NORD LF ANTENNA COURSE

(SECOND EDITION)

MULTRONICS, INC.

NORD LF ANTENNA

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NORD L.F. ANTENNA COURSE
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PREFACE

This book is the first revision of a text which was written as a supplement to an eight hour course on NORD L.F. antennas. Additional material has been added on top-loading, static and dynamic bandwidths, ground systems, and NORD antenna system configurations. This text is not meant to be a complete treatise on L.F. antennas, but is intended as a basic refresher in L.F. antenna theory. 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.

It should be noted that there are patents pending covering the design of the NORD Antenna Systems.

The Authors

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SECTION 1

I. GENERAL:

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

II. 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 a short antenna having a height of much less than a quarter wavelength (always our case), arranged vertically on the surface of the earth, the radiation resistance R_r may be approximately calculated by one of the following formulas:

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

where

$\frac{\ell}{\lambda}$ = height of antenna in wavelengths.

or:

$$R_r = 10\,G^2 \qquad (2)$$ [2]

where G_o = electrical height of antenna in radians

or:

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

where R_b = base resistance in ohms and

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

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. Neglecting ground system losses, the base resistance can be considered to be equal to the radiation resistance.

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 (an antenna whose height is less than 45^{o}) can be expressed as:

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

Where:

X_A = antenna input reactance in ohms

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

θ = electrical height 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 and 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 resonance (zero reactance or antenna equal to one electrical quarter wavelength) at a height slightly less than 90° or one physical 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 (a common height used in the standard broadcast band, 540-1600 kilocycles) would tower nearly 2500 feet above the ground. Such a radiator would be extremely expensive.

In practive at 100 kilocycles, antennas whose physical height is approximately 300 to 800 feet are employed. Electrically such antennas are very small structures. Their height is but 3% to 8% 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 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 as many as fourteen guy loading wires are used) as the loading elements. These guys are electrically connected to the top of the tower and their length is fixed by the insertion of guy insulators at desired points in the guys.

Belrose (5) describes a number of experiments in top loading geometry and reports on their results in terms of radiation efficiency.

These experiments were made using a 70 foot vertical radiator and 8 umbrella wires. Figure 1 shows a profile of the experimental structure.

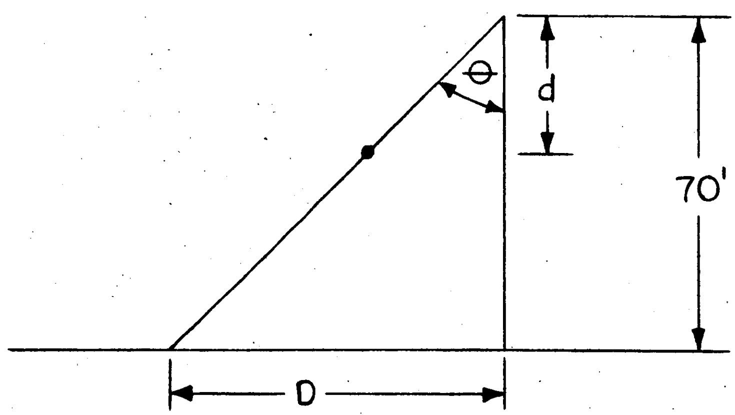


FIGURE 1

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, equal to the tower height, making θ equal to 45°. The maximum value of D was 200 feet and at this distance θ became 70.7°. Parameter d was thus varied over the range of 70 feet to 5 feet.

The antenna radiation resistance progressively increased as D was increased from the 70 foot minimum value to the 200 foot maximum figure. Considering 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 this experimental work were 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 by 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 effect of top loading that can be obtained by use of umbrella top loading wires on short antennas.

It is:

$$G_{eff} = TL_p \times 0.705 + G_{11} \qquad (5)$$

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_{11} = 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 short antennas (less than 35° at 150 kc) finds its greatest use in helping to realize a higher feed point resistance rather than an appreciable increase in radiation efficiency.

NAVSHIPS 92675, "Naval Shore Station Electronics Criteria" (14), on Page 2-16, shows the following recommended tower heights for certain transmitter powers. We have added the height figures in wavelengths and degrees to this table:

		50 KC		150 KC	
15KW	450 feet	.0227λ	- 8.17°	.0681λ	- 24.5°
15KW	600 feet	.0315λ	- 10.88°	.0908λ	- 32.7°
50KW	600 feet	.0315λ	- 10.88°	.0908λ	- 32.7°
50KW	800 feet	.0403λ	- 14.53°	.1209λ	- 43.5°

E. Current Distribution:

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

The distribution of current on an antenna can be directly related to its radiation pattern and efficiency. Figure 2 illustrates the typical short series fed antenna.

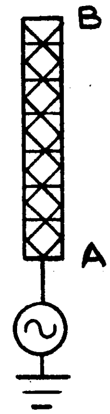


FIGURE 2

SHORT SERIES FED ANTENNA

Referring to Figure 2, 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 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 it is zero, for the current at A represents current charging the rest of the antenna, while at point B no current flows since there is nothing further to which it can flow.

Figure 2 can be modified to increase its effective height or efficiency if capacity loading is used.

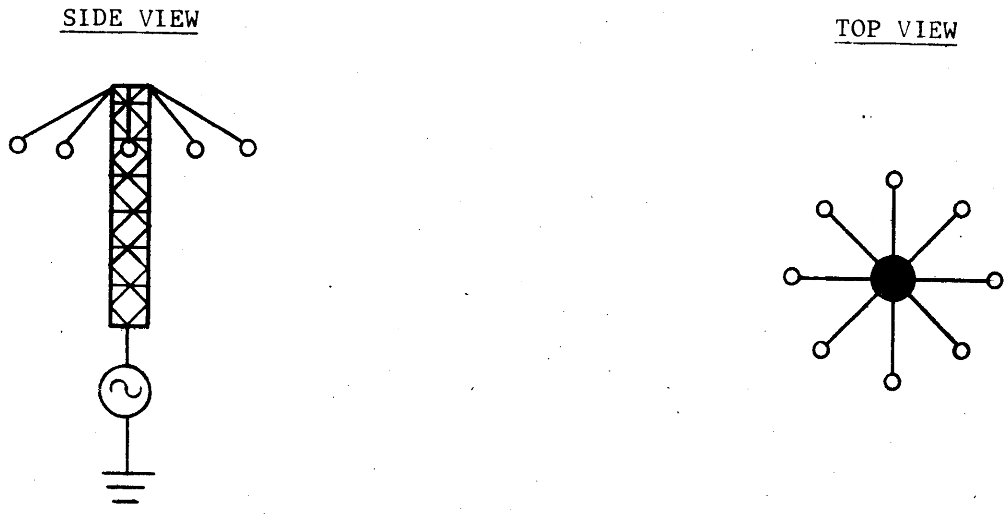


FIGURE 3

SHORT SERIES FED ANTENNA WITH GUY WIRE TOP LOADING

Referring to Figure 3 above, it will be noted that it illustrates a typical series fed vertical antenna where top loading is achieved by the use of eight 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.

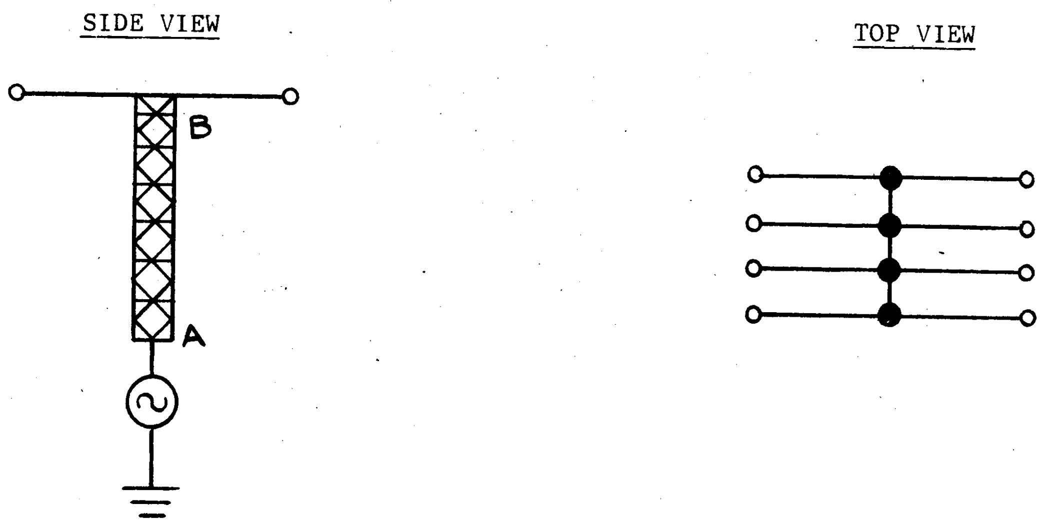


FIGURE 4

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

Referring to Figure 4 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 3 and 4, in comparison to Figure 2, 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 the effective current distribution change on a structure will be greatest 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 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: (6)

(a) Resistance of the ground system.

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

(c) Eddy currents in neighboring conductors.

(d) Poor dielectrics.

(e) Leakage paths.

(f) Corona effect.

With respect to items (a) and (b), the losses involved are in the nature of heat effect or 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 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 resistance, 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. (7) 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 that with the galvanizing thickness tripled, the loss was reduced to 0.075 ohms. Therefore, at L.F. consideration must be given to the type of the material used for the antenna.

Losses due to item (c), eddy currents, will occur in neighboring conductors, particularly those within the induction field, and these losses depend upon the type of material in the conductor, its size and shape, 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, item (d), 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 lossy 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 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, with 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 listed as item (e) may exist across the base and strain insulators of an antenna system. These paths will be affected by weather conditions and chemical composition of the atmosphere. Smith (3) found that throwing a pitcher of water over the base insulator of a short series-fed vertical radiator caused the measured base resistance to increase by a factor of three. This was due to increased losses. 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, item (f), 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 lowered 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 causes 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 (a) through (f) contributing to the loss of energy in an antenna system is approximately illustrated in Figure 5.

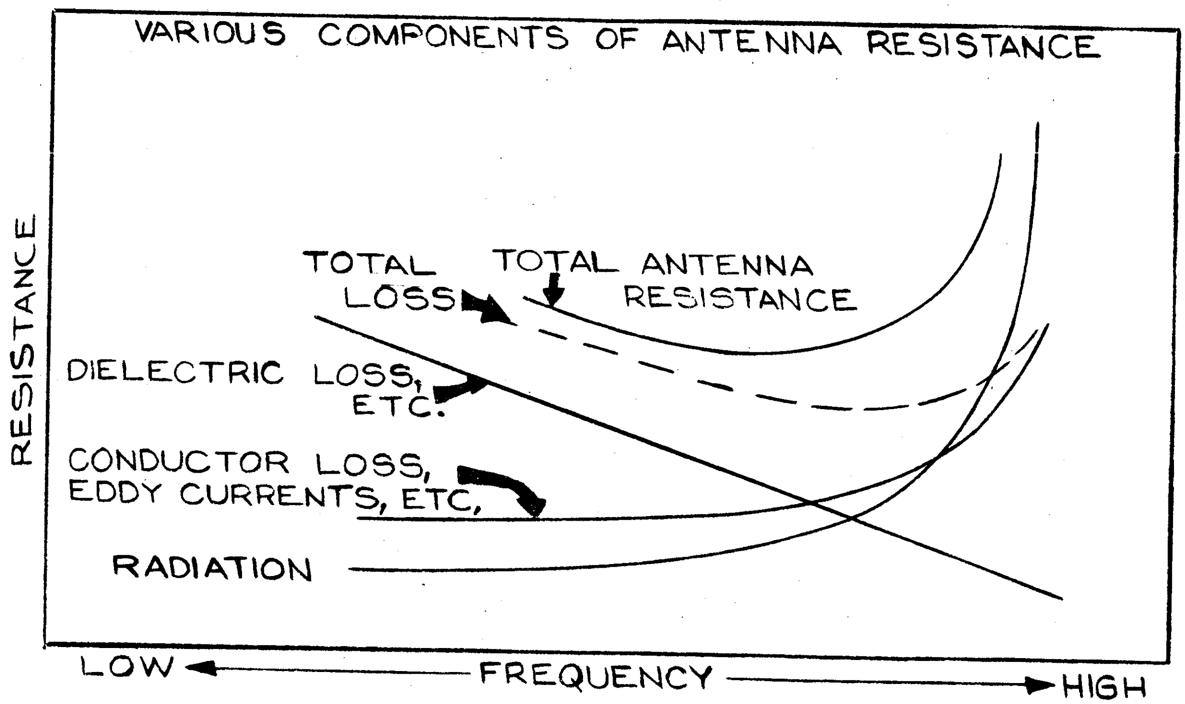


FIGURE 5

Figure 5 shows the variation of the various equivalent resistance components of the antenna 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 which 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 conisder the effect of feeding and coupling methods upon the overall efficiency of antenna systems. When dealing with antennas for which the resistance component of the feed point impedance 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 possible number of components should be employed.

To illustrate how serious the coupling losses can be, we shall conisder 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 resistance and reactance of the antenna for each frequency in order to determine the value of helix reactance necessary to resonate the antenna. We shall neglect losses other than those of the helix.

To determine the base or radiation resistance (neglecting losses) 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:

G = electrical height of antenna in degrees.

Using this approximation for resistance we develop the following:

FREQ. (KC)	G(degrees)	R_r(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:

$$X_A = - j (Z_o \text{ Cot } \theta) \quad (10)$$

Where:

X_A = antenna input reactance in ohms,

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

θ = electrical height 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(degrees)	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:

$$Q = \frac{X_A}{R_H} \quad (11)$$

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(degrees)	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(degrees)	R_r (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 radiation resistance for G = 5.46° and 10.92°, and quite close to it 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 an assumed 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_r and R_H in series so that I_A for 1 KW will be developed by:

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

Then:

FREQ. (KC)	G (degrees)	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 coil and thereby 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 Q. Since the antenna itself has a high ratio of $\frac{X}{R}$ or Q, the additional 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 characters.

For successful transmission of square on-off keying pulses, the fundamental and third harmonic side frequencies of the keying pulse frequency must be passed by the antenna system (2). The maximum permissable Q of the antenna is:

$$Q_{max} = \frac{f}{7.4F} = \frac{2f}{7.4B}$$

Where:

f = transmitting frequency in cycles.

F = keying pulse frequency.

B = keying baud rate.

7.4F = required bandwidth.

The keying pulse frequency for 25 WPM CW keying is 10. Thus at 50 KC, for example, the Q should not be greater than 676 for faithful reproduction of the 25 WPM keying pulses. For higher keying speeds, the Q would have to be reduced considerably.

Bandwidth and its effects on system losses will be discussed futher in Section 5 of this manual. Bandwidth is also discussed in the Appendix.

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 the number of ground radials which should be employed for an antenna system. A ground system of 113 to 120 radials evenly disposed around an antenna is generally considered good engineering practice 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, we shall briefly review the main purpose of 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 that of 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 skin effect. If there are ground radials present the earth

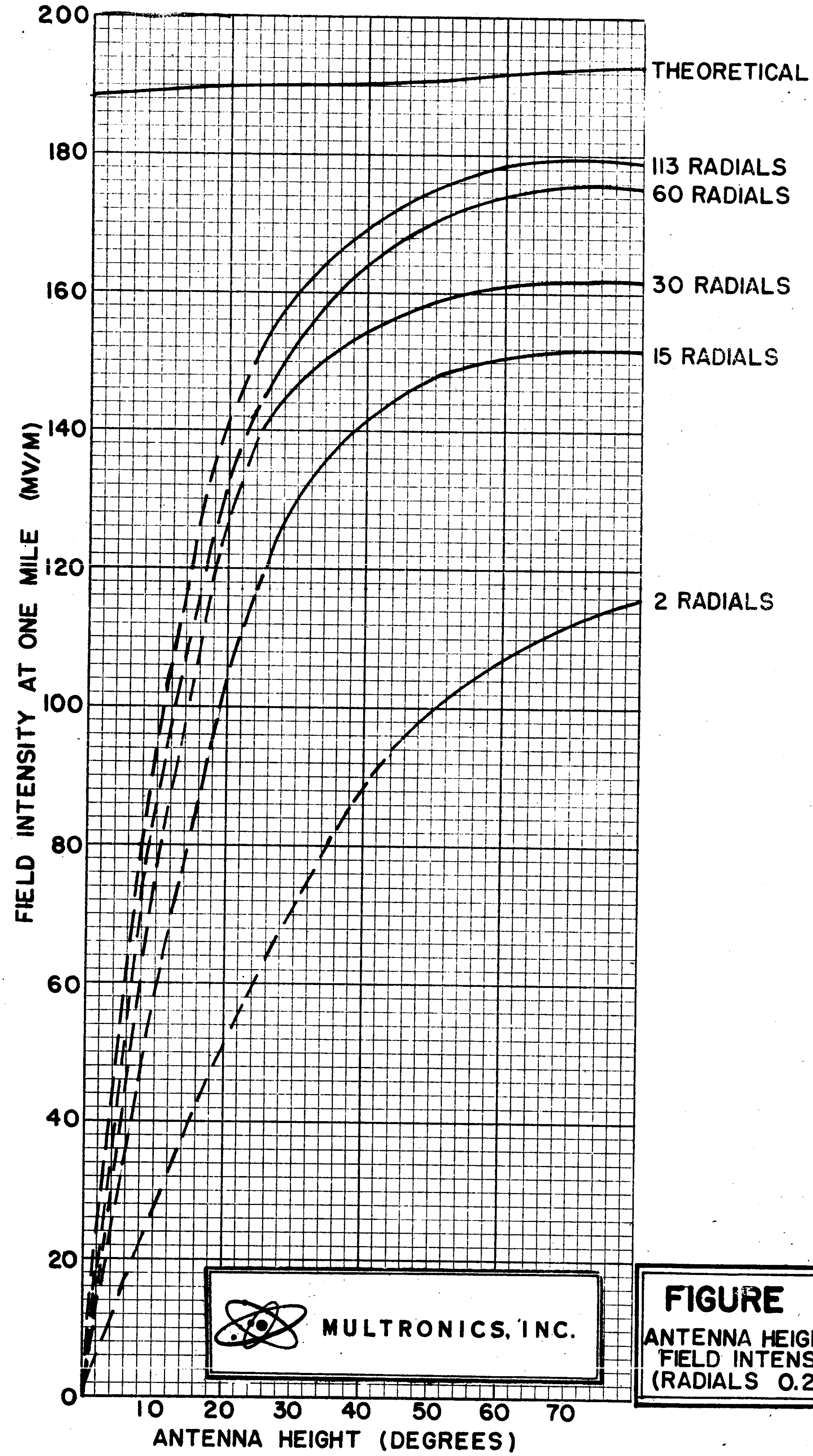


FIGURE 6

ANTENNA HEIGHT VS. FIELD INTENSITY (RADIALS 0.274λ) current will be made up of that 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. (8) 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^{o} ground system with a 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^{o} long.

HEIGHT OF ANTENNA G^{o}	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^{o} 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^{o} the difference is not as pronounced, but it is quite apparent that the 113 radial system is preferable in each case.

It should be noted that Figure 6 is for a 99.5^{o} long ground system. As a matter of information, the radius of a 99.5^{o} ground system is shown:

FREQUENCY	RADIUS
50 KC	4960 ft.
100 KC	2480 ft.
150 KC	1653 ft.

In actual practice the typical LF ground system length is closer to 500 feet which is a much smaller portion of a wavelength. Therefore the losses for typical ground systems are even higher.

(2) <u>Radiation Efficiency</u>:

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

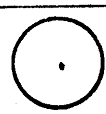
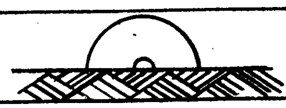
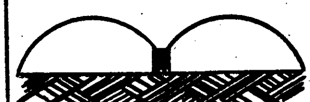
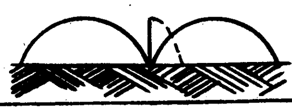
Unfortunately, in military antenna work, radiation efficiency is usually expressed as a percentage of power without stating that power is the reference. Therefore, when comparisons between antennas are made some confusion can exist unless one states what reference is being used.

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 in addition coverage of a station must be determined by measurement of the field radiated to obtain field strengths at different distances.

During World War II and thereafter it became common practice to equate efficiency of all types of 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 efficiency.

TYPE OF ANTENNA	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 VERTICAL		194.9	3.282	5.161

Inasmuch as L.F. antennas will not usually 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 premise or not, we must keep in mind that from an efficiency standpoint this only states that if such an antenna could be designed its field efficiency would be 18.4% less than that of a vertical current element).

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

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

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^o (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 a vertical current element antenna becomes shorter than a quarter wavelength the field strength remains constant for all practical purposes. (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.

$\sin G \cong G$

$\cos G \cong 1 - G^2/2$

$1 - \cos G \cong G^2/2$

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 a vertical current element 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 system with no losses. This condition will not exist in actual practice, particularly for short antennas. We therefore have to determine the total loss of the antenna system to obtain the actual radiation efficiency.

In Section 1, II, F., we briefly discussed factors which control antenna system losses. The most prominent controlable variable loss is that of the ground system. We therefore will now demonstrate in some detail 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 be at least the tower height.

(3) Examples of Computation of 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 and of the Mutual Broadcasting System, and studies made by Multronics, Inc., on short antennas. It should be noted that during the last

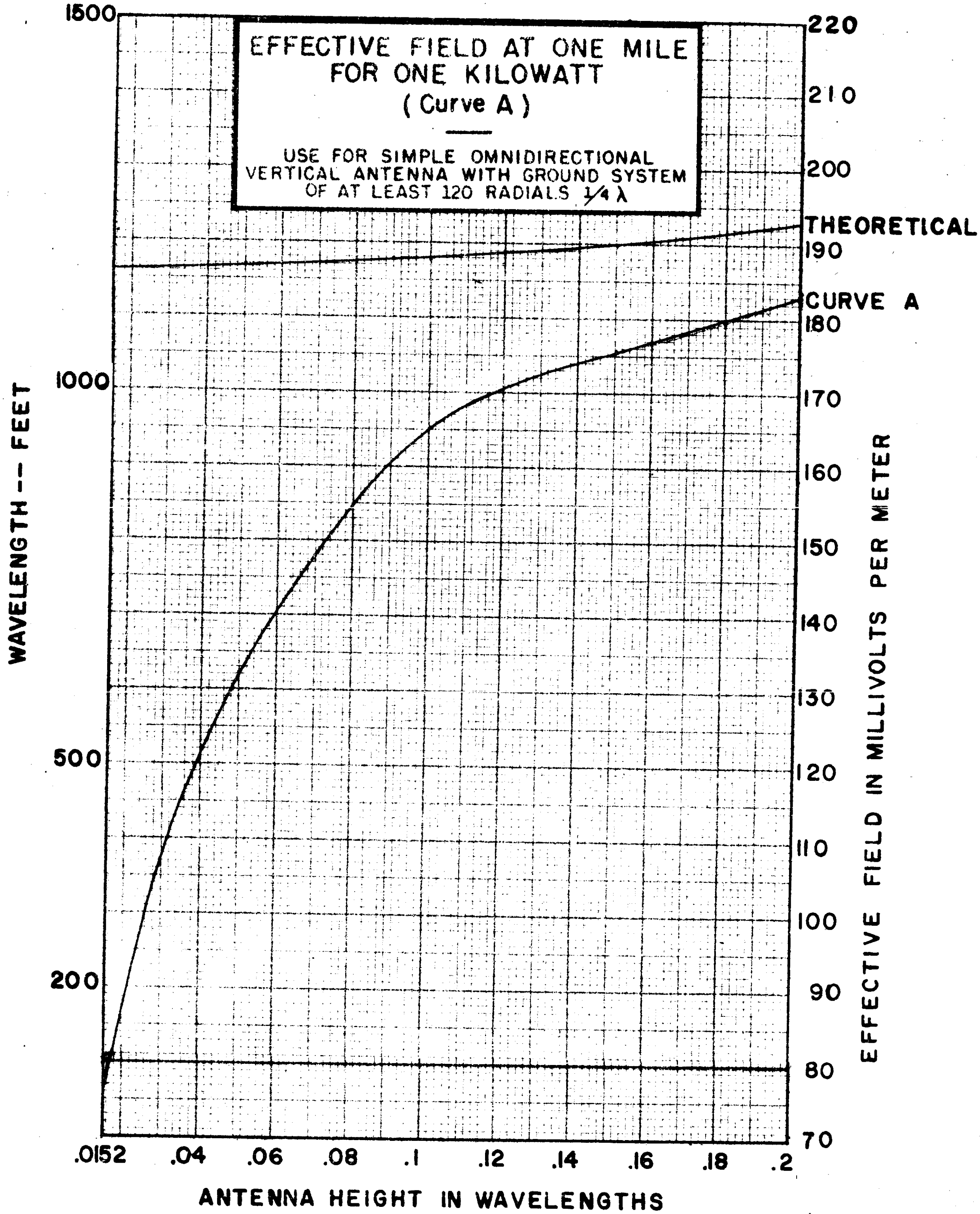


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FIGURE 7

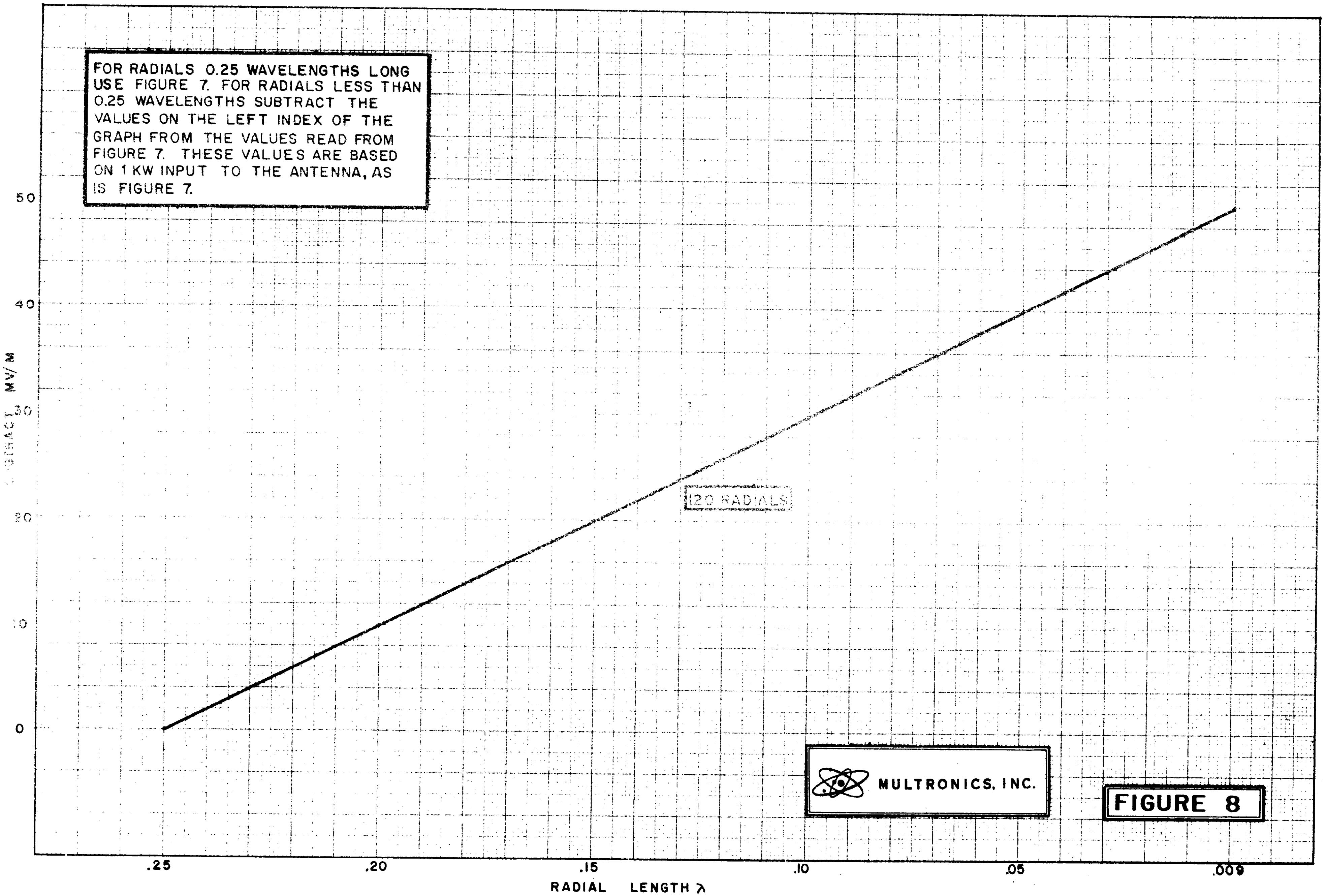
FOR RADIALS 0.25 WAVELENGTHS LONG USE FIGURE 7. FOR RADIALS LESS THAN 0.25 WAVELENGTHS SUBTRACT THE VALUES ON THE LEFT INDEX OF THE GRAPH FROM THE VALUES READ FROM FIGURE 7. THESE VALUES ARE BASED ON 1 KW INPUT TO THE ANTENNA, AS IS FIGURE 7.
SUBTRACT MV/M
50
40
30
20
10
0
120 RADIALS
.25
.20
.15
.10
.05
.009
RADIAL LENGTH λ
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FIGURE 8

thirty years appreciable information concerning antenna efficiencies has been filed with the Federal Communications Commission in the form of field intensity measurements made on over 4000 commercial broadcast antennas. The Commission in Part 73 of its Rules and Regulations has published a theoretical curve and an 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 to 0.68 wavelengths. (18^{o} to 244^{o}).

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 and 0.2 wavelengths. Figure 7 assumes the ground system to be 120 radials one quarter wavelength long. It is based on 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 with radials <u>less than</u> one quarter wavelength long.

In view of the fact that we are concerned with short antennas between 50 and 150 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).

<u>Case #1:</u>

Given: 300 foot series fed vertical antenna with a ground system consisting of 120 radials 400 feet long, operating at a frequency of 50 KC.

Determine: The field and power efficiencies.

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

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 long. Operating frequency is 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. 400 foot ground system is 14.6^{o} or 0.0406 wavelengths 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 keeping the antenna height 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

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

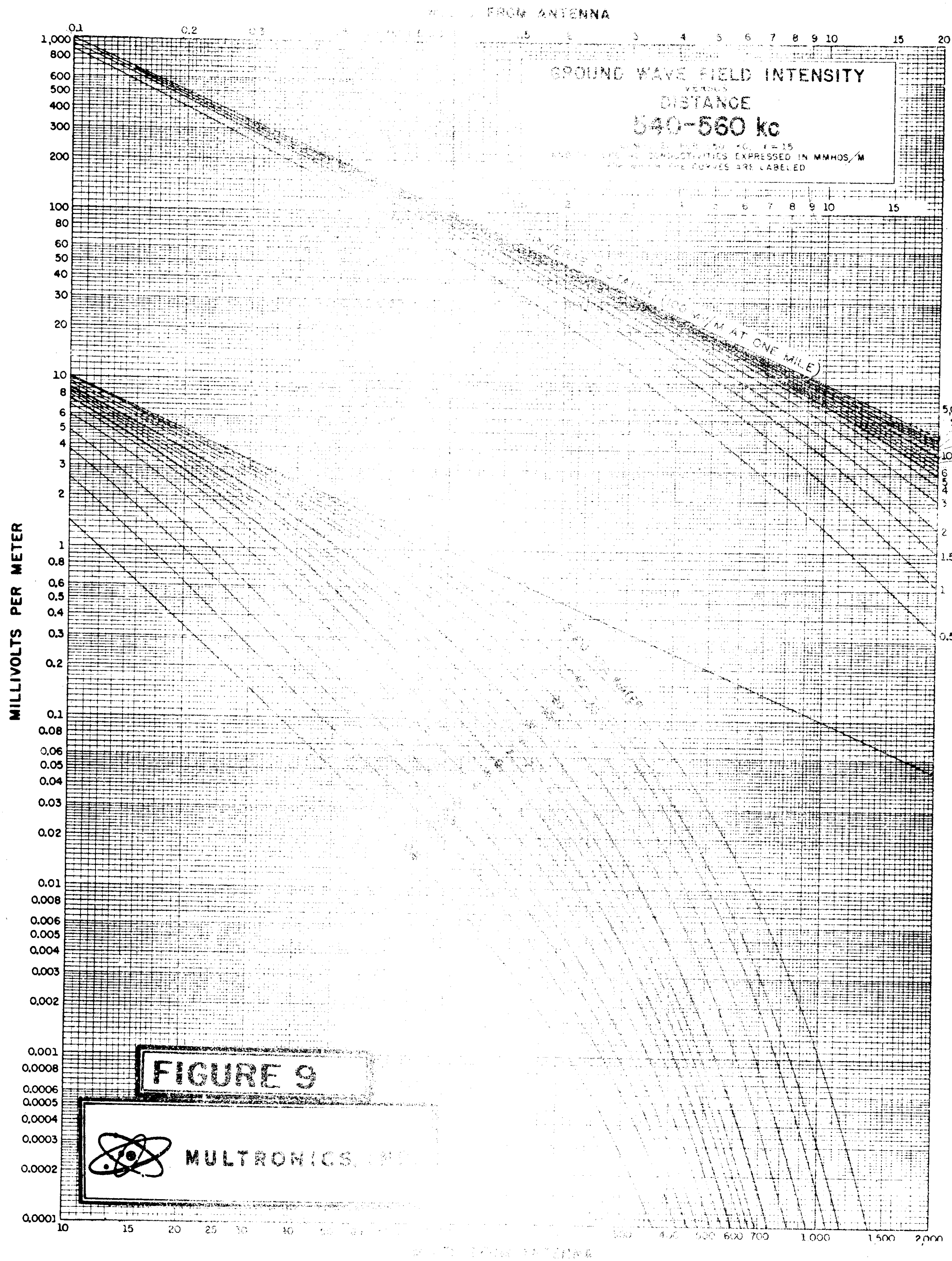
The above efficiencies are materially lower than those assumed by many engineers who have not made detailed studies of how much field and power efficiency can be obtained with various types of vertical antenna (series fed, NORD, UG's or Pan Polars) with a 300 foot height and a limited ground system.

It should now be apparent that regardless of the type of vertical antenna used, if the height is 300 feet between 50 and 150 KC (5.46^{o} to 16.38^{o}) with a ground system consisting of 120 radials 400 feet long, the <u>maximum expected</u> field efficiency will not exceed approximately 47% and the power efficiency would be on the order of 22%. (This also assumes an inherent limited bandwidth). The only way to increase the antenna efficiency for a given antenna height would be to materially increase the ground system length. Due to 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, we would expect to measure 186.3 mv/m at one mile, 93.15 mv/m at two miles, and to continue to measure reduced fields in an inverse proportion with distance. This assumes the earth to be a perfect conductor. When a signal follows this inverse relationship it is said to follow the inverse distance law and the field intensity at one mile is called the unattenuated or inverse distance 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 perfectly 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 and parallel to the surface of the earth. The surface of the earth is the guiding conductor just as in the case of propagation of energy along a transmission line, but instead of having a uniform conductor for propagation we have the vertically polarized field diminishing in magnitude inversely with the distance from the transmitting antenna. However, because we are dealing with an imperfect earth, we have to keep in mind that the electrostatic field has a slight forward tilt resulting from a downward component of energy which supplies earth losses. Therefore because the earth is not a perfect conductor, it absorbs or attenuates some of the signal and the conductivity of the path over which the signal travels will determine the amount of absorption or attenuation. Norton (9) has published data on attenuation


FROM ANTENNA
GROUND WAVE FIELD INTENSITY
DISTANCE
540-560 kc
CONDUCTIVITIES EXPRESSED IN MMHOS/M
CURVES ARE LABELED
INVERSE DISTANCE (100 mV/M AT ONE MILE)
MILLIVOLTS PER METER
FIGURE 9
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that is universally used.

Figure 9 is an example of a series of attenuation curves for a frequency range of 540-560 KC published by the Federal Communications Commission in Part 73 of its Rules and Regulations. It will be noted that sixteen different attenuation curves are shown. They are based on ground conductivities expressed in millimhos per meter (mm/m), assuming a dielectric constant of 15.

Referring again to Figure 9 we note that 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.

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

We note that the inverse distance field at one mile is 100 mv/m. At two miles it is 50 mv/m, and continues on down in accordance with the inverse distance law. For sea water (highest conductivity), we have a small amount of absorption but its real effect does not start to show up until the distance from the antenna is over 100 miles. In the case of a conductivity of 3 mm/m, however, the effect 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 3mm/m conductivity 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 due to ground conductivity must be considered before an accurate inverse distance field can be determined.

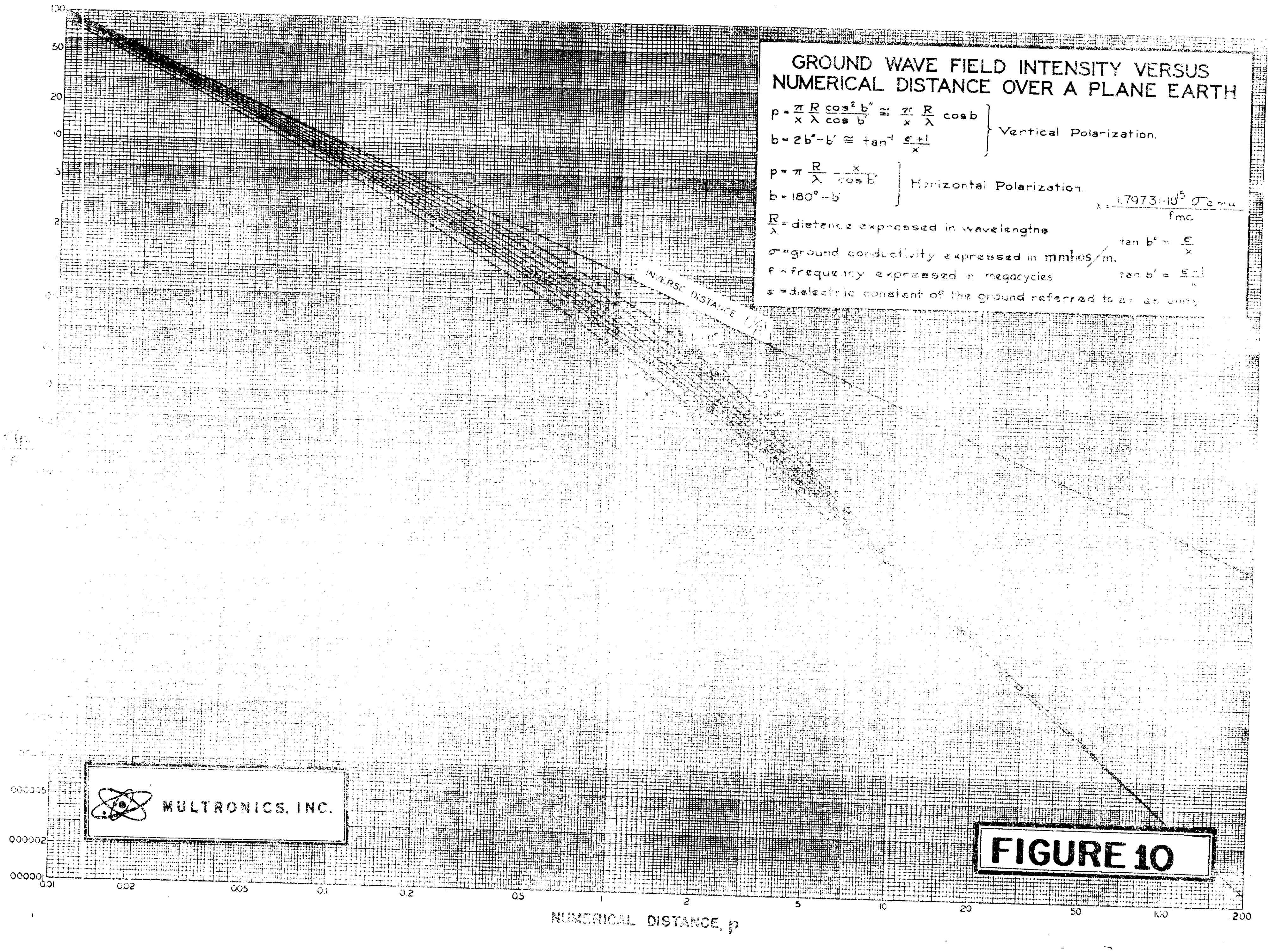
GROUND WAVE FIELD INTENSITY VERSUS NUMERICAL DISTANCE OVER A PLANE EARTH
$p = \frac{\pi}{x}\frac{R}{\lambda}\frac{\cos^2 b''}{\cos b'} \cong \frac{\pi}{x}\frac{R}{\lambda}\cos b$
$b = 2b'' - b' \cong \tan^{-1}\frac{\epsilon+1}{x}$
Vertical Polarization.
$p = \pi\frac{R}{\lambda}\frac{x}{\cos b'}$
$b = 180° - b'$
Horizontal Polarization.
$x = \frac{1.7973 \cdot 10^{15}\,\sigma_{emu}}{f_{mc}}$
$\frac{R}{\lambda}$ = distance expressed in wavelengths
$\tan b' = \frac{\epsilon}{x}$
σ = ground conductivity expressed in mmhos/m.
f = frequency expressed in megacycles
$\tan b' = \frac{\epsilon-1}{x}$
ε = dielectric constant of the ground referred to air as unity
INVERSE DISTANCE
NUMERICAL DISTANCE, p
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FIGURE 10

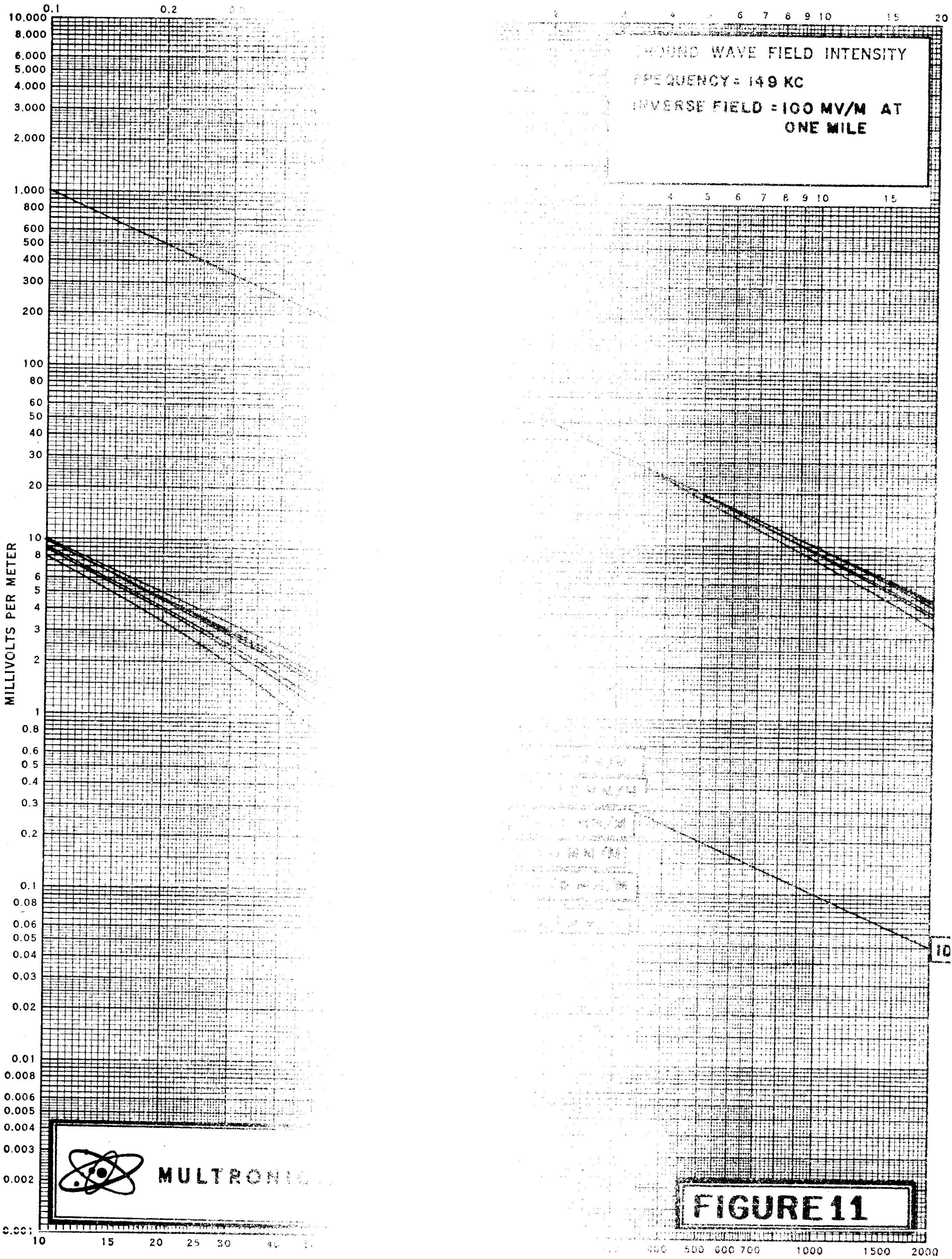
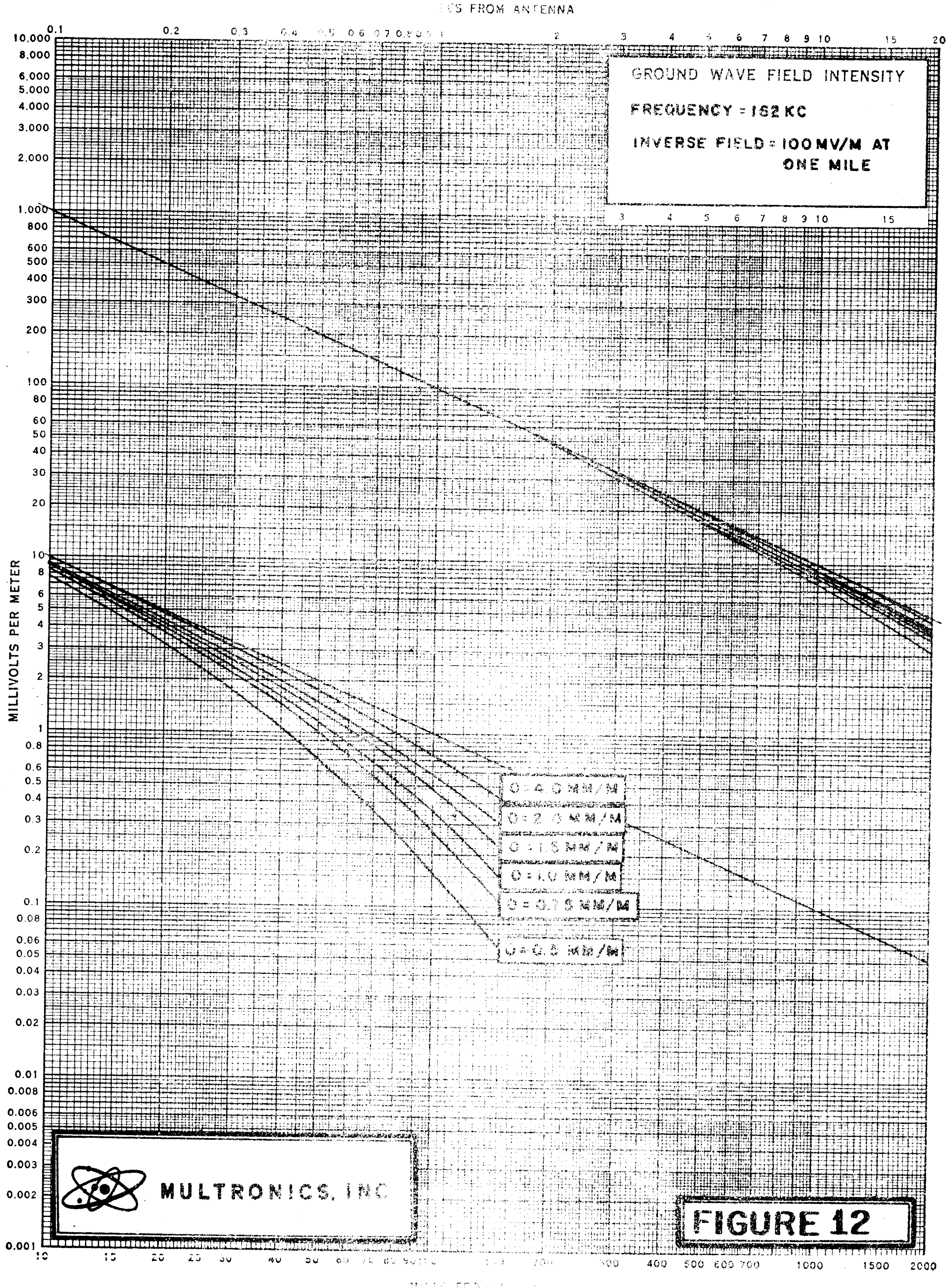

WAVE FIELD INTENSITY
149 KC
FIELD = 100 MV/M AT
ONE MILE
MILLIVOLTS PER METER
10,000
8,000
6,000
5,000
4,000
3,000
2,000
1,000
800
600
500
400
300
200
100
80
60
50
40
30
20
10
0.1
0.08
0.06
0.05
0.04
0.03
0.02
0.01
0.008
0.006
0.005
0.004
0.003
0.002
0.001
0.2
500 600 700 1000 1500 2000
10 15 20 25 30

FIGURE 11



GROUND WAVE FIELD INTENSITY
FREQUENCY = 162 KC
INVERSE FIELD = 100 MV/M AT ONE MILE
MILLIVOLTS PER METER
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
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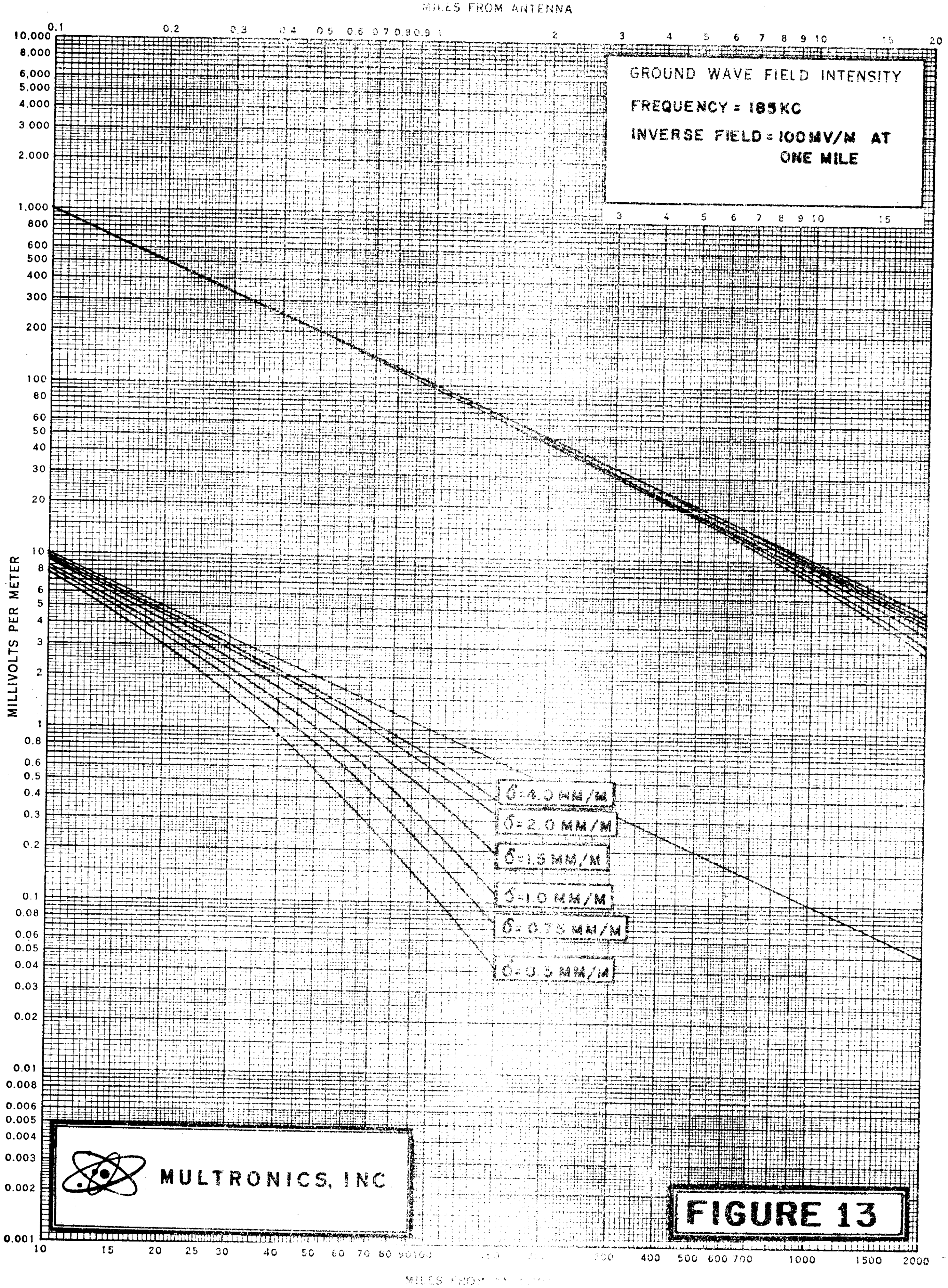
FIGURE 12



MILES FROM ANTENNA
GROUND WAVE FIELD INTENSITY
FREQUENCY = 185KC
INVERSE FIELD = 100MV/M AT ONE MILE
MILLIVOLTS PER METER
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
MULTRONICS, INC.

FIGURE 13

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

A. Attenuation or Absorption:

Attenuation or absorption at L.F. is less than at the 540 to 1600 KC broadcast frequencies, but it does exist. In order to make use of field intensity measurements and accurately determine unattenuated field intensity, one must have a family of conductivity curves to which to compare measurements for analysis purposes.

Figure 10 is a copy of Graph 21 of Part 73 of the F.C.C. Rules and Regulations, entitled "Ground Wave Field Intensity Versus Numerical Distance 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 effect of the conductivity, particularly where low effective conductivity is encountered, it 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 from ten miles back to the antenna, but beyond 10 miles the effects of low conductivity are material.

The same type of information as presented in Figures 9 through 13 can be shown in another way, as a plot of field intensity versus distance for various frequencies, for a given ground condition. Curves of this type taken from

GROUND–WAVE FIELD INTENSITY AGAINST DISTANCE CURVES
FOR VARIOUS FREQUENCIES IN MEGACYCLES PER SECOND
FOR
VERTICAL POLARIZATION
ANTENNAS AT THE EARTH'S SURFACE
TRANSMITTING ANTENNA INVERSE DISTANCE FIELD INTENSITY
OF 186.3 MILLIVOLTS PER METER AT ONE MILE
"POOR" GROUND, $\epsilon = 5$, $\sigma = 10^{-3}$ MHOS/M

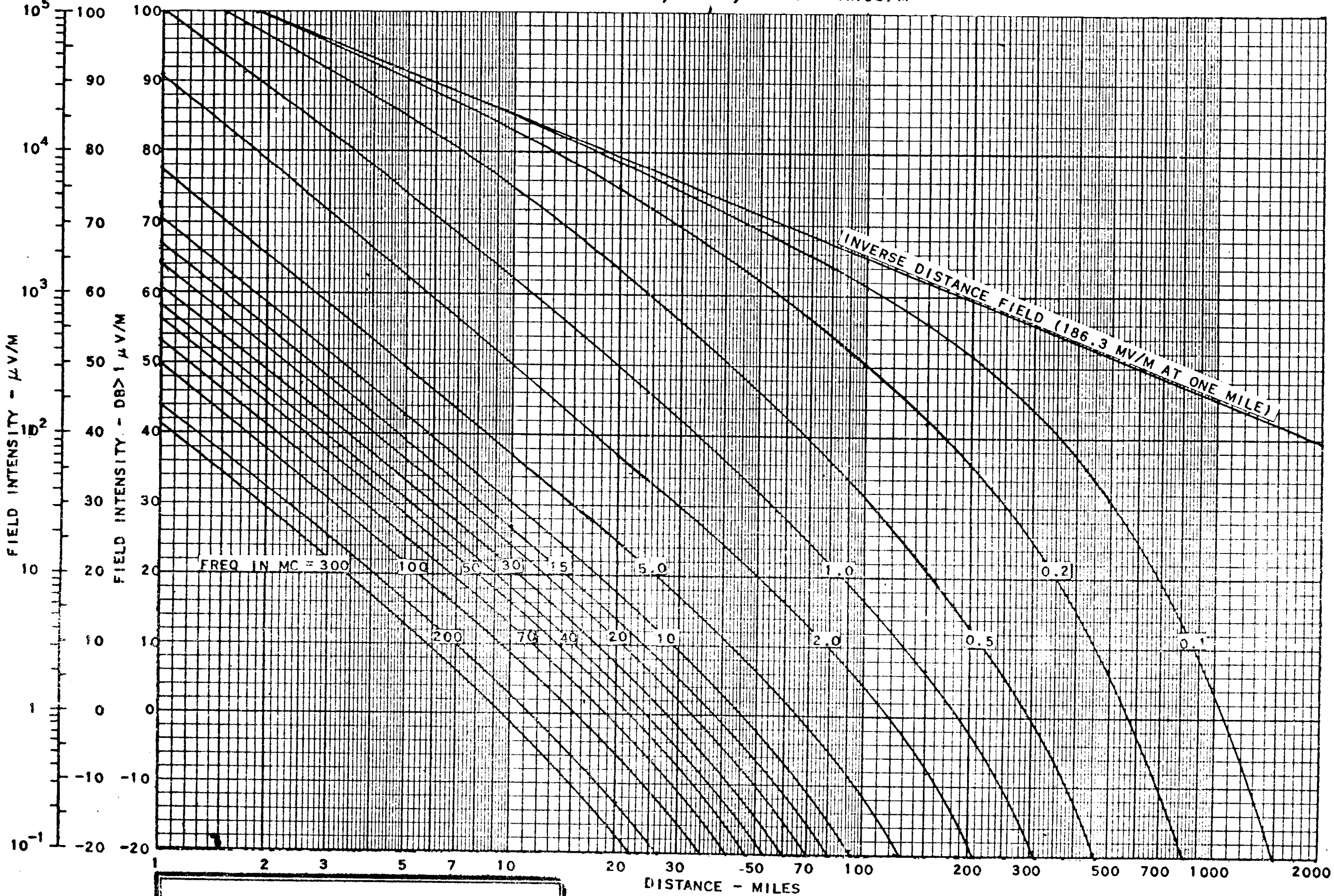


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FIGURE 14

GROUND-WAVE FIELD INTENSITY AGAINST DISTANCE CURVES
FOR VARIOUS FREQUENCIES IN MEGACYCLES PER SECOND
FOR
VERTICAL POLARIZATION
ANTENNAS AT THE EARTH'S SURFACE
TRANSMITTING ANTENNA INVERSE DISTANCE FIELD INTENSITY
OF 186.3 MILLIVOLTS PER METER AT ONE MILE
"POOR" GROUND, $\epsilon = 5$, $\sigma = 10^{-3}$ MHOS/M

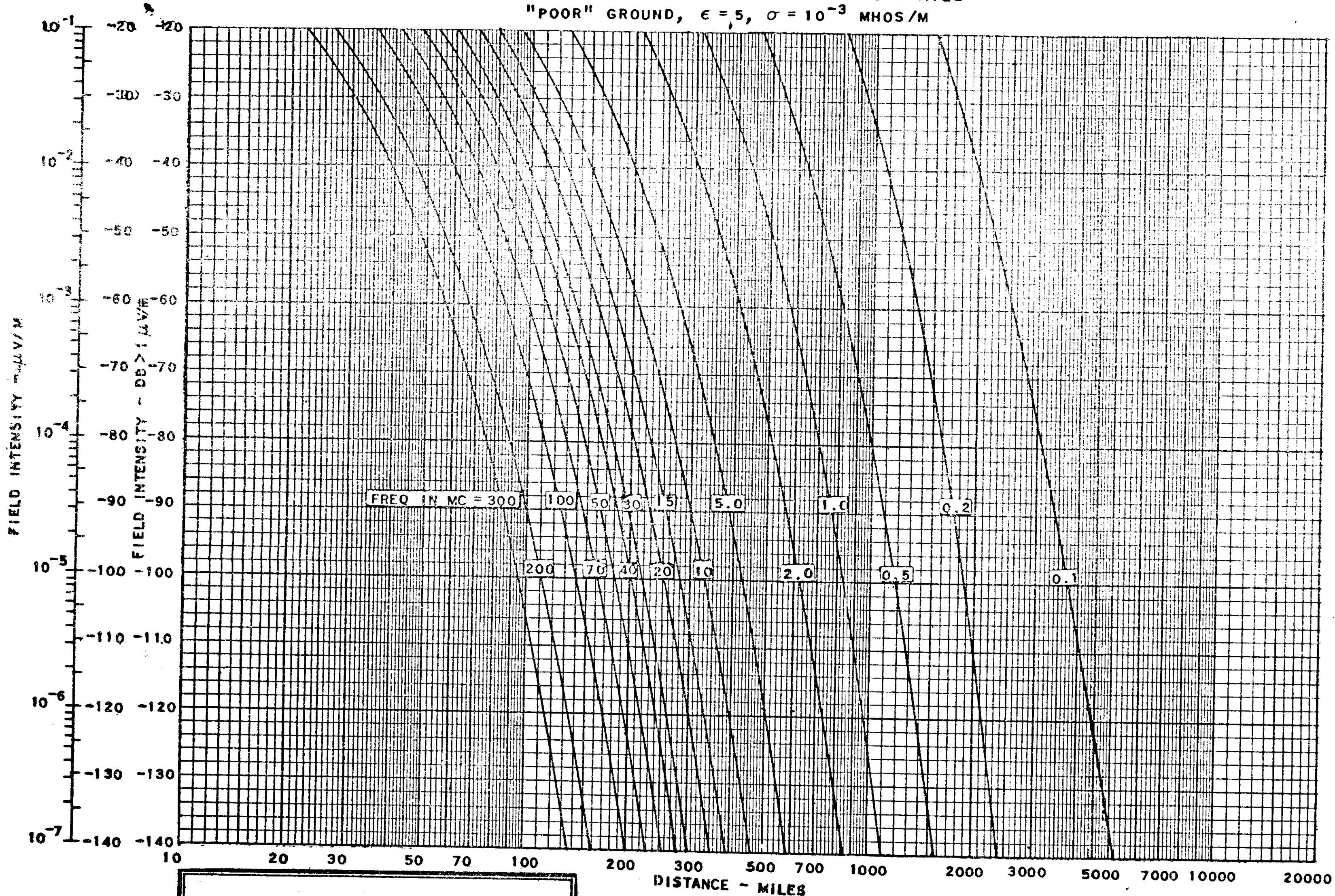

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FIGURE 15

GROUND-WAVE FIELD INTENSITY AGAINST DISTANCE CURVES
FOR VARIOUS FREQUENCIES IN MEGACYCLES PER SECOND
FOR
VERTICAL POLARIZATION
ANTENNAS AT THE EARTH'S SURFACE
TRANSMITTING ANTENNA INVERSE DISTANCE FIELD INTENSITY
OF 186.3 MILLIVOLTS PER METER AT ONE MILE
"GOOD" GROUND, $\epsilon = 15$, $\sigma = 10^{-2}$ MHOS/M

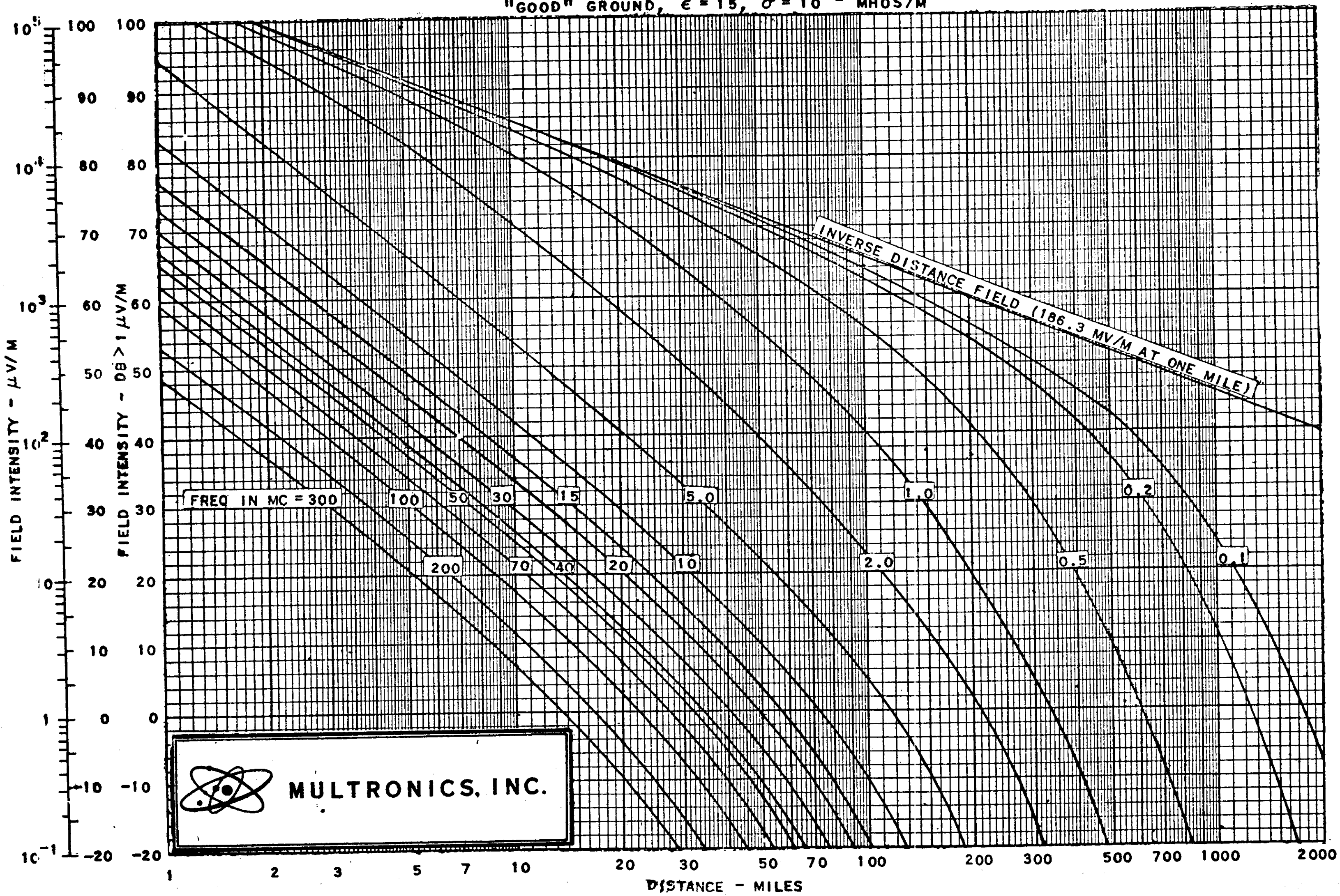

FIGURE 16

GROUND-WAVE FIELD INTENSITY AGAINST DISTANCE CURVES
FOR VARIOUS FREQUENCIES IN MEGACYCLES PER SECOND
FOR
VERTICAL POLARIZATION
ANTENNAS AT THE EARTH'S SURFACE
TRANSMITTING ANTENNA INVERSE DISTANCE FIELD INTENSITY
OF 186.3 MILLIVOLTS PER METER AT ONE MILE
"GOOD" GROUND, $\epsilon = 15$, $\sigma = 10^{-2}$ MHOS/M

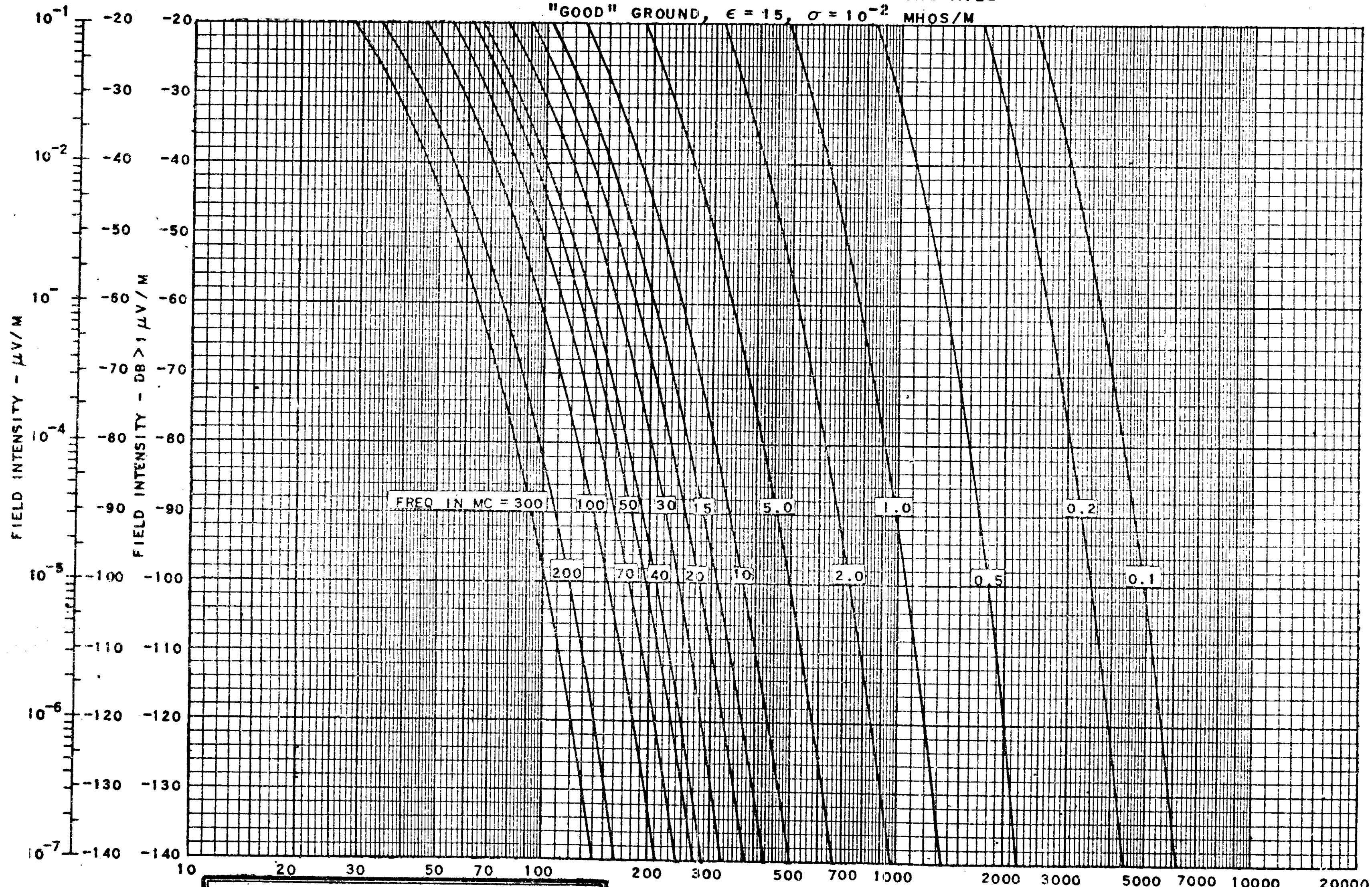

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FIGURE 17

GROUND-WAVE FIELD INTENSITY AGAINST DISTANCE CURVES
FOR VARIOUS FREQUENCIES IN MEGACYCLES PER SECOND
FOR
VERTICAL POLARIZATION
ANTENNAS AT THE EARTH'S SURFACE
TRANSMITTING ANTENNA INVERSE DISTANCE FIELD INTENSITY
OF 186.3 MILLIVOLTS PER METER AT ONE MILE
SEA WATER, $\epsilon = 80$, $\sigma = 5$ MHOS/M

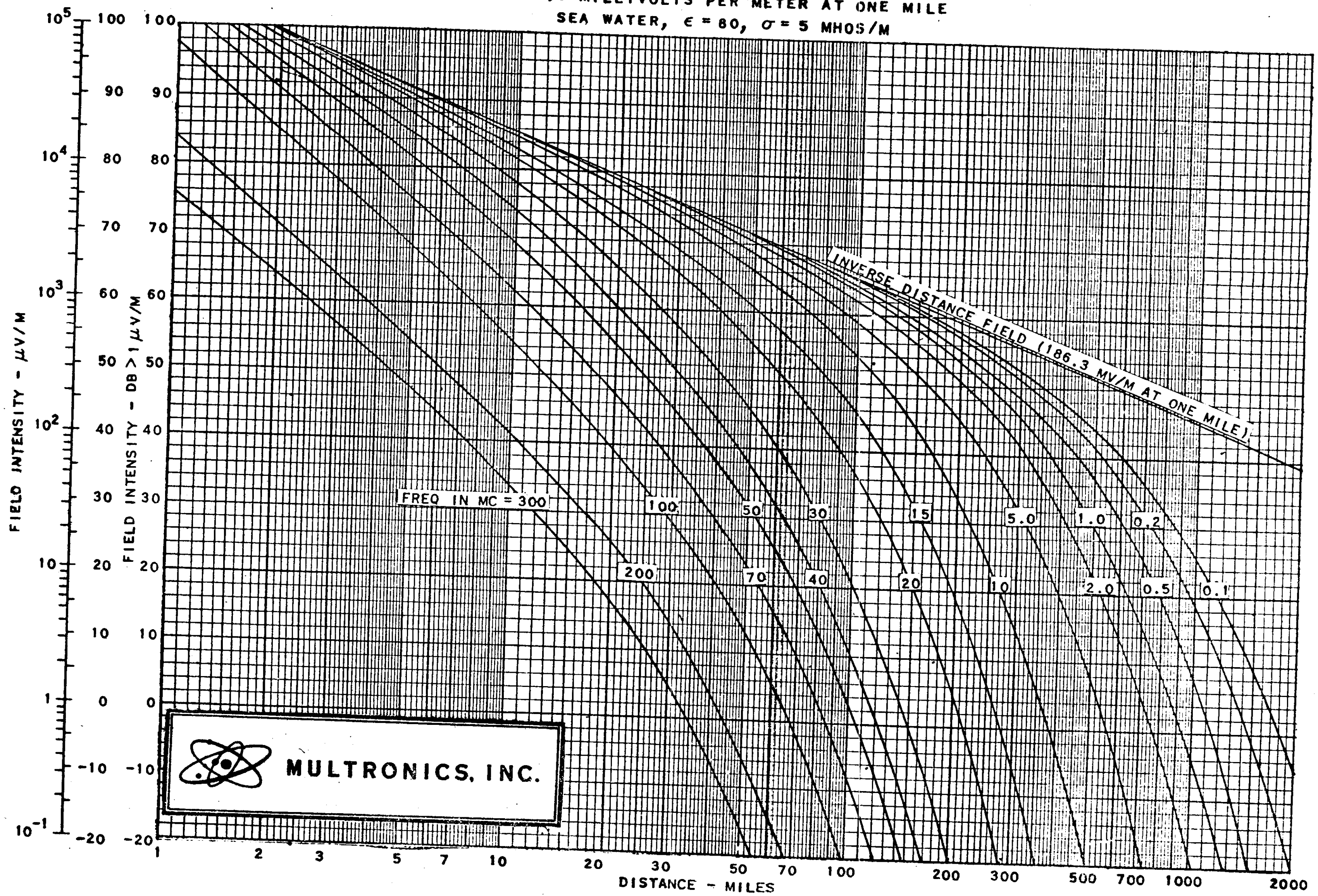

FIGURE 18

GROUND—WAVE FIELD INTENSITY AGAINST DISTANCE CURVES
FOR VARIOUS FREQUENCIES IN MEGACYCLES PER SECOND
FOR
VERTICAL POLARIZATION
ANTENNAS AT THE EARTH'S SURFACE
TRANSMITTING ANTENNA INVERSE DISTANCE FIELD INTENSITY
OF 186.3 MILLIVOLTS PER METER AT ONE MILE
SEA WATER, $\epsilon = 80$, $\sigma = 5$ MHOS/M

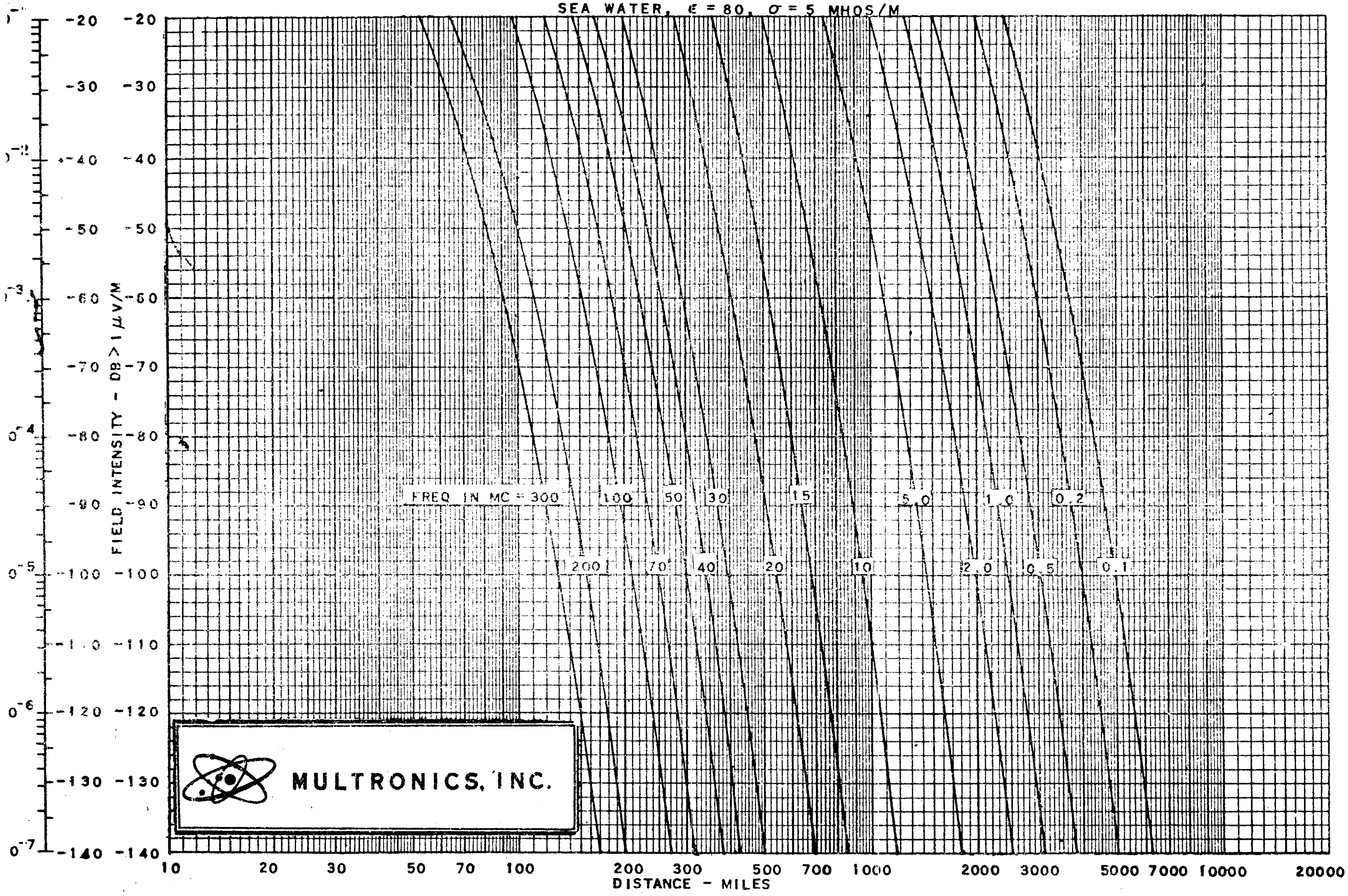

FIGURE 19

TM-11-486-6 (13) are shown in Figures 14, 15, 16, 17, 18 and 19. These curves clearly show the effect of frequency on ground wave propagation over various types of ground (including sea water). These curves were prepared using 186.3 mv/m as the inverse distance field (current element with 1 KW).

There is one school of thought which states that 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 that one can then determine unattenuated field by taking the measured field strength times distance (E x D). This technique in theory is correct to a limited extent, but in practice field intensity measurements cannot be so precisely taken that the effects of reradiation, reflections and instrumentation error can be ignored. In addition, the effects of conductivity must be taken into account. Further, because wide variations at identical distances (different radials in several directions from antenna) in field intensity can be measured, it is imperative that measurements be made at a large number of points on at least eight radials.

The reasons for these statements are clearly shown in Figures 14, 16 and 18. Over sea water (Figure 18) the measured field from 50 to 200 KC approaches the inverse distance line (E x D value) at distances out to 100 miles. However, over "poor" ground (Figure 14) the measured field drops considerably below the inverse distance line at distances beyond 5 miles. Not taken into account in these curves are variations due to reflections, reradiation and instrument error. Therefore a large number of measuring points on at least eight radials should be used.

An example of the futility of using inadequate data for analysis follows:

Field intensity measurements were made on two antennas, one operating on 162 and the other operating on 185 KC. At a given location (it appeared 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 established a field ratio of 2.36 (4500/1900 equals 2.36). It also established a power ratio of 5.58 (2.36^2 equals 5.58). Continuing on the same radial to Point B (also an excellent location), the field at 162 KC was 2200 microvolts and the field at 185 KC was 4000 microvolts. This established another 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 varying from 3.3 to 5.8, depending upon whether point A or B was selected. This is an appreciable difference in efficiency. This difference in apparent efficiency based on using only one or two points for an analysis most certainly points up the necessity for a series of measurements at varying distances on the same path which must then be carefully analyzed taking into account ground conductivity 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 shall assume a frequency of 1000 KC and a 90^{o} antenna and a 120 radial ground system with radials 90^{o} 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 use of the Norton (9) 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	570.0

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 the true efficiency of any antenna system the existence of effective ground conductivity along a path cannot be ignored, and that the effective conductivity cannot be determined 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 in order to accurately determine the efficiency of a vertical antenna system, a large number of field intensity measurements should be made on eight or more radials to obtain the efficiency as well as the effective conductivity. The Federal Communications Commission for over thirty years has required that a very precise method be employed by engineers in making field intensity measurements to assure that the data obtained is accurate, and to insure that 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 and Regulations sets forth a method for making and analyzing these 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 accurate values of efficiency.

The following is a suggested procedure based on F.C.C. practices 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 is not a point source of radiation) but starting at points no closer to the antenna than one wavelength, measurements should 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 at greater distances from the antenna if needed. Where the antenna is rurally located and unobstructed measurements can be made, there should 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, measurements should be made on each radial at as many unobstructed locations as possible, even though the intervals may vary from those 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 field intensity as the ordinate and distance as the abscissa.

(c) Prepare a family of conductivity curves for the frequency of interest, by use of Figure 10. Curves similar to Figure 11 through 13 will result. Figures 14 through 19 could be duplicated in this manner. In fact, for an assigned frequency of 100 KC for example, Figures 14 through 19 could be used directly for the conductivities involved.

(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. In the case of a long radial it may be found that the conductivity changes as one proceeds through certain areas (such as over water). Thus the curve may not be a continuous line but may have several breaks or changes. This curve should then be drawn on the sheet on which the points were plotted, together with the corresponding inverse distance curve. The unattenuated field at 1 mile for the radial concerned will 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 which gives the inverse distance field pattern at one mile should be plotted on polar coordinate paper from the several radial fields obtained. 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} of the antenna. As a check of this analysis use Figures 7 and 8 to determine its reasonableness by checking the theoretical field for a given antenna system and power input.

(f) For information purposes, the depth in meters of penetration of waves into ground, taken from CCIR documents (15), is shown here:

Frequency	$\sigma = 5 \times 10^{-11}$ e.m.u $\epsilon = 81$	$\sigma = 1 \times 10^{-13}$ e.m.u. $\epsilon = 10$	$\sigma = 1 \times 10^{-14}$ e.m.u. $\epsilon = 5$
10 kc/s	2	50	150
100 kc/s	0.67	15	50

In this table the depth of penetration is that depth where the wave has been attenuated to 37% of its value at the surface.

It will be noted that for good ground, the depth of penetration at L.F. is slight. However, it is particularly important to take lower strata into account when upper strata are of poor conductivity, since in this case more energy penetrates to the lower levels and is lost.

It is for this reason that siting considerations for any antenna which employs a ground system (VLF, LF, or MF) are very important. For the best ground wave propagation (lowest losses due to conductivity), the surface strata should be of good conductivity. Swampy, marshy loam and tidewater areas make excellent sites for such facilities. A site survey with actual field intensity test measurements should be made before a site is definitely selected.

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:

$$\text{Efficiency (\%)} = \frac{P_{out}}{P_{in}} \times 100 = \frac{P_{out}}{P_{out} + P_{lost}} \times 100 \qquad (16)$$

Where:

P_{in} = power into network in watts.

P_{out} = power delivered to antenna in watts.

P_{lost} = power lost in components in watts.

The determination of 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 the 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.

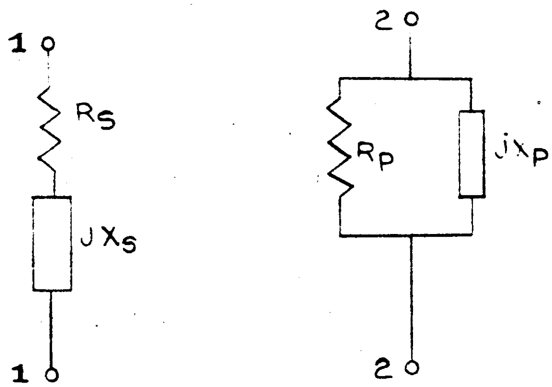

FIGURE 20

Figure 20 illustrates a series and parallel circuit having identical magnitude of impedance between terminals 1,1 and 2,2 where at the operating frequency:

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

Equation (17) can also be expressed as:

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

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 20 is:

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

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 20 can be expressed as:

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

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 for 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 ohm generator. First we use equation (23) and substitute 50 ohms for the series R_s 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 by substitution 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 is 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) will be:

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

Substituting in equation (21) we have:

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

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. A more detailed discussion follows.

(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:

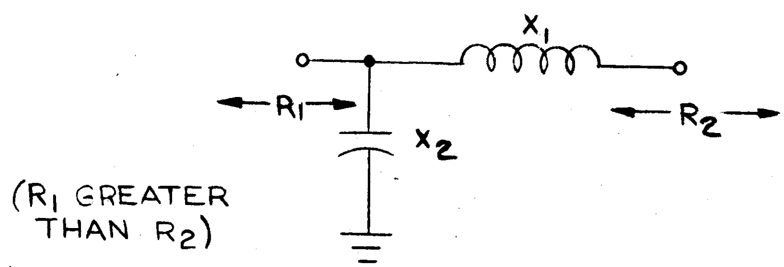

FIGURE 21

or as:

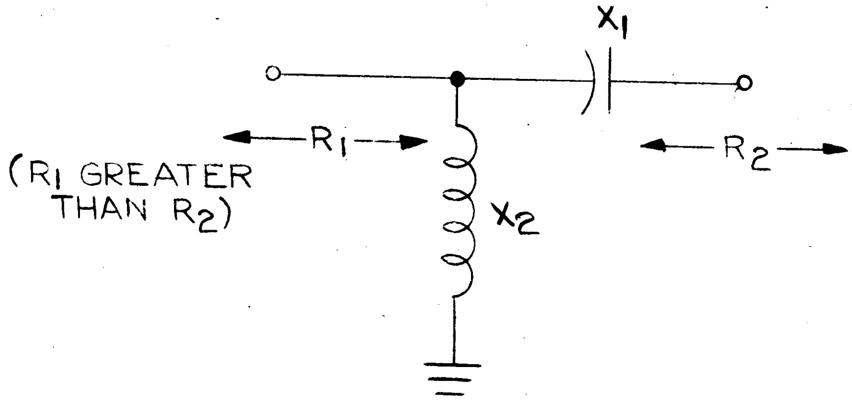

FIGURE 22

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 21 or 22, the value of the inductance and capacitance to be used can be determined from the equations:

$$L = \frac{X_L}{2\pi f} \qquad (26)$$

$$C = \frac{1}{2\pi f X_c} \qquad (27)$$

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 usually has reactance, the output reactor of the L network will have to be equal in value but opposite in sign to the antenna reactance, plus the value of reactance 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 equation:

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

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. The Folded Unipole is the first step in the design of 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 when operating at second resonance. A study of basic transmission line theory will explain its operation.

We know that a transmission line which is less than 90^0 in length and shorted at its far end will appear inductive at its input terminals. If this line is increased in length so that its electrical length equals a quarter wave, it will appear to be a parallel resonant circuit at its input, with a very high input impedance.

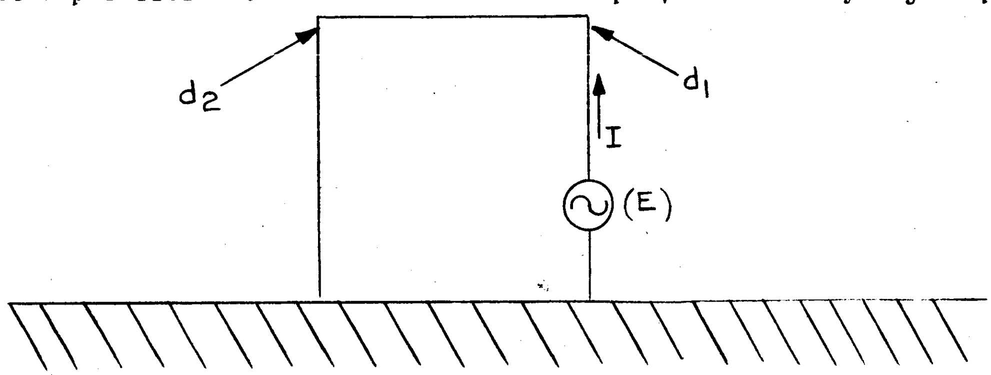

FIGURE 23

Figure 23 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 23. Roberts (11) has outlined a method for analysis of a folded unipole antenna. Figure 23 becomes an equivalent circuit shown in Figure 24.

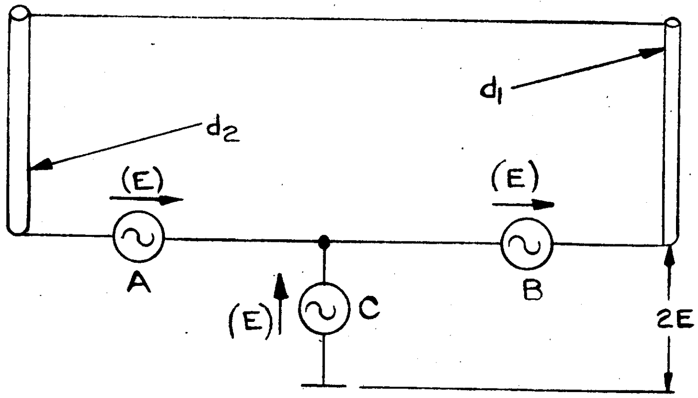

FIGURE 24

Our reason for using three generators in Figure 24 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.

Referring to Figure 24, 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 effectively grounded so far as any voltage is concerned.

Generators B and C impress a voltage, 2E, on the lower end of element d_1; therefore, Figure 24 is equivalent to Figure 23.

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 90^0 transmission line, shorted at the far end, their input 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 as far as Generator C is concerned (by the zero internal impedance of A and B), the two elements act as a simple 90^0 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:

$$I_1 = \frac{1}{2} \times \frac{E}{R} \qquad (29)$$

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 $\frac{1}{2} \times \frac{E}{R}$ plus a very small amount produced by Generators A and B working in series 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 R will approximate that of a single radiator, and the impedance multiplication due to folding is approximately four.

The impedance transformation can be expressed as follows:

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

Where:

Z_1 = input impedance of the folded unipole antenna.

Z_0 = input impedance of a single antenna.

n = current ratio $\frac{I_2}{I_1}$ $\left(\frac{I_2}{I_1} = 1 \text{ for equal size conductors}\right)$

Up to this point, we have discussed equal size conductors. That is, the diameter of the tower and the fold conductor is the same. However, with the introduction of the transformation ratio, as noted in (30) above, we can now turn to discussion of the operation of a folded unipole antenna with unequal diameter conductors. Figure 25 illustrates the folded unipole antenna with unequal size conductors.

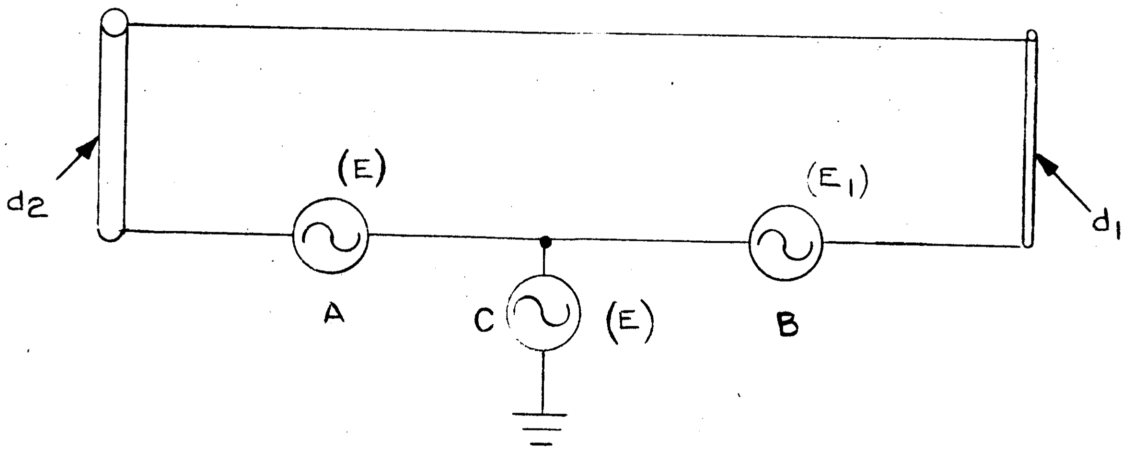

FIGURE 25

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 (12) demonstrates a method for determining this voltage. Roberts (11) has also demonstrated methods for determining this voltage. We will use the electrostatic 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 while the voltage ratio will be the inverse of the capacity ratio. To solve the problem then, we must assign undefined capacities c_1 and c_2 to elements d_1 and d_2. Then:

$$\frac{E}{E_1} = \frac{c_1}{c_2} \qquad (31)$$

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 because of the very high input impedance of the quarter-wave section (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:

$$R\left(1 + \frac{C_2}{C_1}\right)^2 \tag{35}$$

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 or tower. 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 (11) 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:

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

Where:

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

Z_2 = the characteristic impedance of a two conductor transmission line made up of conductors of the larger diameter, spaced the center-to-center distance of the two conductors in the antenna.

The above equation assumes that the power will be fed to the smaller conductor (fold) and that the tower will be grounded. Thus, an impedance step-up of greater than four will always be achieved.

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

A folded unipole antenna shorter than a quarter wave high can provide a wide range of input resistance by variation of the ratio of the diameters of 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^{0} to 30^{0} do not approach this, having a radiation resistance of only 1 to 4 ohms. Consequently, this type of antenna has excessive losses. In this frequency range, the use of a top-loaded folded unipole antenna is extremely desirable, inasmuch as this antenna can be operated at first resonance, or at lesser heights.

"First resonance" is defined as that antenna height which is equal to an electrical quarter wave, or 90^{0}. The antenna looks like a quarter wave section of transmission line shorted at its upper end, with an extremely high input impedance. When a shorting bar is moved down the fold, effectively reducing the length of the fold below an electrical quarter wave, the input impedance, which consists of R + jX, is steadily reduced in value. At some point which is usually about one half of its former height the R term of the input R + jX will be close to 50 ohms. At this point the remaining jX term will reduce to zero and will then become negative in sine. This point where the folded unipole antenna input impedance is non-reactive is commonly called "second resonance". By reducing the height of the antenna, or of the fold itself, we can resonate the antenna so that it will match a 50 ohm coaxial line merely by use of a series capacitor whose negative reactance equals the + jX of the antenna input. This + jX will not be a large value, so that even at high powers the r.f. voltages involved will be of reasonable magnitude.

It should be noted that a folded unipole antenna can go into first resonance at a frequency at which its electrical length is 90^0, but its physical length is only 60^0, due to the L/D of its conductors. Thus we can say that if a folded unipole antenna goes into first resonance at an equivalent physical length of 60^0, we would expect second resonance to occur at approximately one half of this physical length, or 30^0. The base impedance for a top-loaded folded unipole antenna at second resonance can be expressed as: (10)

$$R_{2r} = 1580 \left(\frac{h_{2R}}{2r} \times \frac{\log 4S^2/d_1 d_2}{\log 2S/d2} \right)^2 \qquad (37)$$

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

A <u>top-loaded</u> folded unipole antenna can be used to obtain a base resistance on the order of 12 to 15 ohms for antennas as short as 10^0.

The currents in the fold wires in the antenna of a folded unipole at lengths less than first resonance are in phase just as they are at first resonance, hence there is no cancellation of field due to out-of-phase currents and the end result is an increase of 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, therefore 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. This section will deal with the factors which control the useful bandwidth of an antenna and with a simple procedure for determination of this useful bandwidth.

II. DISCUSSION:

A. General:

The bandwidth of an antenna depends upon its input impedance and the rate with which its reactance and resistance change with frequency. The useful bandwidth is commonly considered to be the frequency band within which the power is equal to or greater than one-half the power at resonance. When the impedance versus frequency is plotted on a Smith chart, this useful bandwidth is that within a 5.83/1 VSWR circle.

There are two types of bandwidth to be considered. One is the static bandwidth which is the antenna reactance divided by the antenna radiation resistance and is the bandwidth which would be obtained if the antenna system had no losses. The other is the loaded or dynamic bandwidth which is the net bandwidth after consideration is given to total antenna system losses and the 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 90^0 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 network) or a coupling transformer. Conversely, if the antenna is a folded unipole or grounded type its input 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 resistance 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, the half-power bandwidth condition is where the excursion of X on either side of the operating frequency equals R. ($\tan^{-1} \frac{X}{R} = 1$)

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, and the resistance and reactance curves do not vary symmetrically but vary 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.

As stated previously, the useful bandwidth of a system is the frequency difference between the low frequency points where fifty percent of the applied power is delivered to the load, which in this case is the antenna.

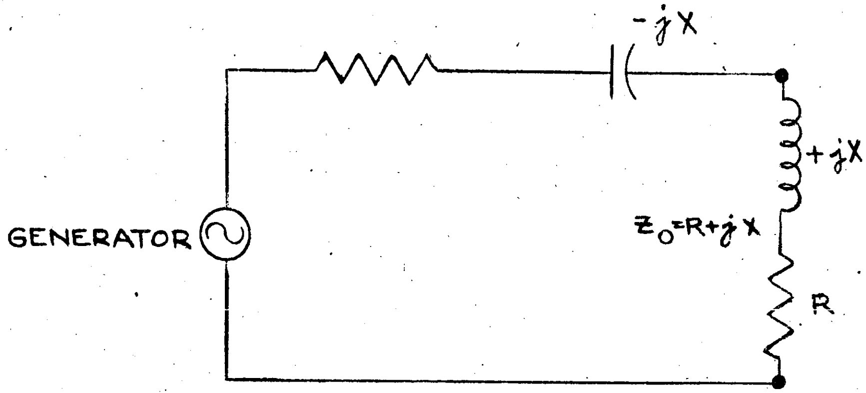

FIGURE 26

Figure 26 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 where 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.

By connecting a signal generator to the VSWR meter and transmission line and varying the generator frequency above and below the operating frequency (frequency

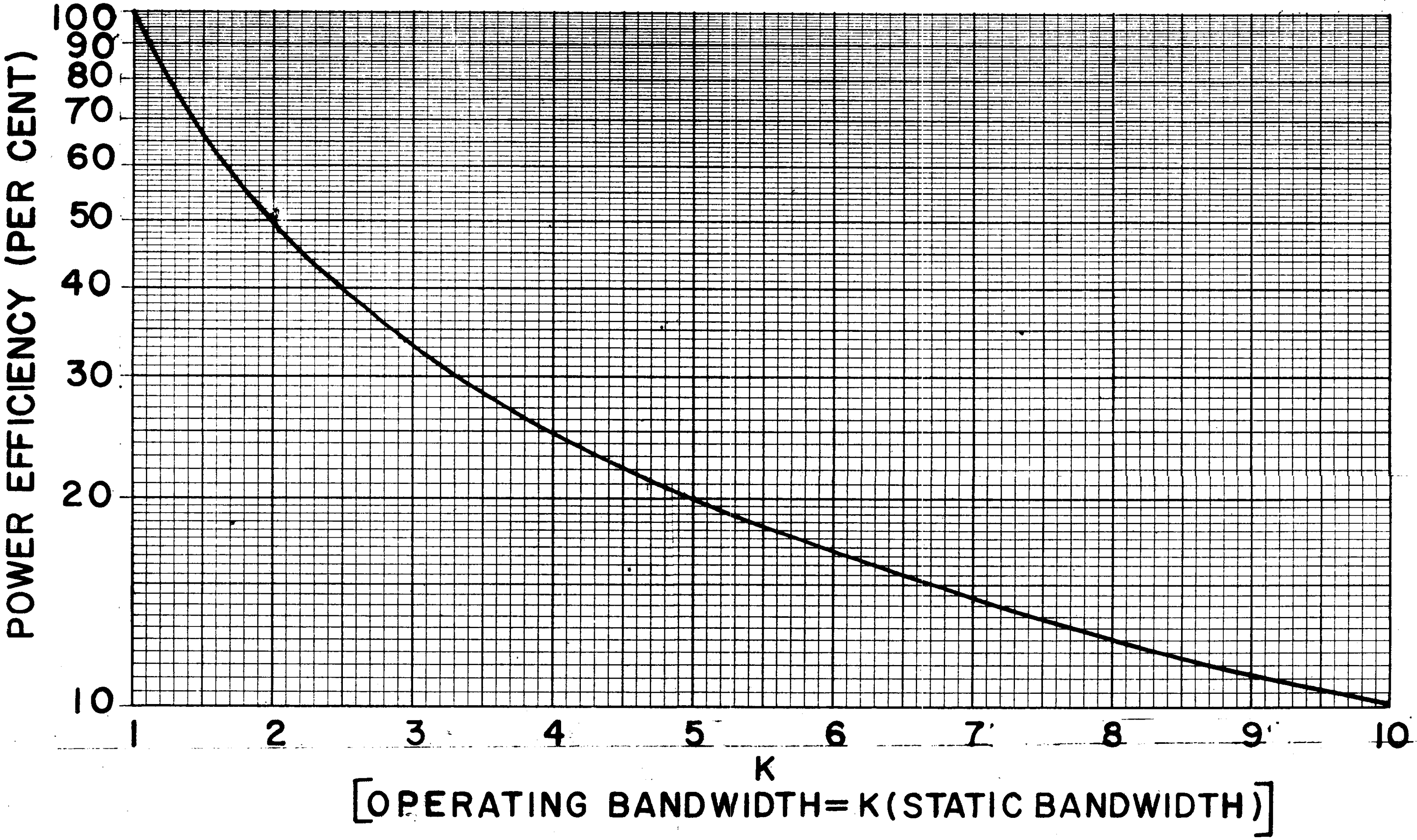

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FIGURE 27

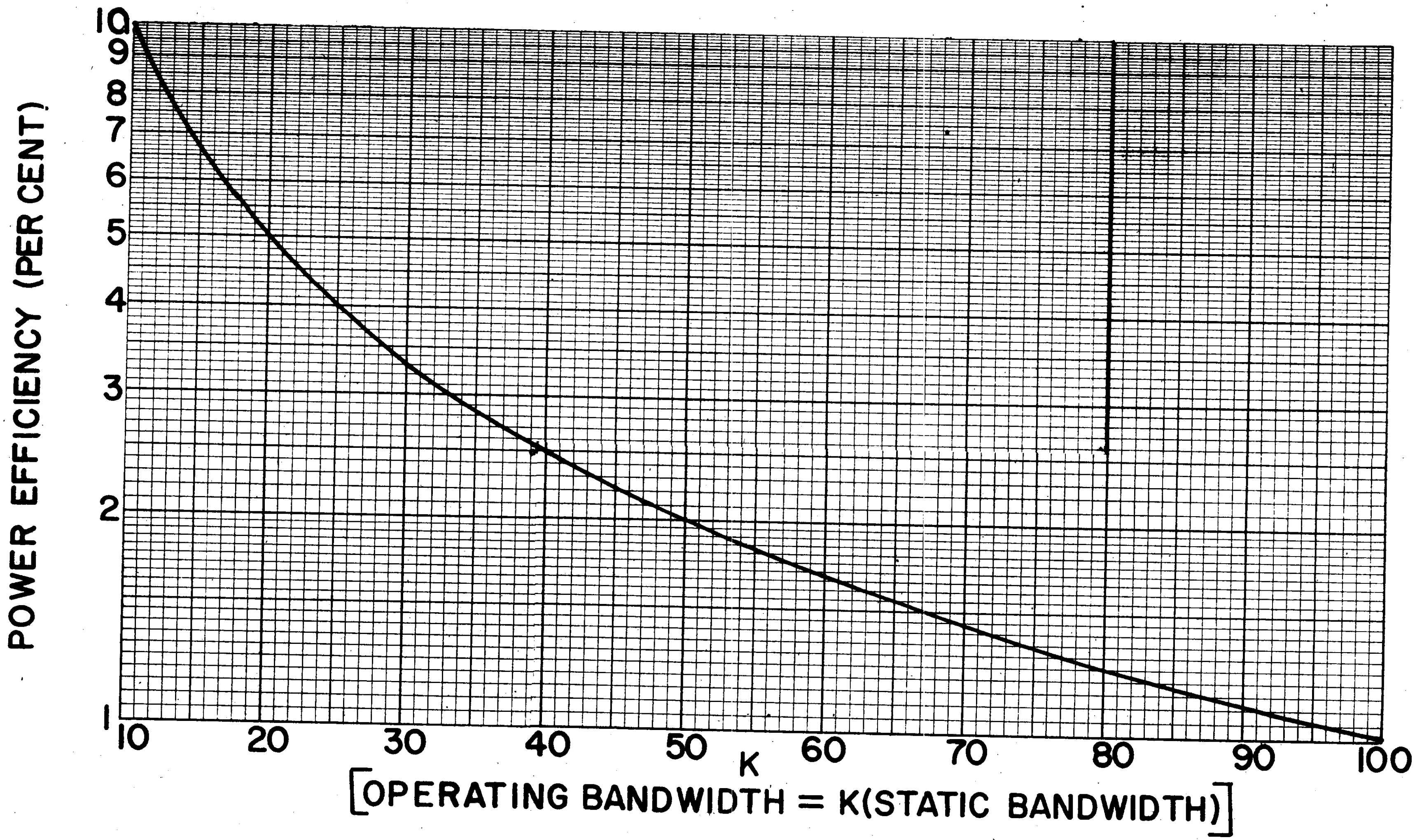

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FIGURE 28

determined by frequency counter) of the antenna system until VSWR r adings of 5.83: 1.0 are obtained, the half power points are located, and the bandwidth thus known.

C. Bandwidth Efficiency Product:

Figures 27 and 28 are bandwidth efficiency product curves. They can be used to determine the power efficiency or bandwidth of an antenna 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 or dynamic bandwidth equals K times the static bandwidth. As stated in Section 5.II.A., the static bandwidth is the antenna bandwidth which would be obtained if the antenna system had no losses. Figures 27 and 28 cover ranges of power efficiency from 10 to 100 percent and 1 to 10 percent respectively.

In order to determine the bandwidth efficiency product for any antenna, it is first necessary to determine the static Q, assuming the antenna under consideration is a perfect radiator with no system losses. First it is necessary to compute the radiation resistance by means of formula (1), (2), or (3). The base reactance is next determined by means of equation (4). The static Q of the antenna then becomes:

$$Q = \frac{Xa}{2Ra} \quad \text{(assuming a matched generator)} \qquad (40)$$

Where:

X_a = base reactance of the antenna in ohms.

R_a = radiation resistance in ohms assuming no loss.

We have already discussed how to determine the radiation efficiency of a vertical antenna but we have not yet pointed 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 consideration its bandwidth efficiency product.

Assume a frequency of 80 KC and an antenna 400 feet (.0325 wavelengths or 11.7 degrees high, with a ground system consisting of 120 radials 500 feet long (.0406 wavelengths). Then determine the static bandwidth, which is the bandwidth for 100% efficiency for this antenna, assuming no system losses. This is accomplished by using equation (3) where we determine:

$$R_b = (11.7)^2 \ / \ 312 = 0.438 \text{ ohms} \qquad (41)$$

The characteristic impedance of a short antenna is determined from the following equation:

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

For a triangular cross-section tower of 400 feet height with 3 foot sides, assume an effective diameter of 2.7 feet. Then:

$$Z_o = 138.2 \log_{10} 148 + 23.2 \qquad (42)$$

$$Z_o = 323.2 \text{ ohms.}$$

The base reactance is:

$X_a = - j(Z_o \text{ Cot } \Theta)$, where $\Theta = .0325$ wavelengths or 11.7 degrees.

$$X_a = - j(323.2 \text{ Cot } 11.7)$$

$$X_a = - j \ 1560 \text{ ohms.}$$

The static Q is:

$$Q = \frac{Xa}{2Ra} = \frac{1560}{2 \times 0.438} = 1780 \qquad (43)$$

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

$$F = \frac{fo}{Q} \qquad (44)$$

Where:

F = 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 the static bandwidth:

$$f = 80{,}000 \ / \ 1780 = 45.0 \text{ cycles.} \qquad (45)$$

It has thus been shown that the loaded static bandwidth for a 400 foot antenna of triangular cross-section having 3 foot sides at 80 KC is 45.0 cycles. This bandwidth represents <u>100% efficiency</u> for the structure (assumes no system losses).

Now that we know the static Q for our antenna, we can determine how much the bandwidth is increased and the radiation efficiency is reduced by 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 0.0325 wavelengths high has an unattenuated field efficiency of 111 mv/m at one mile for 1 KW input. Figure 8 shows that for a ground system of 120 radials 0.0406 wavelengths long the loss factor is -42 mv/m. This means that the net unattenuated field intensity at one mile for 1 KW input is 111 minus 42 or 69 mv/m. This, however, is not equivalent to a field of 100% efficiency, but is instead a field efficiency of 37.10% (69/186.3 = .371). Power efficiency is therefore equal to (0.371^2) or 13.76%.

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

(a) for the lossy condition, radiated power = 1000 x 13.76% = 137.6 watts

$$I = \left(\frac{137.6}{0.438}\right)^{1/2} = (314)^{1/2} = 17.72 \text{ amperes.} \qquad (46)$$

(b) power loss = 1000 - 137.6 = 862.4 watts = I^2R loss = 314 R loss,

R loss = 862.4/314 = 2.75 ohms.

(c) total R = 2.75 = 0.438 = 3.188 ohms.

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

$$Q = \frac{1560}{2 \times 3.188} = 244.5 \text{ (assuming a matched generator)} \qquad (47)$$

(e) the dynamic bandwidth therefore is:

$$F = \frac{80,000}{244.5} = 326.8 \text{ cycles} \quad (48)$$

It can now be stated that this 400 foot antenna with a ground system of 120 radials 500 feet long at 80 KC would have a power efficiency of 13.76% and a dynamic bandwidth of 326.8 cycles. This can be verified by using Figure 27, where we find that for power efficiency = 13.76%, K will equal 7.25 and bandwidth is 7.25 times 45.0 or 326.8 cycles. A Smith Chart plot of this antenna's bandwidth is shown in the Appendix.

By following the step by step procedure of the example, power efficiency and its associated dynamic 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 27 and 28. For example, the antenna described would have a power efficiency of 2.63% when its dynamic bandwidth is made 1700 cycles by series resistance loading.

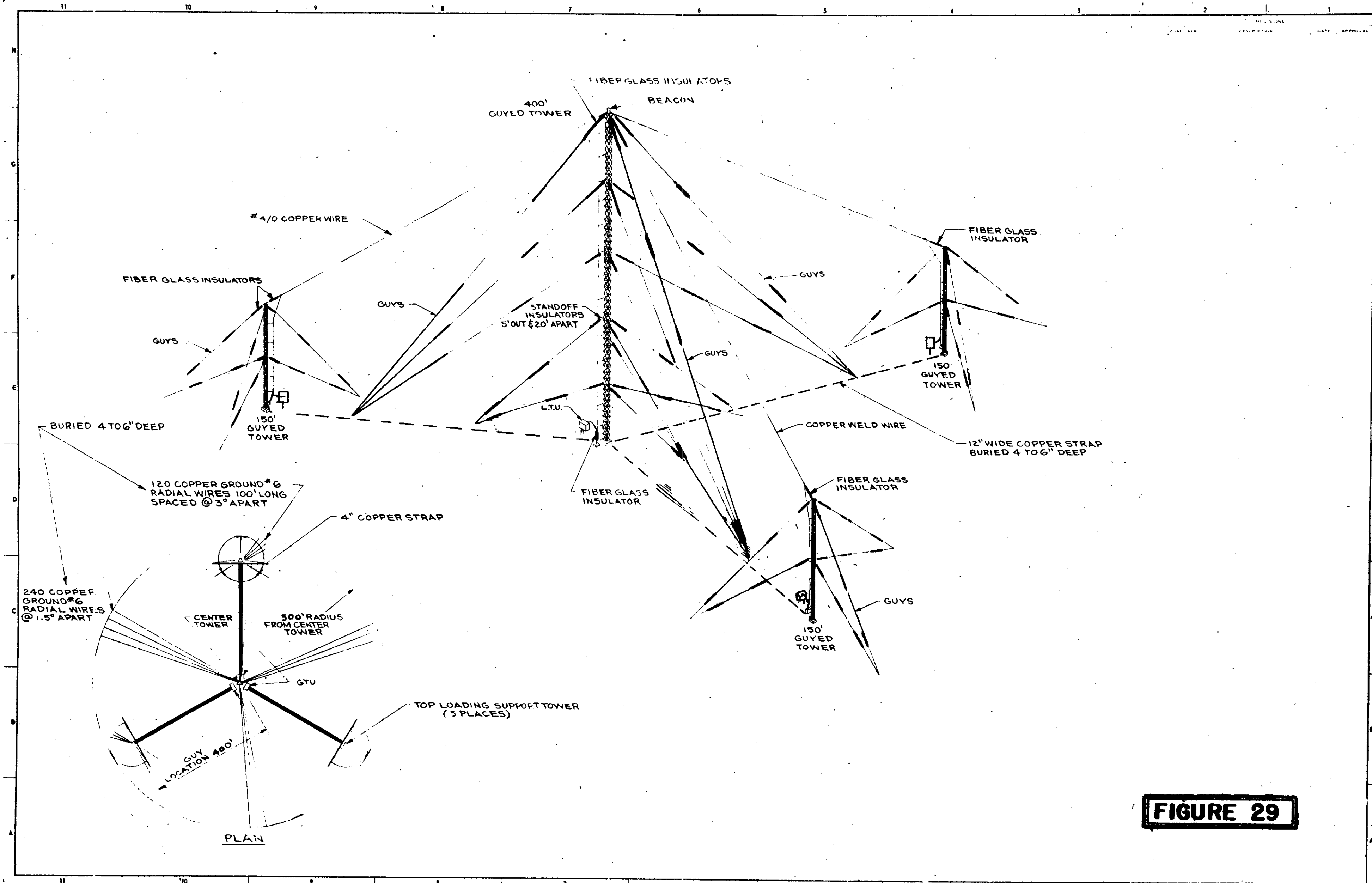

FIBER GLASS INSULATORS
BEACON
400' GUYED TOWER
#4/0 COPPER WIRE
FIBER GLASS INSULATOR
GUYS
FIBER GLASS INSULATORS
GUYS
STANDOFF INSULATORS 5' OUT & 20' APART
GUYS
150 GUYED TOWER
150' GUYED TOWER
L.T.U.
BURIED 4 TO 6" DEEP
COPPERWELD WIRE
12" WIDE COPPER STRAP BURIED 4 TO 6" DEEP
FIBER GLASS INSULATOR
FIBER GLASS INSULATOR
120 COPPER GROUND #6 RADIAL WIRES 100' LONG SPACED @ 3° APART
4" COPPER STRAP
240 COPPER GROUND #6 RADIAL WIRES @ 1.5° APART
CENTER TOWER
500' RADIUS FROM CENTER TOWER
GUYS
150' GUYED TOWER
GTU
TOP LOADING SUPPORT TOWER (3 PLACES)
GUY LOCATION 400'
PLAN

FIGURE 29

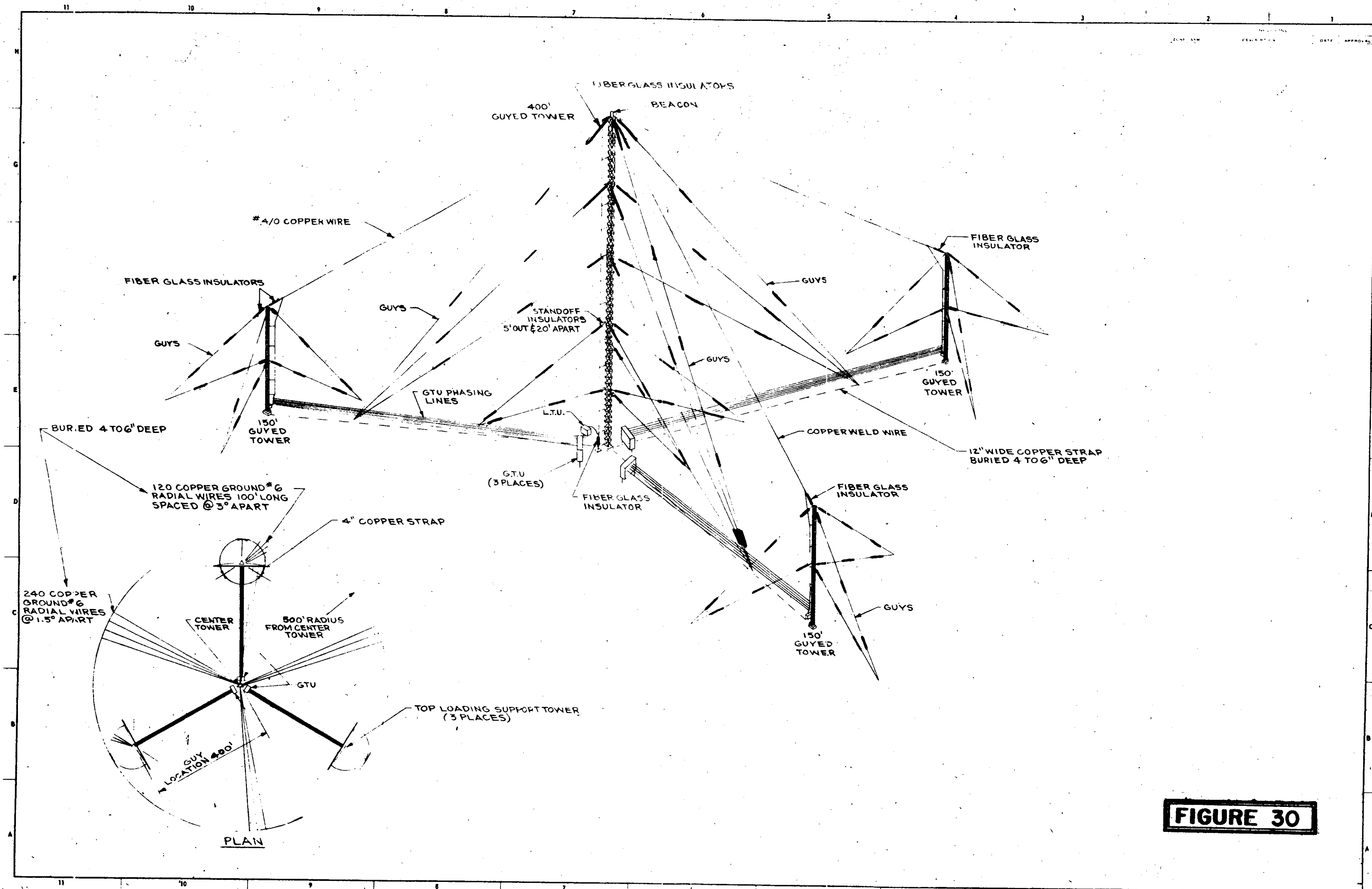

FIBERGLASS INSULATORS
BEACON
400' GUYED TOWER
#4/0 COPPER WIRE
FIBER GLASS INSULATORS
GUYS
GUYS
STANDOFF INSULATORS 5' OUT & 20' APART
GUYS
GUYS
FIBER GLASS INSULATOR
150' GUYED TOWER
GTU PHASING LINES
L.T.U.
150' GUYED TOWER
BURIED 4 TO 6" DEEP
G.T.U (3 PLACES)
FIBER GLASS INSULATOR
COPPERWELD WIRE
12" WIDE COPPER STRAP BURIED 4 TO 6" DEEP
120 COPPER GROUND #6 RADIAL WIRES 100' LONG SPACED @ 3° APART
FIBER GLASS INSULATOR
4" COPPER STRAP
240 COPPER GROUND #6 RADIAL WIRES @ 1.5° APART
CENTER TOWER
500' RADIUS FROM CENTER TOWER
GUYS
150' GUYED TOWER
GTU
TOP LOADING SUPPORT TOWER (3 PLACES)
GUY LOCATION 400'
PLAN

FIGURE 30

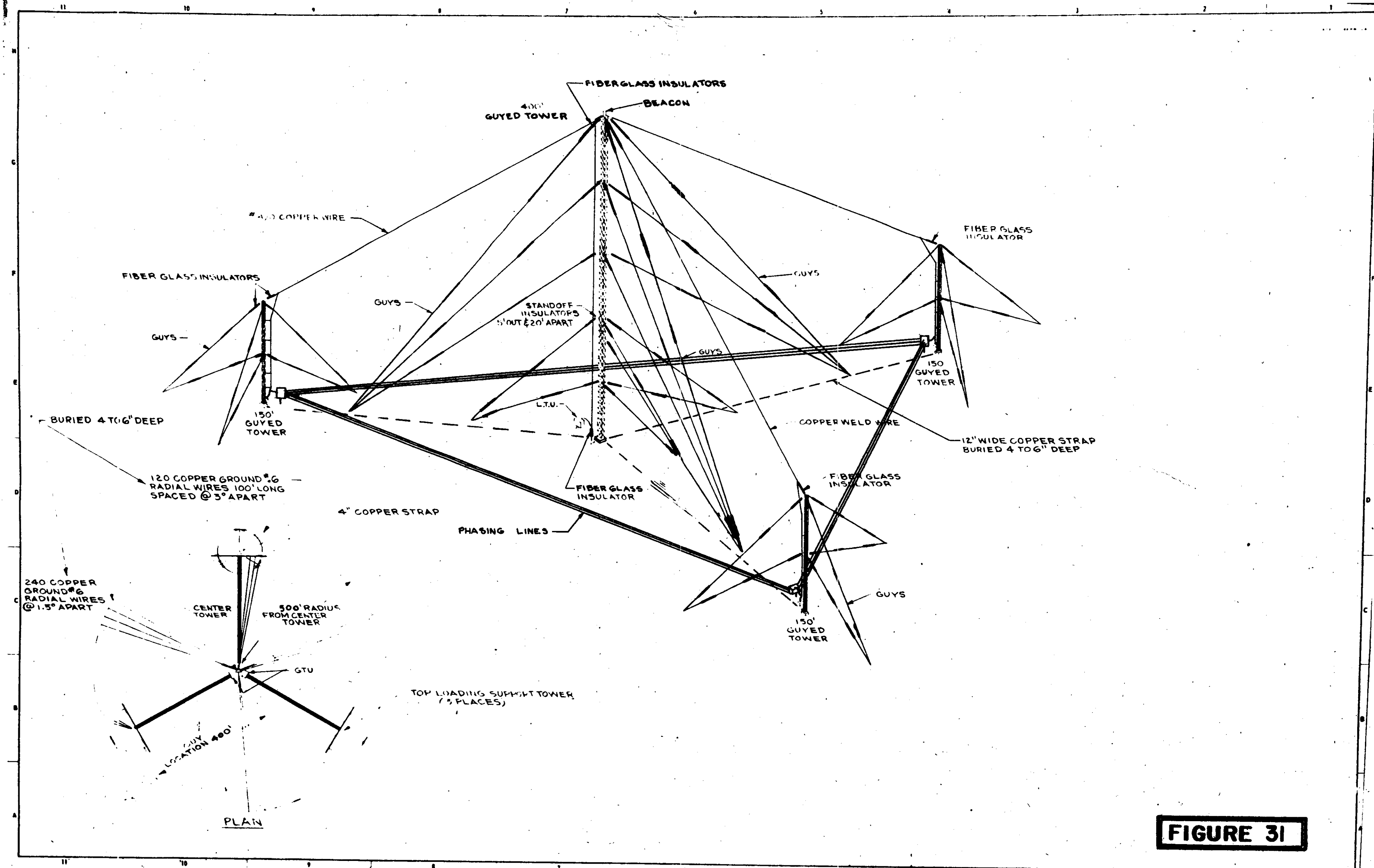

FIBERGLASS INSULATORS
BEACON
400' GUYED TOWER
#4/0 COPPER WIRE
FIBER GLASS INSULATOR
FIBER GLASS INSULATORS
GUYS
STANDOFF INSULATORS 5' OUT & 20' APART
150 GUYED TOWER
150' GUYED TOWER
L.T.U.
BURIED 4 TO 6" DEEP
COPPER WELD WIRE
12" WIDE COPPER STRAP BURIED 4 TO 6" DEEP
120 COPPER GROUND #6 RADIAL WIRES 100' LONG SPACED @ 3° APART
FIBER GLASS INSULATOR
4" COPPER STRAP
PHASING LINES
240 COPPER GROUND #6 RADIAL WIRES @ 1.5° APART
CENTER TOWER
500' RADIUS FROM CENTER TOWER
GTU
TOP LOADING SUPPORT TOWER (3 PLACES)
GUY LOCATION 400'
PLAN

FIGURE 31

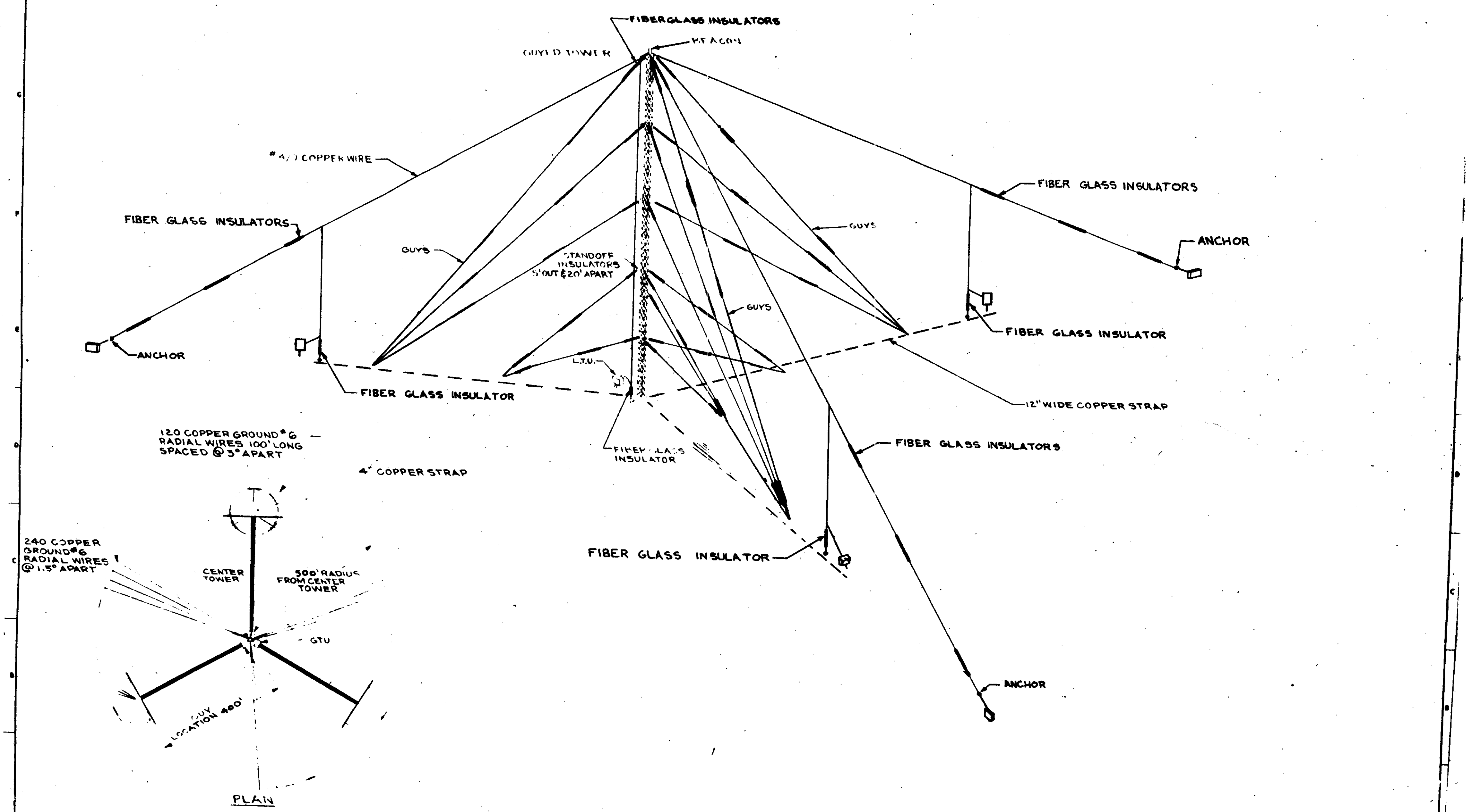

FIBERGLASS INSULATORS
BEACON
GUYED TOWER
#4/0 COPPER WIRE
FIBER GLASS INSULATORS
FIBER GLASS INSULATORS
GUYS
GUYS
GUYS
STANDOFF INSULATORS 5'OUT & 20' APART
ANCHOR
ANCHOR
ANCHOR
L.T.U.
FIBER GLASS INSULATOR
FIBER GLASS INSULATOR
12" WIDE COPPER STRAP
FIBERGLASS INSULATOR
FIBER GLASS INSULATORS
FIBER GLASS INSULATOR
120 COPPER GROUND #6 RADIAL WIRES 100' LONG SPACED @ 3° APART
4" COPPER STRAP
240 COPPER GROUND #6 RADIAL WIRES @ 1.5° APART
CENTER TOWER
500' RADIUS FROM CENTER TOWER
GTU
GUY LOCATION 400'
PLAN

FIGURE 32

SECTION 6

I. GENERAL:

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

II. DISCUSSION:

(1) Types of NORD's:

There are five basic types of NORD's used in L.F. communications. The first type is called an "A" System and a typical installation is shown in Figure 29.

The second type is called a "B" System and a typical installation is illustrated in Figure 30.

The third type is called a "C" System. It is illustrated in Figure 31.

The fourth type is called a "D" System, and it is very similar to the "A" System of Figure 29 in appearance, except that a base insulator is used under the main tower.

The fifth type is called the "E" System, and it is a transportable version, designed for quick erection. It is equal to the "D" System but has no perimeter towers. Instead, the top guys continue on beyond the terminating insulators to anchors in the ground. It is shown in Figure 32.

(2) Basic Information:

The NORD antenna, based on the folded unipole principle, is basically a vertical tower radiator which is electrically grounded at its base and fed as a folded unipole 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^{0} 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 which are located at a distance equal to the height of the tower plus approximately one third the tower height 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 the pole. From the end of each of the three top loading wires a connection is run down to a Guy Termination Unit. The G.T.U. is used for controlling the feed point impedance of the antenna. If desired the three G.T.U.'s can also be used to control the phase angles and magnitudes of the termination currents to provide a limited directional radiation effect. The input impedance phase angle, and radiation characteristics of the antenna itself can be controlled by the following design parameters:

(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 fold wires.

(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 input resistance and reactance of the antenna.

The NORD base resistance between 50 and 200 KC for a short tower (300 to 400 feet) can be varied from approximately 20 to several hundred ohms. Its base reactance can be designed to be always inductive or positive, varying from a few ohms to approximately + j400.

The electrical features of an L.F. NORD short antenna are thus materially different from those of the typical series fed Marconi Antenna of the same height. 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 high, and because the operating Q's are also quite high, the Marconi antenna has a limited power handling ability and limited bandwidth capability.

Therefore, the NORD, 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. With the antenna grounded no lighting transformer or base insulator is required, inasmuch as the entire mechanical structure is then at D.C. ground potential. 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 tower. 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 because of the lower voltages encountered.

7. Depending upon power, a material saving in the antenna termination building or Line Termination Unit can be realized, versus the cost of the large copper-lined Helix house required for a series fed antenna.

(3) Basic Theory of A NORD:

In order to more readily understand the theory of a NORD antenna 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:

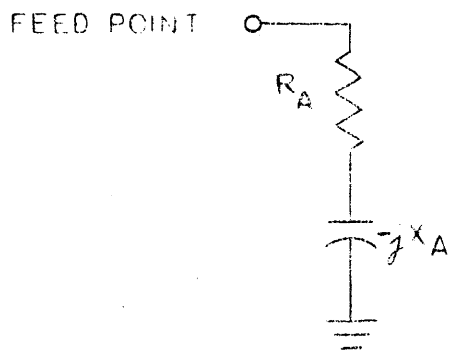


FIGURE 33A

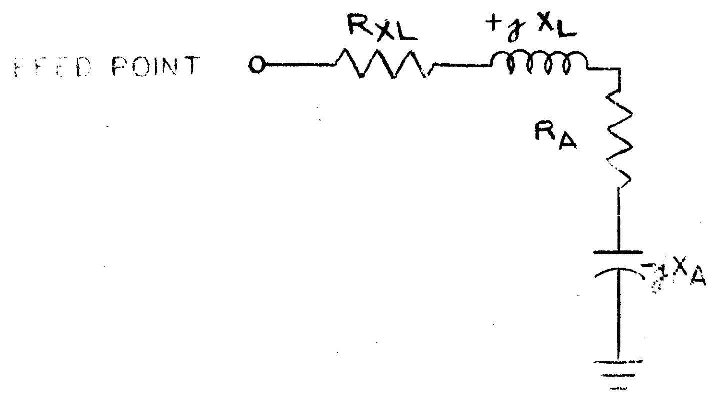


FIGURE 33B

In order to transfer power from a generator or transmitter it is necessary to resonate the circuit of Figure 33A by means of a Helix or inductance "L" having the same magnitude X_L as X_A. We now have a series circuit as shown in Figure 33B. The current in a series circuit can be expressed as:

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

Where:

E = voltage at input of antenna in volts.

R = total antenna resistance plus resistance of helix ($R_A + R_{XL}$) in ohms.

X_L = inductive reactance of helix in ohms.

X_c = capacitive reactance of antenna in ohms.

The frequency at which maximum current occurs is called the resonant frequency, and the condition of maximum current flow is called resonance. The curves of Figure 34 are resonance curves.

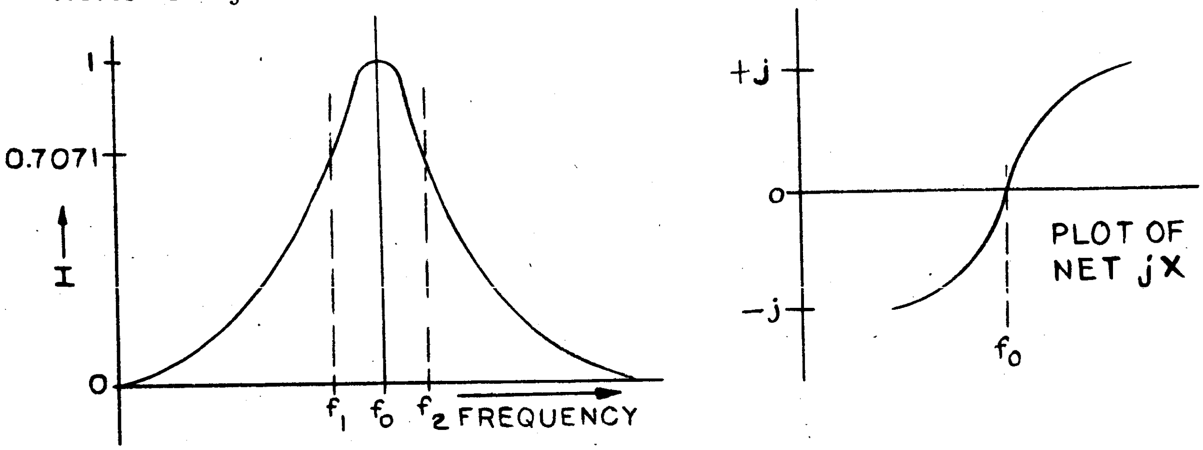


FIGURE 34

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 33 illustrated the equivalent circuit for a short series fed antenna.

Figure 35A shows the equivalent circuit of the same short antenna assuming folded unipole feed.

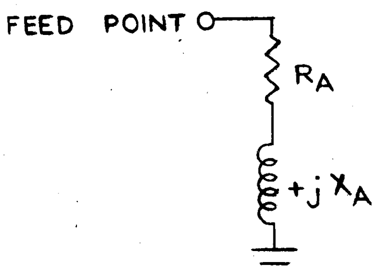


FIGURE 35A

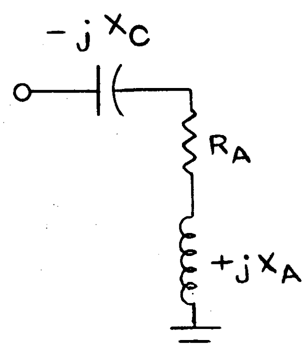


FIGURE 35B

This antenna must be resonated by a series capacitor "C" which at L.F. has a very low loss resistance which can be neglected. This new series circuit is shown in Figure 35B. 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.

Now consider a parallel resonant circuit (which our antenna will eventually be if we consider the matching networks). Figure 36A shows a parallel resonant circuit, also sometimes called an anti-resonant circuit because at resonance the impedance looking into terminals 1,1 is a maximum. R represents the resistance of the inductance L. The resistance of the capacitor is small enough to be neglected.

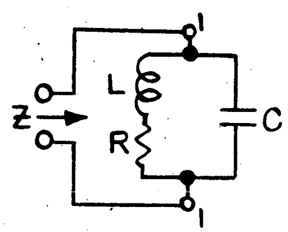


FIGURE 36A

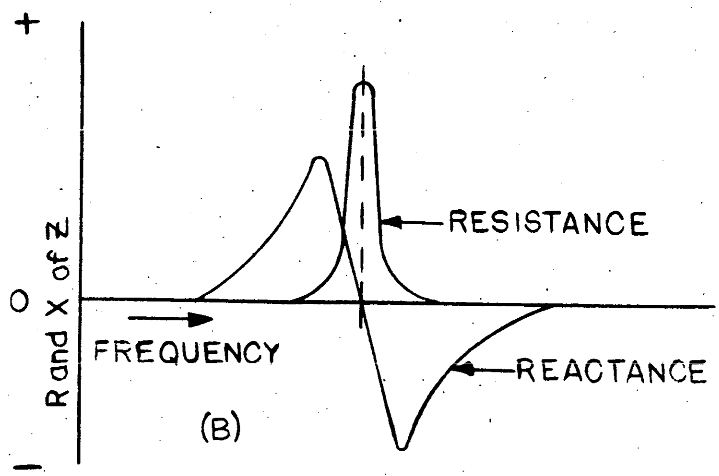


FIGURE 36B

If we were to assume that the series circuit of Figure 33A were shunted by a parallel circuit such as Figure 36A, we would then have:

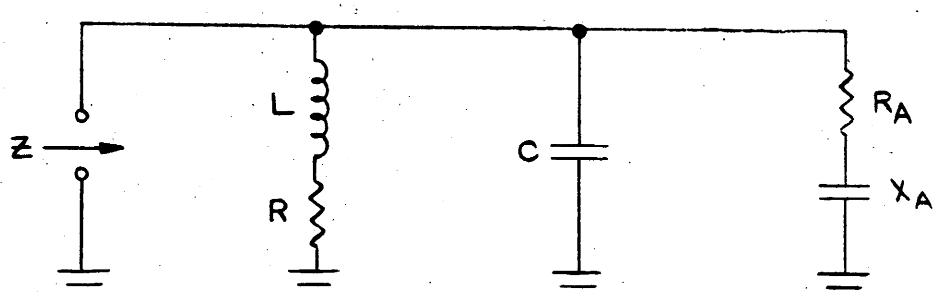


FIGURE 37

The net reactance of Figure 37 is determined by combining the values for both the parallel circuit and the series circuit over the frequency band of interest.

The net reactance for Figure 37 can then be shown as the dashed curve of Figure 38.

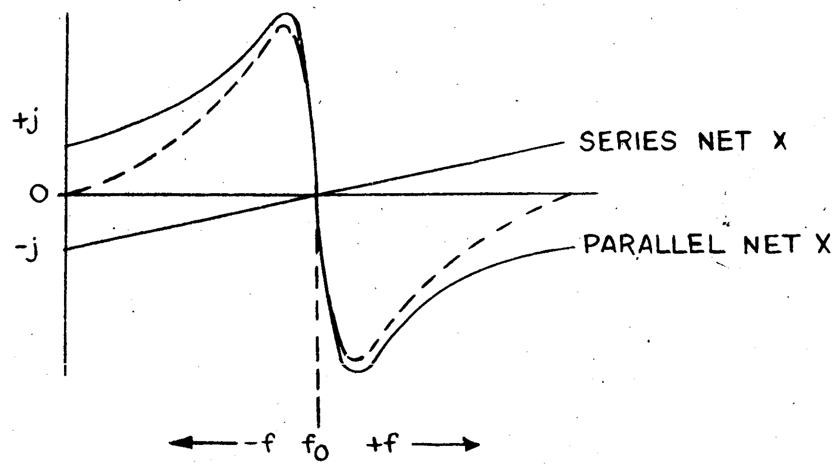


FIGURE 38

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

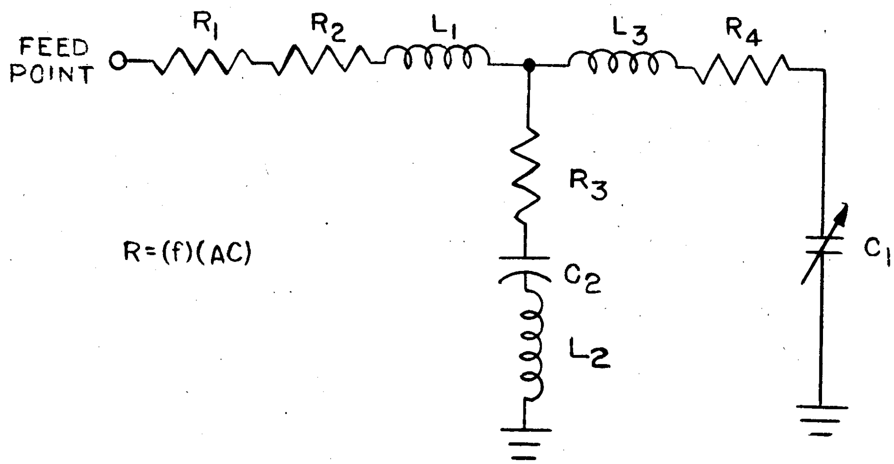


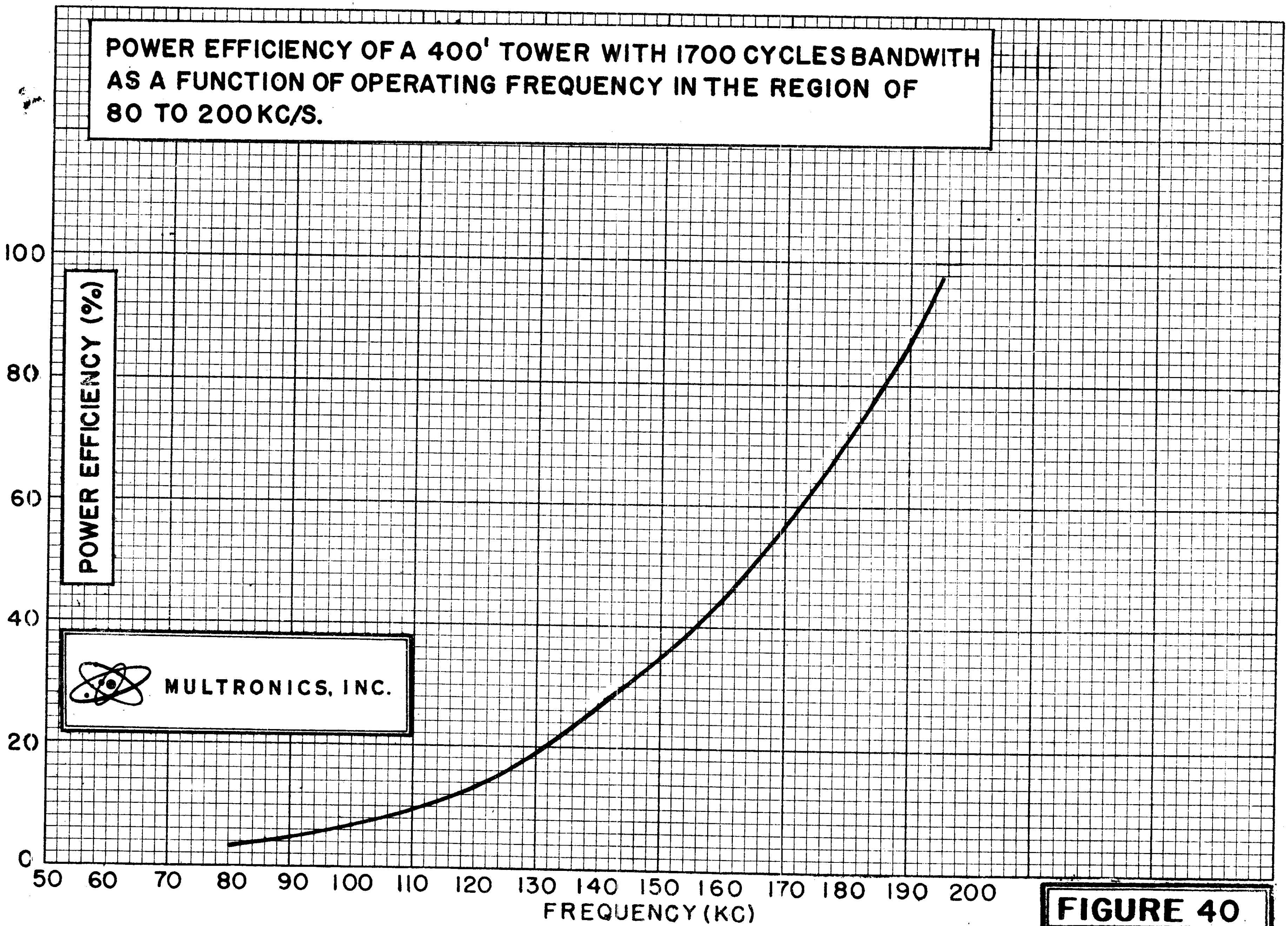
FIGURE 39

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 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 an adjustable element of the "A", "B", "C", "D", and "E" systems, by which we can change and control the feed point resistance. In the "D" System L_2 is made adjustable by insertion of a base insulator under the tower and connecting the tower to ground through an inductance. 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 38. 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, the addition of non-terminated



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.

FIGURE 40

top-loading wires, and by adjustment of L_2 ("D" and "E" System only).

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 F of 1700 cycles has not been shown. Figure 40 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 3.0 to 98%. This is equivalent to a variation in field efficiency of approximately 9.0 to 99%.

Personnel of military agencies have been accustomed to speaking in terms of radiated power, or of the power efficiency, of an antenna. This term is not really meaningful to the communications engineer. The standard concept of determining the radiated field from an antenna in millivolts per meter (mv/m) at a distance of one mile, commonly called the unattenuated field, is much more meaningful. This concept was discussed at length in Section 2. It has been used by the Federal Communications Commission for many years in determining the performance of antenna systems for MF broadcasting stations.

(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 capacitor switching links as 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 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.

(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, AN/URM-6 Field Intensity Meter, or equivalent.
3. An AN/URM-25D 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 50 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 connecting links are properly connected between capacitor sections. (Refer to instruction manual).

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 connect the test clip of the bridge to the antenna. 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 50 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 three 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 50 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 50 ohms of feed point resistance is maintained with all G.T.U. counter dial numbers and capacitor connecting links identical.

8. The resistance is now 50 ohms, but there is 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 series network (components L, and C, as required) for the proper total reactance value at the operating frequency.

The bandwidth for the system can be determined by means of the method already discussed in Section 5 of this course. 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.

If the bandwidth is not as desired, adjustment of L_2 in the "D" System can be made to change it. Herein lies one of the advantages of the "D" System. L_2 can control the bandwidth, and adjustment of the G.T.U. capacitors can be used to maintain the feed point resistance at 50 ohms.

The tables below show how bandwidth varies with adjustment of L_2, while input resistance can be held constant by adjustment of the G.T.U. capacitors. The data was taken on a typical 450 foot NORD System. Tests 1 and 5 were made using an "A" System configuration with the tower grounded. Tests 2,3,4,6,7, and 8 were made using the "D" System configuration, and the value of X_{L2} is shown.

	Test 1	Test 2	Test 3	Test 4
Frequency (KC)	50	50	50	50
Static Bandwidth (Cycles)	9.8	13.8	12.6	10.4
Dynamic Bandwidth (KC)	6.55	2.34	2.70	3.05
Power Efficiency (%)	.15	.59	.47	.34
Field Efficiency (%)	3.9	7.7	6.9	5.85
Input Resistance (ohms)	50	50	50	50
X_{L2}	*	+j70	+j60	+j50

	Test 5	Test 6	Test 7	Test 8
Frequency (KC)	75	75	75	75
Static Bandwidth (Cycles)	40.4	98	94	81
Dynamic Bandwidth (KC)	5.8	2.37	2.66	2.80
Power Efficiency (%)	.696	4.14	3.50	2.90
Field Efficiency (%)	8.33	20.35	18.70	17.05
Input Resistance (ohms)	50	50	50	50
X_{L2}	*	+j70	+j60	+j50

* No base insulator or inductor used.

For purposes of comparison, the parameters of the same 450 foot tower, series-fed, are shown below. A series "swamping" resistance is used for the purpose of causing the antenna to appear as a broadband load to the transmitter. Note the very high values of negative input reactance which must be cancelled out by use of a Helix coil. Compare this tabulation with Tests 2 and 6 above, respectively.

Frequency (KC)	50	75
Static Bandwidth (Cycles)	11.92	60.4
Dynamic Bandwidth (KC)	2.34	2.37
Power Efficiency (%)	.51	2.55
Field Efficiency (%)	7.15	15.94
Swamping Resistor (ohms)	42.00	18.80
Input Resistance (ohms)	42.21	19.28
Input Reactance (ohms)	-j1800	-j1190

9. Ready for Power: After the tuning of all elements has been set and all "J" plugs and connecting links have been put in place, completely remove all measuring 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 meter. 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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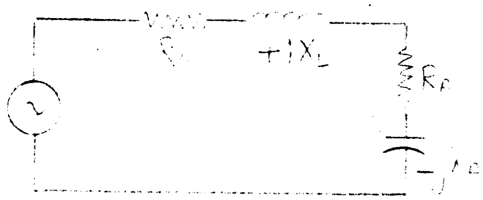
APPENDIX

THE TRANSIENT RESPONSE OF AN ANTENNA SYSTEM, AND ITS RELATION TO BANDWIDTH.

(1) A simple series fed short antenna, properly resonated and matched to the transmitter output impedance, may be represented as follows:



(The generator impedance R_o equals R_A, for the matched condition.)

FIGURE 1

It should be noted that, in some instances, the coupling unit provides an impedance transformation to furnish an "optimum" load to the transmitter. The optimum value (for good power transfer and acceptable distortion, etc.) does not necessarily correspond to the matched condition. In such a case, the loaded bandwidth need not be twice the intrinsic bandwidth ($R_o = 0$). However, for the following example we shall assume a tone conjugate match at the operating frequency. Thus $R_o = R_A$ and $R_T = 2R_A$. Since the field intensity in a receiver located in the far field is directly proportional to the antenna loop current, we solve for the transient response of the current after a sudden step of source voltage.

$v(t) = u(t) \times Vo \sin \omega t$ $\qquad v(p) = \frac{Vo\, \omega}{\omega^2 + p^2}$

$$I(p) = \frac{v(p)}{pL + R_T + \frac{1}{pC}}$$

$$= \frac{pC\, Vo\, \omega}{p^2LC + pCR_T + 1)\,(\omega^2 + p^2}$$

Let $\omega_o^2 = \frac{1}{LC}$ $(\omega_o^2 LC = 1)$ and $\delta = \frac{R_T}{2\omega_o L}$

$$I(p) = \frac{V_o}{R_T} \frac{\left(\frac{pC}{\omega_o^2 LC} \times \frac{R_T}{R_T} \times V_o \frac{\omega}{\omega_o 2}\right)}{\left[\left(\frac{p}{\omega_o}\right)^2 + \left(\frac{p}{\omega_o}\right)\frac{R_T}{\omega_o L} + 1\right]\left[\left(\frac{\omega}{\omega_o}\right)^2 + \left(\frac{p}{\omega_o}\right)^2\right]}$$

Let $\omega_v = \frac{\omega}{\omega_o}$

$$I(p) = \frac{V_o}{R_T} \frac{\left(\frac{p}{\omega_o}\right) 2\,\delta\,\omega_v}{\left[\left(\frac{p}{\omega_o}\right)^2 + 2\delta\left(\frac{p}{\omega_o}\right) + 1\right]\left[\left(\frac{p}{\omega_o}\right)^2 + \omega_v^2\right]\omega_o}$$

From the change of time scale relation for Laplace transforms: $\mathcal{L}\, f\left(\frac{t}{a}\right) = aF(ap)$

$$i\left(\frac{t}{\omega_o}\right) = \mathcal{L}\, i(t_v) = \omega_o\, I(\omega_o\, p) = \frac{V_o}{R_T}\left[\frac{2\,\delta\, p\, \omega_v}{(p^2 + 2\delta p + 1)\,(p^2 + \omega_v^2)}\right], \quad t_v = \frac{t}{\omega_o}$$

This transform can be expanded into partial fractions, as follows:

$$\mathcal{L}\, i(t_v) = \frac{V_o}{R_T}\left[\frac{Wp + X}{p^2 + 2\,\delta\, p + 1} + \frac{Yp + Z}{p^2 + \omega_v^2}\right]$$

In the above expression, the terms in X and Z correspond to damped and to undamped sine waves, respectively, while the terms in W and Y correspond to damped and undamped cosine waves. Note that the undamped waves, which correspond to the steady state solution, occur at frequency ω_v, the input frequency, while the damped waves always occur at $\omega_v = \sqrt{1-\delta^2}$ $\left(\omega = \left(\sqrt{1-\delta^2}\right)\omega_o\right)$, which is the natual damped ringing frequency of the system.

The simplest, and most common situation is that for which $\omega = \omega_o$, so that a complex conjugate match is achieved between generator and load at the operating frequency. Thus, $\omega_v = 1$ and the above expression becomes:

$$\mathcal{L}\, i\ (t_v) = \frac{V_o}{R_T}\left[\frac{Wp + X}{p^2 + 2\,\delta\, p + 1} + \frac{Yp + Z}{p^2 + 1}\right]$$

The simultaneous equations in W, X, Y, and Z are obtained and solved as follows:

$$(Wp + X)(p^2 + 1) + (Yp + Z)(p^2 + 2\delta p + 1) = 2\delta p$$

$$Wp^3 + Wp + Xp^2 + X + Yp^3 + 2\delta Yp^2 + Yp + Zp^2 + 2\delta Zp + Z = 2\delta p$$

Equating the coefficients of the various powers of p on both sides of the equation yields,

$$W + Y = 0$$

$$X + Z + 2\delta Y = 0$$

$$W + Y + 2\delta Z = 2\delta$$

$$X + Z = 0$$

whose matrix is the following:

$$\begin{vmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 2\delta & 1 \\ 1 & 0 & 1 & 2\delta \\ 0 & 1 & 0 & 1 \end{vmatrix} = \begin{vmatrix} 0 \\ 0 \\ 2\delta \\ 0 \end{vmatrix}$$

W is given by:

$$W = \frac{\begin{vmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 2\delta & 1 \\ 2\delta & 0 & 1 & 2\delta \\ 0 & 1 & 0 & 1 \end{vmatrix}}{\begin{vmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 2\delta & 1 \\ 1 & 0 & 1 & 2\delta \\ 0 & 1 & 0 & 1 \end{vmatrix}}$$

The numberator of W, obtained by subsituting the right hand matrix in place of the first column of the left hand matrix is:

$$2\delta \begin{vmatrix} 0 & 1 & 0 \\ 1 & 2\delta & 1 \\ 1 & 0 & 1 \end{vmatrix} = 0 \text{ since two columns are identical}$$

Therefore, $W = 0$ and we can evaluate the other coefficients by inspection.

$W = 0$

$Y = 0$

$Z = 1$

$X = -1$

Our transform is now written:

$$\mathcal{L}\, i\,(t_V) = \frac{V_o}{R_T}\left[\frac{1}{p^2 + 1} - \frac{1}{p^2 + 2\delta + 1}\right]$$

The normalized time function can be obtained directly from the above by taking the inverse transform.

$$i(t_V) = \frac{V_o}{R_T}\left[\sin t - \frac{1}{\sqrt{1 - \delta^2}}\, e^{-\delta t} \sin\left(\sqrt{1 - \delta^2}\right) t\right]$$

The non-normalized time is then obtained by substituting ot for t in the above. Thus:

$$i(t) = \frac{V_o}{R_T}\left[\sin \omega_o t - \frac{1}{\sqrt{1 - \delta^2}}\, e^{-\delta \omega_o t} \sin \omega_o\left(\sqrt{1 - \delta^2}\right) t\right]$$

The first term is the steady state current while the second term represents a damped sinusoid at the damped resonant frequency of the circuit. In order to obtain a simple approximation, we write:

$$\sin \omega_o\left(\sqrt{1 - \delta^2}\right)t = \sin\left(\omega_o t + \omega_o\left(\sqrt{1 - \delta^2}\right)t - \omega_o t\right)$$

$$= \sin\left(\omega_o t + \omega_o\left(\sqrt{1 - \delta^2} - 1\right) t\right)$$

if we let $\omega_o\left(1 - \sqrt{1 - \delta^2}\right) = \Omega$, the above becomes:

$$\sin \omega_o\left(\sqrt{1 - \delta^2}\right)t = \sin\left(\omega_o t - \Omega t\right)$$

$= \sin\omega_0 t \cos\Omega t - \cos\omega_0 t \sin\Omega t$

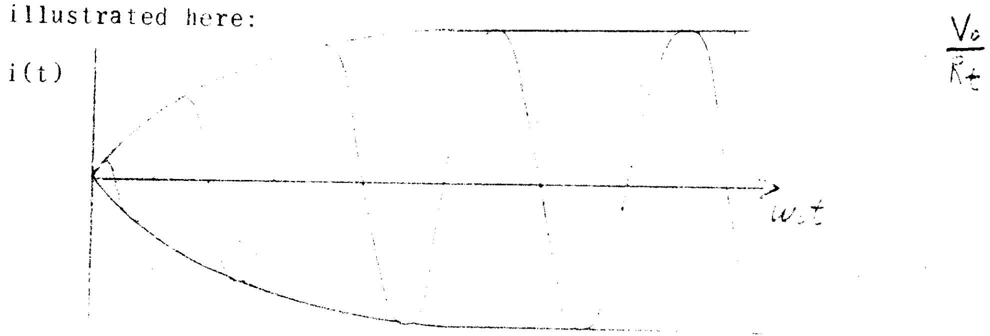
Substituting this back into the expression for i(t) gives:

$$i(t) = \frac{V_o}{R_T}\left[\left(1 - \left(\frac{\cos\Omega t}{1-\delta^2}\right)e^{-\delta\omega_0 t}\right)\sin\omega_0 t - \left(\frac{\sin\Omega t}{1-\delta^2}\right)e^{-\delta\omega_0 t}\cos\omega_0 t\right]$$

For small values of δ ($\delta \ll 1$), $\cos\Omega t$ is approximately equal to 1, and $\sin\Omega t$ is approximately equal to 0 over the range of times of interest. Therefore we can write:

$$i(t) \cong \frac{V_o}{R_T}\left(1 - e^{-\delta\omega_0 t}\right)\sin\omega_0 t$$

This expression represents the transient response of a single tuned antenna, which is illustrated here:



The time constant of the exponential buildup is given by:

$$\tau = \frac{1}{\delta\omega_0} = \frac{1}{\frac{R_T\,\omega_0}{2\,\omega_0 L}} = \frac{2L}{R_T} = \frac{2}{\omega_0}\,\frac{\omega_0 L}{R_T} = \frac{2Q}{\omega_0}$$

where $Q = \frac{\omega_0 L}{R_T}$

The total rise time from 0 to 90% of full current is given by:

$$T = 2.3\tau = \frac{4.6\,L}{R_T} = 4.6\,\frac{Q}{\omega_0} = \frac{4.6\,Q}{2\,\pi\, f_o} = 0.73\,\frac{Q}{f_o}$$

Thus, for a given Q, the maximum possible keying rate is limited by the operating frequency. Or, we can express T as follows:

$$\tau = 0.73 \frac{\frac{fo}{\Delta f}}{fo} = \frac{0.73}{\Delta f}, \text{ where } Q = \frac{fo}{\Delta f}$$

Here we see exactly that the R.F. carrier envelope rise time is inversely proportional to the system bandwidth.

The minimum bandwidth required for 8 channels of frequency division multiplex is 1700 cycles. In frequency division multiplex systems currently in use such as the AN/FGC-29, AN/FGC-60 and AN/FGC-61, the channel spacing is 170 cycles, the lowest channel frequency being 425 cycles, and the highest being 1615 cycles. The frequency shift per channel is $\pm$ 42.5 cycles. The lowest mark frequency is thus 382.5 cycles, and the highest space frequency is 1657.5 cycles.

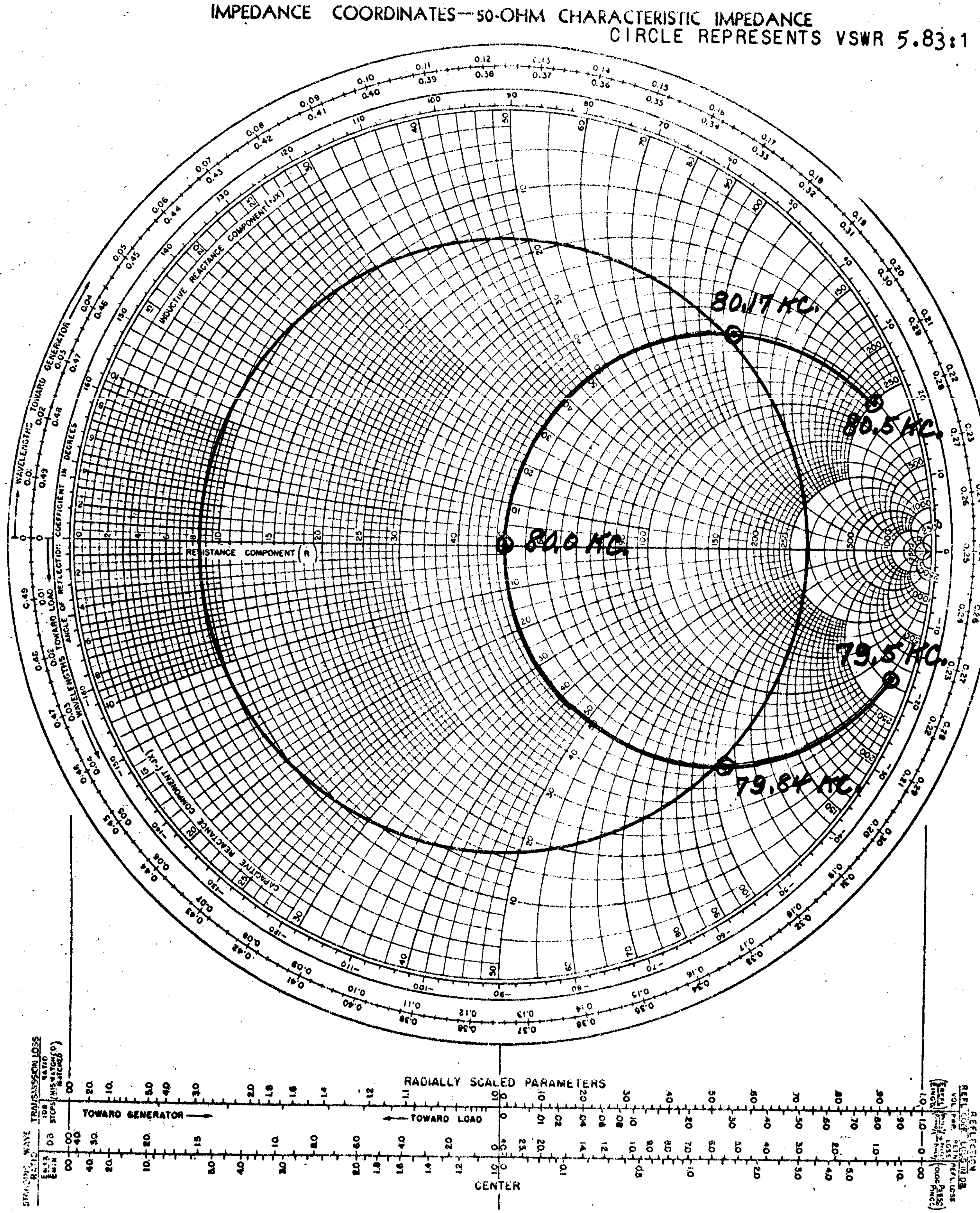
Present standards of the Defense Communication System (16) state the relationship of the composite power level to the zero dbm level in a multichannel system. It is that the power per channel Pc equals the zero dbm reference power level divided by the number of channels. Thus, to find the level per channel in dbm the following equation is used:

$$\text{Level per channel (dbm)} = -10 \log_{10} \frac{1.0}{Pc \times 10^{-3}}$$

For an 8 channel system the power level per channel is - 17.7 dbm. When zero dbm is equated to transmitter PEP then the level per channel is - 17.7 db below PEP level.

This relationship is important because components in an antenna system must be rated to stand the peak voltages and currents of PEP level, yet the average power level and power per channel are much lower. For an 8 channel system reference (16) specifies a composite power level of - 8.7 dbm as being standard.

Smith Chart plot of input impedance of the antenna described in Section 5.II.C., pages 53 and 54.



SAMPLE LOG OF FIELD INTENSITY MEASUREMENTS

STATION__________
POWER__________
FREQUENCY__________

FIELD METER DATA:
TYPE__________
SERIAL__________

RADIAL NO.__________
BEARING__________
ENGINEER__________

POINT NUMBER	DATE / TIME	FIELD MV/M	DISTANCE MILES	DESCRIPTION