = f_o/Q \tag{44}$$

Where:

Δf = half power point bandwidth of antenna in cycles.

f_o = operating frequency in cycles.

Q = static Q of antenna.

Substituting in equation (44) we determine:

$$\Delta f = 80{,}000 \ / \ 3{,}514 = 22.8 \text{ cycles.} \tag{45}$$

It has been shown that the static bandwidth for a 400 foot antenna having a 3 foot side at 80 KC's is 22.8 cycles. This bandwidth represents 100% efficiency for the structure (assumes no loss).

Now that we know the static Q for our antenna we can now determine how much the bandwidth has increased and the radiation efficiency been reduced because of the losses introduced in the antenna system. (Keep in mind that as the losses are added to the radiation resistance the Q will go down which in turn means greater bandwidth). Referring to Figure 7, we determine that an antenna 0.03261 wavelengths has an unattenuated efficiency of 111 mv/m at one mile for 1 KW input. Figure 8 shows that for a ground system 0.0406 wavelengths the loss factor should be -42 mv/m. This means that the net unattenuated field intensity at one mile for 1 KW input is 69 mv/m. This, however, is not equivalent to 100% efficiency but rather a field efficiency of 37.10% ($E_1/E_r = 69/186.3 = .371$). Power efficiency is therefore equal to (0.371^2) or 13.76%.

In order to obtain the bandwidth for this antenna it is necessary first to compute the total resistance and Q one would expect for the antenna system. This is determined as follows:

(a) for lossy condition power out = 137.6 watts

$$I = \left[\frac{137.6}{0.444}\right]^{\frac{1}{2}} = (310)^{\frac{1}{2}} = 17.61 \text{ amperes} \qquad (46)$$

(b) power lost = 862.4 watts = I^2R = 310 R loss

R loss = 2.78 ohms

(c) total R = 2.78 + 0.444= 3.224 ohms

(d) knowing the total R we can now obtain the dynamic Q

$$Q = \frac{1560}{3.224} = 484 \qquad (47)$$

(e) the dynamic bandwidth is:

$$\Delta F = \frac{80,000}{484} = 165 \text{ cycles} \qquad (48)$$

It can now be stated that a 400 foot antenna (3 foot side) with a ground system of 120 radials 500 feet long at 80 KC's would have a power efficiency of 13.76% and a bandwidth of 165 cycles. This can be verified by using Figure 21 where we find that for power efficiency = 13.76%, K will equal 7.22 and bandwidth is (7.22) (22.8) = 165 cycles.

By following the step by step procedure of the example power efficiency and its associated bandwidth for any low frequency antenna can be readily determined. Where the desired operating bandwidth is known the amount of loss which must be introduced, and the resulting power efficiency can be obtained by use of the curves of Figures 21 and 22.

SECTION 6

I. GENERAL:

This section will discuss the theory and operation of a NORD antenna system.

II. DISCUSSION:

(1) Basic Information:

The NORD antenna, fed by the folded unipole principle, is basically a vertical tower radiator which is grounded at its base and fed by one or more feed wires (or folds) which are connected to the very top of the tower. In addition to feeding the antenna at its base as a folded unipole type, three wires attached to the top of the tower and spaced at 120^{o} intervals are used for top loading. The antenna is completely over top loaded. The three top loading wires extend from the top of the tower to three termination poles or towers located at a distance equal to the height of the tower plus 100 feet from its base. These poles are one third the height of the tower. At the top of each pole an insulator is inserted between the top loading wire and ground. From the end of each top loading wire, a connection is run down to the Guy Termination Unit. The G.T.U. is used for controlling the feed point impedance of the antenna. If desired they can also be used to control the phase angles of the termination currents to provide a limited directional radiation effect. The impedance or phase angle of the antenna itself can be controlled by the following:

(a) Spacing of the fold, or folds, from the tower.

(b) The diameter of the tower, as well as the diameter of the folded wire, or wires.

(c) The angle (top loading depression angle) at which the guy wires come off the tower, and the height of the grounded top loading support structures.

(d) The length of the top loading wires.

(e) Use or non-use of an interconnecting skirt wire connecting the outer ends of the three top-loading guy wires to completely enclose the cone.

(f) Use of a shorting stub connection between the fold, or folds, and the antenna.

(g) Location of the G.T.U.'s at the termination poles, versus locating them at the base of the tower and returning the currents by transmission lines.

(h) The number of folds.

(i) The height of the grounded tower.

(j) The type of ground system used.

(k) The type of network used at the guy wire terminations.

The above items are the most controlling factors for determining the impedance of the antenna.

The NORD base resistance between 100 to 200 KC's for a short tower (300 to 400 feet) can be varied from approximately 20 to several hundred ohms. Its base reactance is always inductive or positive, varying from a few ohms to approximately j400.

The electrical features of an L.F. NORD 300 foot antenna are thus materially different from those of the typical series fed Marconi Antenna. A similar height Marconi at L.F. has very low resistance (on the order of 1 ohm or less) and very high negative reactance; hence, the Marconi requires a large Helix coil for resonating, and this Helix has an effective series loss resistance greater than the antenna's base resistance. The overall system losses are therefore higher, and because the operating Q's are quite high, the Marconi antenna has a limited power handling ability and limited bandwidth capability.

The NORD, therefore, when compared to a series fed Marconi antenna has the following desirable features:

1. Bandwidth is increased materially, especially on very short antennas.

2. At L.F. an approximate 3 db increase in radiated power can be realized for very short electrical towers because of much lower coupling losses, and the ability of the antenna to accept power.

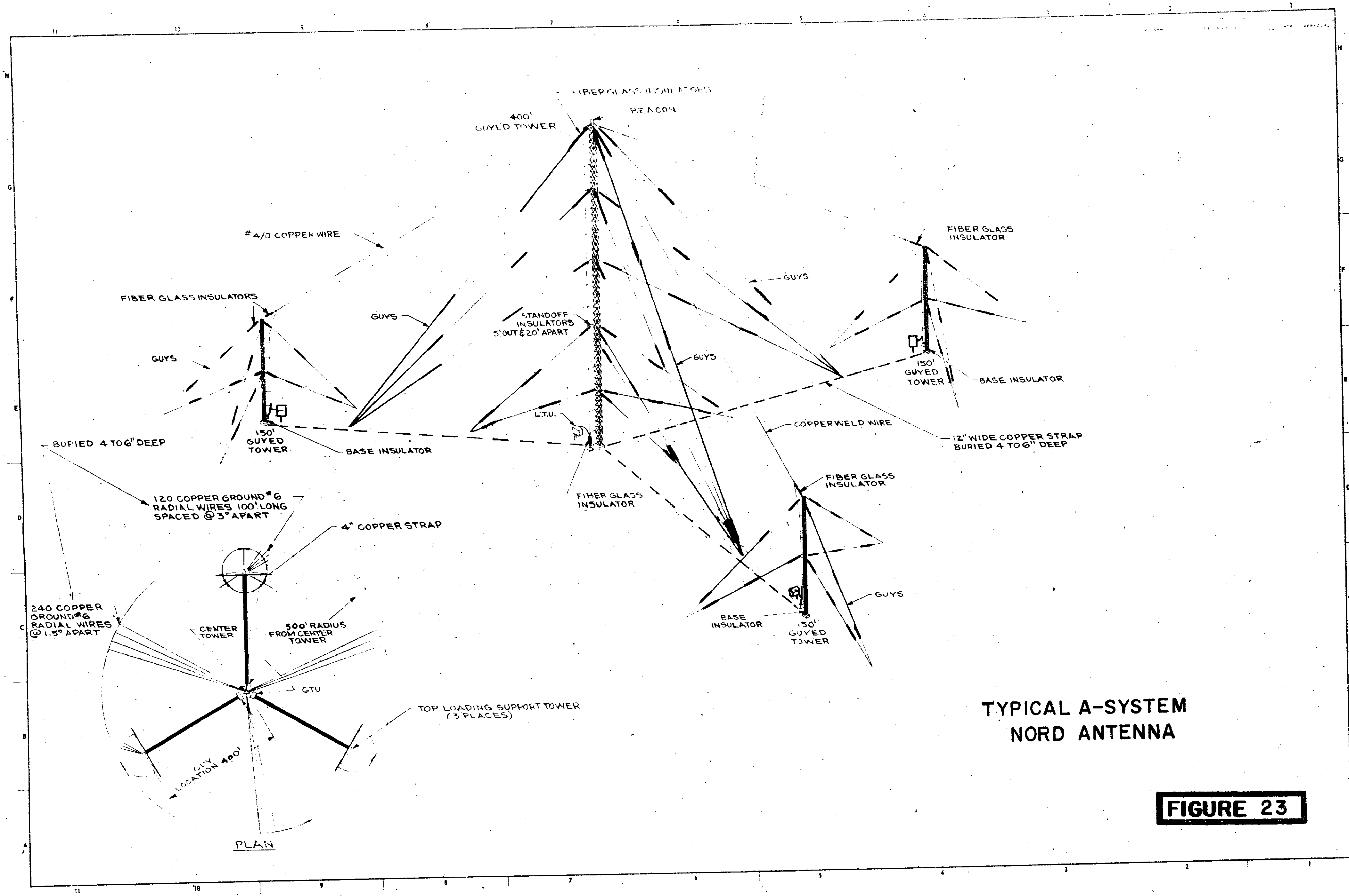
3. Because the antenna is grounded, no lighting transformer or base insulator is required inasmuch as the entire mechanical structure is D.C. grounded. Obstruction lighting, and de-icing in areas where it is required, is simplified in terms of routing 60 cycle A.C. service wiring onto the towers. In addition, the system is less subject to static discharges and induced lightning surges.

4. Because the NORD antenna feed point reactance is positive, the need for a Helix coil is eliminated.

5. For a given amount of applied power, the NORD offers a considerable reduction in the design and operational problems of managing extremely high voltages and currents.

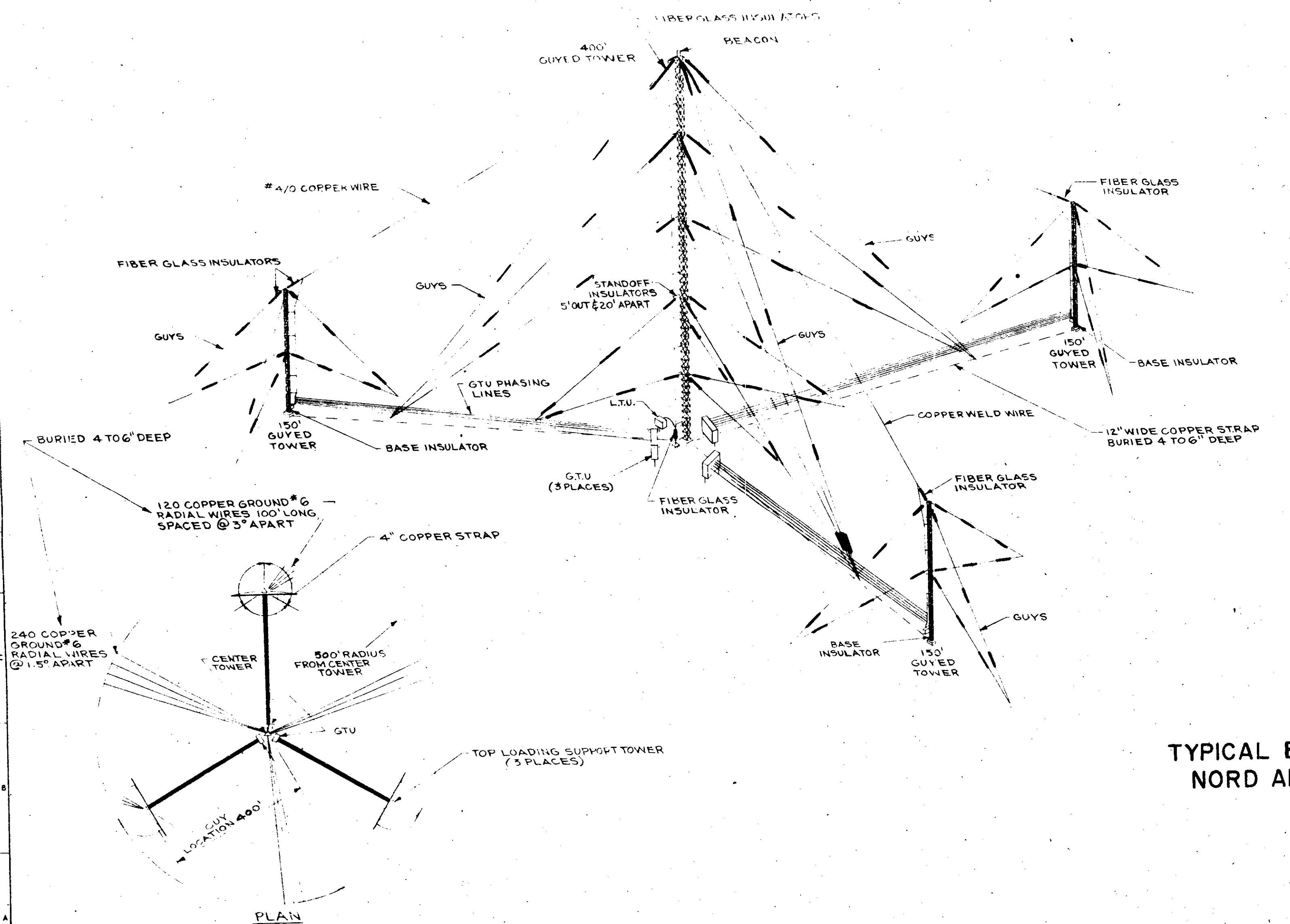
6. A material reduction in guy insulator cost is accomplished.

7. Depending upon power, a material saving in the antenna termination building or L.T.U.'s can be realized, versus the cost of a copper-lined Helix house required for a series fed antenna.



TYPICAL A-SYSTEM NORD ANTENNA

FIGURE 23



TYPICAL B-SYSTEM
NORD ANTENNA

FIGURE 24

(2) Types of NORD's:

There are two basic types of NORD's used in L.F. communications. The first type is called an "A-System" and is arranged as shown in Figure 23. This is the most common type used today.

The second type is called a "B-System" and is illustrated in Figure 24.

The primary difference between the A and B systems is the fact that the Guy Termination Units in the "B-System" are located at the base of the tower and obtain their return currents from the top-loading wires by means of a four to six wire open transmission line. The use of three such type transmission lines has some mechanical disadvantages, but this is offset by the fact that a better method of adjusting the dynamic bandwidth of the system can be realized.

(3) Theory of A NORD:

In order to more readily understand the theory of a NORD let us review some basic factors concerning series and parallel networks in relation to short vertical antennas which are series and folded unipole fed.

The equivalent network for a short series fed antenna can be shown as:

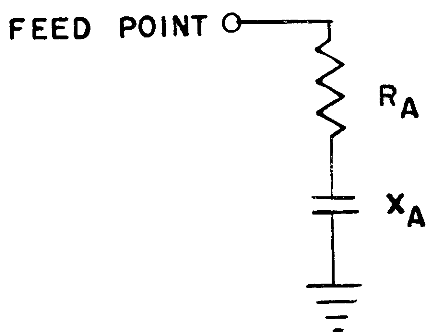


FIGURE 25

In order to transfer power from a generator or transmitter it is necessary to resonant Figure 25 by means of a Helix or inductance having the same magnitude as X_A. We now have a series circuit. The current in a series circuit can be expressed as:

$$I = \frac{E}{R + j\,(X_L - X_C)} \tag{49}$$

Where:

E = voltage at input of antenna in volts.

R = total antenna resistance plus resistance of helix.

X_L = inductive reactance of helix in ohms.

X_c = capacitive reactance of antenna in ohms.

It is evident from examining equation (49) that the reactance is zero at zero frequency and rises to a maximum at infinite frequency.

The frequency at which maximum current occurs is called the resonant frequency. The condition when the frequency is such that the maximum current flows is called resonance. The curve of Figure 26 is a resonance curve.

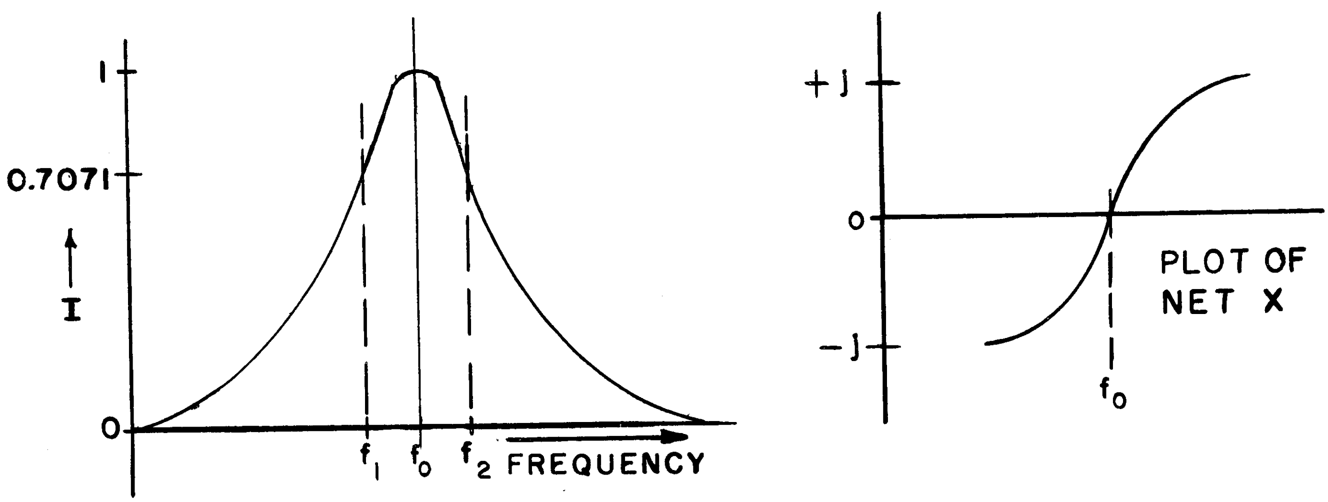


FIGURE 26

The steepness or sharpness of the resonance curve depends on the ratio of L to C and the Q of the circuit. It is evident that the higher the Q, the narrower the bandwidth (f_1 to f_2) will be (f_1 and f_2 have been represented as half power points).

Figure 25 illustrated the equivalent circuit for a short series fed antenna.

Figure 27 shows the same short antenna equivalent circuit assuming folded unipole feed.

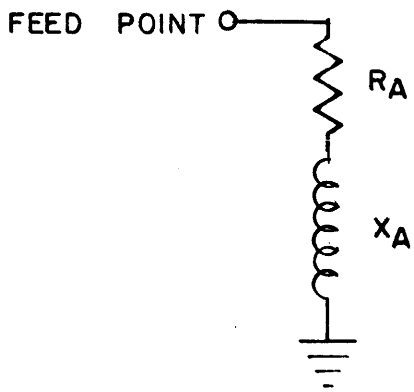


FIGURE 27

This antenna must be resonated by a series capacitor which at L.F. has a very low loss resistance and its resonance curve can also be determined from equation (49). Generally speaking because the fold wires increase the static capacity of a folded unipole, its overall Q will be somewhat lower.

Going further let's now look at a parallel resonance circuit (which our antenna will eventually look like if we consider matching networks).

Figure 28 shows at (a) another type of resonance circuit sometimes called a parallel resonance circuit and sometimes called an anti-resonant circuit because at resonance the impedance looking into terminals 1, 1 goes to a maximum. The resistance represents the resistance of the coil constituting the inductance L. Strictly, a resistance should also be shown in series with the condenser, but usually this resistance is small enough to be neglected.

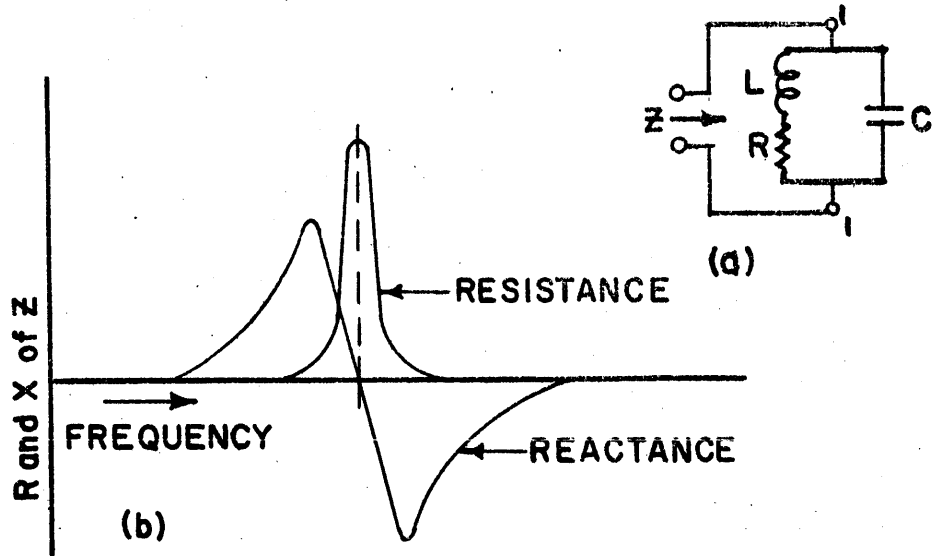


FIGURE 28

If we were to assume that the series circuit of Figure 25 was shunted by a parallel circuit such as Figure 28, we then have:

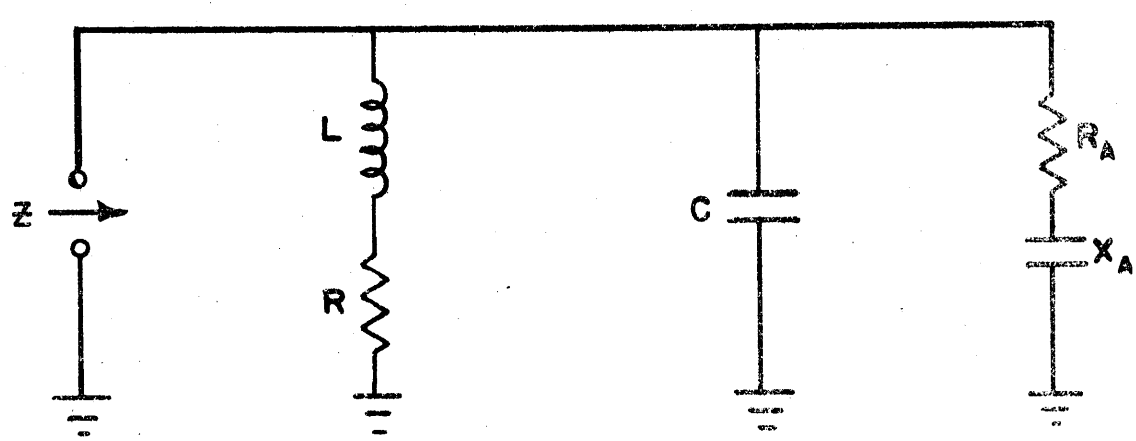


FIGURE 29

The net reactance for Figure 29 can then be shown as the dashed curve of Figure 30.

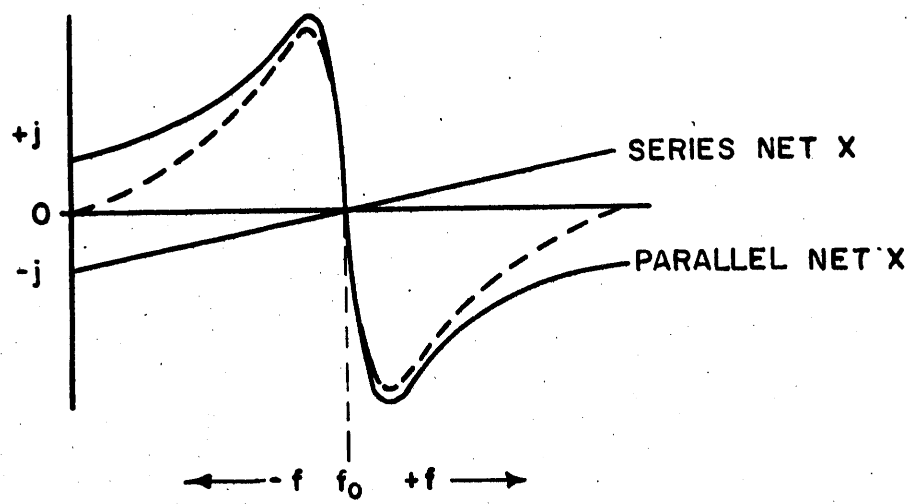


FIGURE 30

The net reactance for Figure 29 is determined by adding the ordinate values for both the parallel and series circuit over the frequency band of interest.

A simple way to show one equivalent circuit for a NORD is:

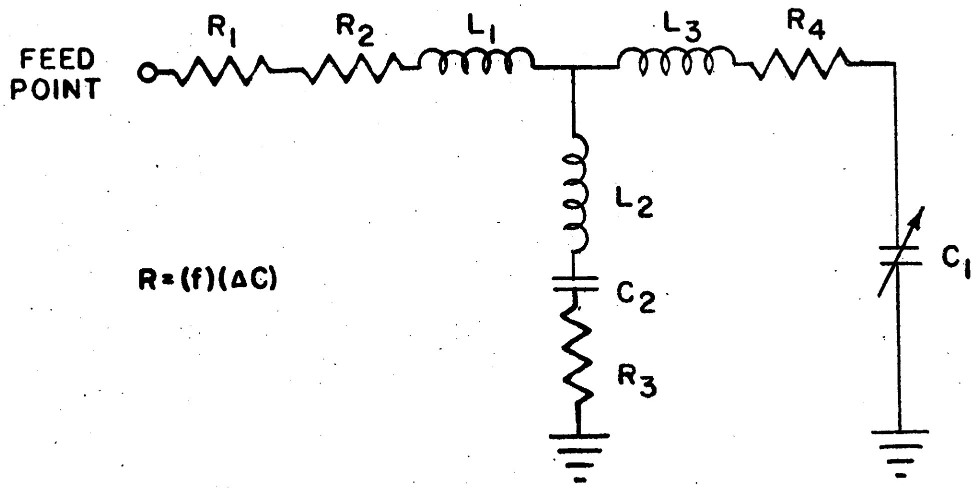


FIGURE 31

R2 and L1 represent the resistance and inductance of the vertical fold wire. R3, L2 and C2 represent the resistance, inductance, and capacitance of the grounded vertical tower. L3, R4 and C1 represent the parallel combined inductance, resistance and capacitance of the three top-loading guy wires including the adjustable guy termination tuning capacitances. C1 is the only adjustable element (other than those controlled in the physical layout), and by its adjustment we can change and control the feed point resistance. R1 is the feed point resistance, and values of R1 are readily obtainable in the order of 100 ohms or less in typical cases. One can, if desired, set the guy termination tuning to produce a feed point resistance of 50 ohms. The inductive reactance may then be cancelled out (resonance) leaving a 50 ohm pure resistance that may then be fed directly by a coaxial cable. This is practically a zero loss tuning condition since a capacitor is used for resonating the feed point. Other values may of course be used depending on specific values of bandwidth and radiation efficiency required. In such cases, a simple "L" matching network is used to transform the characteristic impedance of the transmission line down to the antenna feed point resistance while simultaneously cancelling the antenna reactance.

The net or dynamic bandwidth of the NORD is then determined by computing the net reactance for its parallel and series equivalent circuits and then combining these reactances (algebraic addition of ordinates of net reactance) together as already shown for Figure 30. It should be noted that the NORD parallel equivalent circuit is deliberately tuned to one side of the series resonance frequency so that a non-symmetrical impedance curve is obtained.

(4) Controlling the Bandwidth of a NORD:

The bandwidth of a NORD can be controlled by adjusting the Guy Termination

Unit capacity, the depression angle of the top-loading, and the addition of non-terminated top-loading wires.

Inasmuch as L.F. antenna systems will probably be used for 8 channel multiplex (requiring approximately 1700 cycles bandwidth), the net bandwidth should be adjusted as close to 1700 cycles as possible.

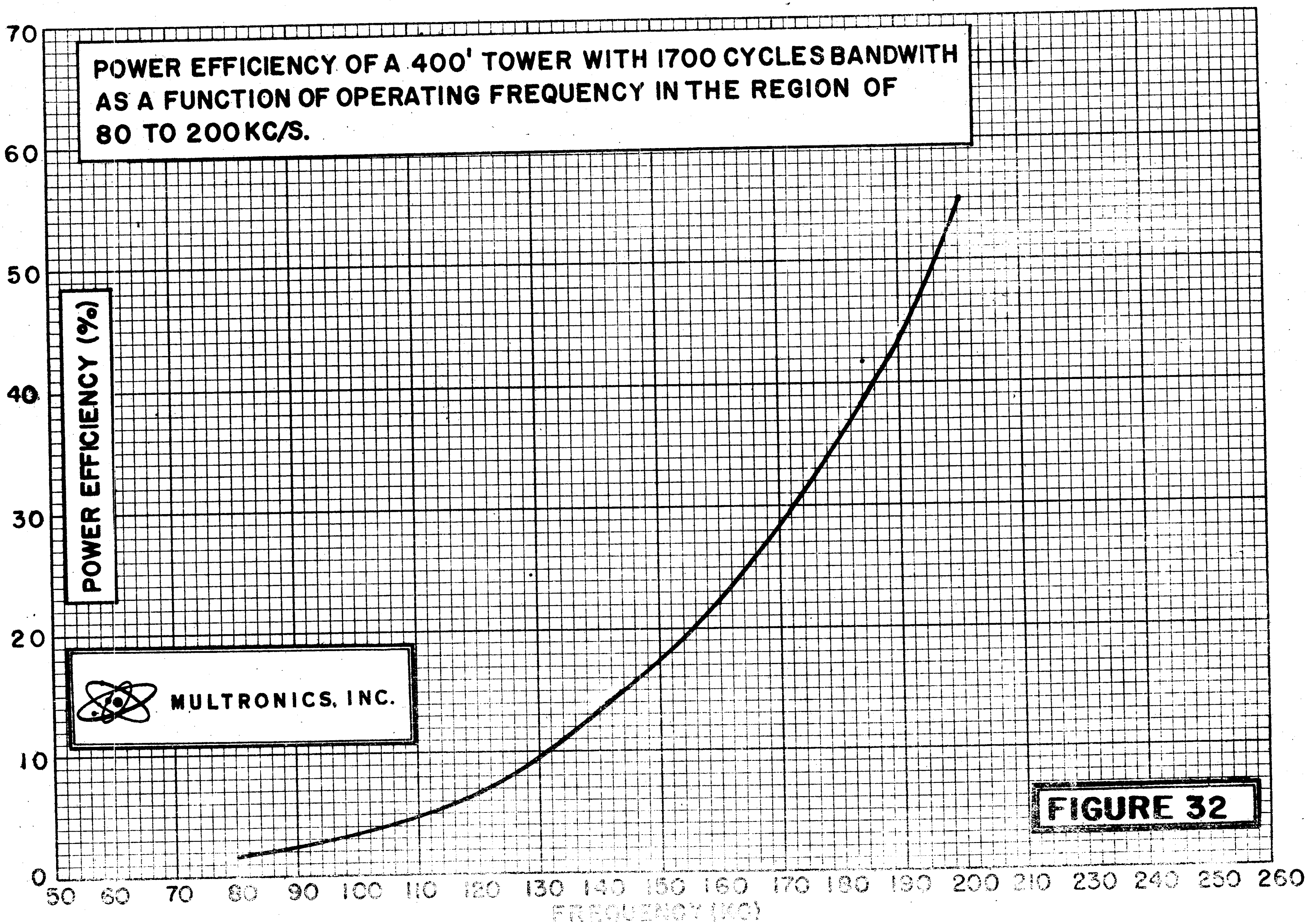
We have already demonstrated that as bandwidth is increased efficiency is reduced. The full impact however of what any vertical antenna system's efficiency looks like with a ΔF of 1700 cycles has not been shown. Figure 32 is a plot of the power efficiency of a 400 foot tower with 1700 cycles bandwidth as a function of operating frequency in the region of 80 to 200 KC's. (Ground system is 120 radials 500 feet long.) It will be noted that the power efficiency of the antenna varies from approximately 1.4 to 55%. This is equivalent to a variation in field efficiency of approximately 11.9 to 74.5%.

(5) Adjustment and Operation:

(a) General:

Once the Multronics field engineers have established the tuning settings for the Line Termination Unit and the three Guy Termination Units and recorded them in the chart provided, shifting to another frequency is simply a matter of re-setting all the tuning dial veeder counters to the specified settings for a given frequency and changing the "J" plug switching points if required. All such tuning and switching must be done with all R.F. power off.

After re-setting all adjustments, a check should be made to see that all current indications match those shown in the chart for given transmitter powers and feed point currents. Permanent meters are mounted and calibrated in the L.T.U. coupler cabinet and a portable meter is provided for checking the G.T.U. currents



POWER EFFICIENCY OF A 400' TOWER WITH 1700 CYCLES BANDWITH AS A FUNCTION OF OPERATING FREQUENCY IN THE REGION OF 80 TO 200 KC/S.
POWER EFFICIENCY (%)
MULTRONICS, INC.
0
10
20
30
40
50
60
70
50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 230 240 250 260
FREQUENCY (KC)

FIGURE 32

at the test point connectors at each G.T.U. Records should be regularly maintained to correlate the antenna instrument readings with the transmitter's final P.A. stage plate currents and any other instrumentation in the transmitter output system. All antenna meters should be read at least once a week. The type of transmission (RTTY, CW, Multiplex and the number of channels) should be noted with each set of readings logged. These readings should also include pressure gauge readings on gas or dehydration equipment associated with the transmitter and antenna system.

(b) Equipment Necessary For Making Impedance and Bandwidth Measurements:

Tuning and adjusting the NORD antenna system requires the following equipment if one wishes to establish tuning counter settings for another frequency or merely check existing frequency impedances and network settings.

1. A General Radio Co. Type 916-AL R.F. Bridge.
2. A detector such as the AN/FRR-21 or R-389/URR low frequency communication receiver or equivalent.
3. A URM-25 R.F. Signal Generator or equivalent.
4. A Digital Frequency Counter.
5. Assorted patch cables for the above.
6. A VSWR Indicator.

(c) How To Set Up Antenna For a Given Base Resistance:

The following description of tuning procedure assumes one desires to set the antenna to a given base resistance (such as the contracting engineer would do on initial installation) and obtain an omnidirectional radiation pattern. It also assumes that the engineer making the adjustments is familiar with use of a Type 916-AL R.F. Bridge.

The following procedure is recommended:

1. Set up all measuring equipment at Line Termination Unit.

2. Balance bridge at desired frequency, which should be established by a frequency counter, and decide what resistance you desire to obtain. (We will assume 30 ohms for discussion.)

3. At each of the Guy Termination Units, adjust the capacity to maximum. This will occur when the veeder counter tuning dial is set at 000 and all "J" plugs are connected in between capacitor sections. (Referring to Multicap).

4. Now at the L.T.U., open up or remove the J plug immediately in series with the feed point (between current transformer and bowl insulator) and on the jack, connect the test clip of the bridge. Depending upon the frequency, you should read anywhere from 5 to 10 ohms resistance and a positive reactance of 100 to 200 ohms.

5. Next have an assistant start to reduce the capacity at one of the G.T.U.'s while the bridge is monitored continuously. As the desired range of antenna resistance is approached while reducing the G.T.U. capacitance, the bridge reading will move more and more out of balance. As this occurs the G.T.U. should be tuned more slowly in order to observe the rising values of antenna resistance.

Continue adjustment until 30 ohms is obtained. A positive reactance also will be obtained, generally greater than the magnitude of the resistance.

6. Keep in mind that we now have one G.T.U. with one value of capacitive reactance (the one we have been varying), and two others with

maximum values. The next step, therefore, is to equalize the counter dial readings on all G.T.U. tuning capacitors in order to keep the capacitances and hence the currents reasonably equal under operation.

7. Go to one of the two G.T.U.'s which are set for maximum capacity and reduce its capacitance. Then proceed to the next G.T.U. and reduce its capacity. Then proceed to the next G.T.U. (first one adjusted) and add capacity so as to produce the desired 30 ohms resistance value. After this, return to the first G.T.U. and start the round trip over again, adjusting a small amount at a time trading off counter readings until 30 ohms of feed point resistance is maintained with all G.T.U. counter dial numbers and "J" plug settings equal.

8. The resistance is now 30 ohms, but there is a positive reactance that must be tuned out before the antenna can be resonated and matched to the 50 ohm coaxial line. This is accomplished by adjusting the L network (components L, and C, as required) for the proper transformation values. The method for determining the values for an L network has already been discussed in Section 3 of this course.

The bandwidth for the system can be determined by means of the method already discussed in Section 5 of this course. It should be noted that because the NORD has an asymmetrical bandwidth curve, in order to obtain maximum efficiency (for multiplex operation) the VSWR should be converted to a power ratio and plotted against frequency. This will then allow the proper power level to be selected for each multiplex channel to obtain maximum information transfer efficiency.

After the above checks have been completed, you are now ready for power.

9. Ready for Power: After the tuning of all elements has been

and all "J" plugs have been put in place, completely remove all measu equipment from the L.T.U. along with all loose test cables and hardware. Switch the transmitter over to its dummy load and check its tuning as well as verify the proper indication of a resistive load on its reflectometer. Then switch the transmitter to the antenna transmission line.

Next raise the carrier level until about 15 KW (assumes a 100 KW P.E.P. transmitter) of power output is indicated on the transmission line. Be sure that no change in the reflectometer reading occurs as the power is raised. At this point, a complete set of current readings should be taken and logged along with the P.A. plate currents. A portable current read-out indicator is provided for making readings at the G.T.U. test points. The G.T.U. currents should be within approximately 30% of each other. If the readings are normal and compare favorably with the original readings established by the contractor's field engineers for the power level involved, the carrier level may now be raised to full power of 50 KW average. Raise the carrier level up slowly enough to observe the plate currents and the reflectometer. As power is varied, there should be no change in the reflectometer indication. Assuming that the transmitter P.A. stage has already been properly tuned and adjusted for linear operation, there will be a direct linear relationship of all antenna currents and the P.A. plate currents.

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