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A Study of the Radiation Characteristics of Shipboard Antenna Systems

(New Construction)

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1. In general, one of the outstanding differences between transmitting antennas employed on Naval combatant vessels as compared with antennas erected on land, lies in the restricted dimensions of the Naval shipboard antennas. This is particularly true of antennas operating in the frequency range below 600 kilocycles. Whereas the land establishment is capable of proportioning the antenna to obtain, to a large extent, most of the characteristics which make for efficiency, the Naval shipboard antenna must be subjugated to the exigencies of military activities. Thus it will be found that instead of antennas which may approach a quarter wave, the service is forced to employ antennas which are only a very small fraction of a wave length. For instance, an antenna 80 feet high is only 0.016 of a wave length at 200 kilocycles.

2. In the following discussion two frequency ranges are considered, frequencies below 600 kilocycles and frequencies in the range of 2,000 to 20,000 kilocycles.

RADIATION FROM AN ANTENNA AT FREQUENCIES BELOW 600 KILOCYCLES

3. For frequencies below 600 kilocycles, the problem of radiating the power developed in the tank circuit of the power amplifier may be divided into three parts; namely,

(a) Transfer of the power from the power amplifier tank circuit to the antenna or to the transmission line.

(b) Where the transmitter and the antenna are separated to a considerable extent, means must be provided for transferring the power from the transmitter to the antenna.

(c) The actual antenna or radiating system.

Transfer of power from the tank circuit to the antenna or transmission line is accomplished through the medium of the antenna coupling circuit and antenna loading inductor in the radio transmitter proper. Transfer of the power from the output terminal of the radio transmitter to the antenna is accomplished by means of the antenna lead-in or by means of a transmission line or trunk. The transmission line or trunk is used when the antenna itself is at a point distant from the transmitter, or when it is necessary to pass through bulkheads, superstructures, or similar areas. The actual radiator is that part of the antenna system which is essentially in the clear and consists of the vertical element which may or may not be provided with flat top loading.

4. While it is possible to thus divide the antenna system into the three parts mentioned above, it is difficult to discuss the efficiency of each discrete part separately due to the reactions between the various parts. For example, as will be described in more detail later, the capacitance of the antenna affects the losses in the loading inductor; the capacitance of the trunk or transmission

line also affects the losses in the loading coil and in turn the actual resistance of the loading inductor affects the transfer of power to the antenna. The efficiency of the entire antenna system is equal to the product of the efficiency of the individual parts. For example, if the efficiency of the loading inductor were 50%, the efficiency of the transmission line 75%, and the radiation efficiency of the antenna were 20%, the overall efficiency of the system would be 50% x 75% x 20% = 7.5%.

5. The radiation efficiency of the antenna, in per cent, may be expressed as follows:

$$\text{Radiation Efficiency} = \frac{R_r\ 100}{R_t} = \frac{100\ R_r}{R_r + R_L}\ \%$$

where

R_r is the radiation resistance of the antenna.

R_L is the loss resistance of the antenna.

$R_t = R_r + R_L$ is the total antenna resistance.

While it is possible to measure the total resistance of an antenna, such measurements do not differentiate between the Radiation Resistance (R_r) and the Loss Resistance (R_L). If the antenna is an appreciable fraction of a wavelength, say a quarter wave, a measurement of the resistance would indicate rather closely the value of radiation resistance since the Radiation Resistance would constitute the major portion of the total resistance. However, when dealing with short antennas, that is, antennas which are essentially less than a quarter wave, the Radiation Resistance would be only a small portion of the total measured resistance. Under these circumstances the actual radiation resistance can be determined only by a series of calculations.

6. The power radiated by the antenna is

$$I^2\ R_r$$

The power loss in the antenna is

$$I^2\ R_L$$

Therefore the total power in the antenna is equal to the sum of the radiated power and the power loss, or

$$I^2\ (R_r + R_L)$$

where I is the radio frequency current at the effective base of the antenna. Attention is invited to the term "effective base of the antenna." This denotes that the current under consideration is not the current read on the antenna ammeter in the radio transmitter nor may it even be the current read at the output end of the trunk or transmission line. For example, if the antenna lead emerging from the trunk or transmission line runs horizontally for some distance and is secured to a grounded object by means of stand-off insulators, care must be taken to see that the current measurement is made at the point where the antenna rises vertically and is essentially in the clear. In determining the effective vertical height of the antenna, measurements should be made from this same point. Thus it will be seen that while the uppermost end of the antenna may be 90 feet above the deck, the useful vertical height may be only 80 feet since the bottom ten feet of the antenna may be surrounded or close to metallic objects.

7. The loss resistance of the antenna is due to the ground resistance, the conductor resistance and the resistance due to bad dielectric in the electric field of the antenna. The effect of nearby bulkheads, masts, or other grounded metallic objects is to partially shield the antenna. In general, this shielding will act as a partial trunk or transmission line and will decrease the effective height and radiation resistance of the antenna. In the subsequent discussion, antennas for operation below 600 kilocycles are treated in two general classes. First, antennas which are essentially in the clear; i.e. antennas that are not seriously affected by the proximity of shielding elements such as stacks and superstructure. Second, antennas which are adjacent to screens or shields; i.e., antennas run close to bulkheads, stacks, etc. In the low frequency region below 600 kilocycles, the most important part of the antenna is that portion which is effective in producing vertically polarized waves. Horizontally polarized waves suffer such high attenuation that they are essentially useless in the frequency range under discussion. Because of the restrictions imposed upon shipboard antennas, particularly as to vertical height (and also as to horizontal length) and since as time progresses the tendency on modern vessels is toward lower masts, it becomes increasingly important to preserve and protect the vertical elements of the antennas against further unnecessary encroachment. The careless designations applied to the vertical sections of radiating systems, such as "lead-ins" and "down-leads," probably have a tendency to obscure the importance of the vertical elements, since such terms tend to indicate that the vertical members are merely connections between the transmitting equipment and the upper or flat-top portions of the antenna. However, when the extreme importance of these vertical elements is understood it is possible for the personnel responsible to guard against harmful practices. The guying of vertical radiators close to the superstructure and bulkheads, or partially or wholly surrounding them with guards and shields, should be avoided wherever possible.

8. For an antenna with a good ground and fairly well in the clear and with very little bad dielectric in its field, the loss resistance would be about 2 ohms. This resistance will vary somewhat with frequency. Thus for a 50% radiation efficiency, the radiation resistance of the antenna must be 2 ohms. This will require a plain vertical antenna, without top loading, to be 0.07 wavelength in height. At 200 kilocycles, 0.07 wavelength corresponds

to an antenna height of 350 feet. If the antenna had top loading in the form of a flat-top three times the vertical height, the antenna would have to be 200 feet high with a 600 foot flat-top in order to have a radiation resistance of 2 ohms at 200 kilocycles. At 600 kilocycles an 80 foot vertical antenna with an 80 foot flat-top will have a radiation resistance of 2.2 ohms. At 200 kilocycles and 75 kilocycles such an 80 foot antenna will have a radiation resistance of 0.23 and 0.029 ohm respectively. The radiation efficiency of this antenna would be about 50% at 600 kilocycles, 10% at 200 kilocycles and 1.5% at 75 kilocycles. Thus it will be seen that for a given antenna, the efficiency decreases rapidly as the frequency is decreased.

9. For frequencies below 600 kilocycles and for transmission lines (trunks) not over 200 feet long, the transmission line will act as a capacitance. This is equivalent to saying that the length of the transmission line is less than $\lambda/4$. Under these conditions the transmission line may be treated as a condenser. This condenser may be considered as connected between the antenna terminal of the transmitter and ground. The resistance of this condenser will be small compared to its capacity reactance. Below 600 kilocycles the antenna will also act as a large capacity reactance in series with the small antenna resistance. The capacitance of a 50 foot transmission line, where 12" and 1/2" are the diameters of the outer and inner conductors respectively, is about equal to the capacitance of an 80 foot vertical antenna without top loading. Thus it can be readily seen that the transmission line capacitance may be many times the antenna capacitance when long transmission lines are used. The capacitance of the transmission line is in parallel with the capacitance of the antenna and the capacitance as measured at the antenna terminal of the transmitter is equal to the sum of these two. When a transmission line is used, it will require less antenna loading inductance to resonate the antenna. Thus it might appear to be advantageous to use a transmission line. However, the resistance of the antenna loading inductor does not change greatly with the amount of antenna loading inductance used because the unused portion is always short circuited and losses will still occur in this part. The transmission line shunts part of the r-f current at the antenna terminal of the transmitter to ground so that the r-f current at the antenna end of the transmission line is always less than the r-f current at the antenna terminal of the transmitter. Let us consider a number of examples.

(a) When the transmission line capacitance is equal to the antenna capacitance, the r-f current at the antenna end of the transmission line is one-half of the current at the transmitter end of the transmission line.

(b) If the transmission line capacitance is one-third of the antenna capacitance, then the r-f current at the antenna end of the transmission line will be three-fourths of the r-f current at the transmitter end of the transmission line.

(c) When the transmission line capacitance is three times the antenna capacitance, the r-f current at the antenna end of the transmission line is only one-fourth of the r-f current at the transmitter end of the transmission line.

An increase in the capacitance of the antenna decreases the percentage of the r-f current shunted to ground by the transmission line. Therefore, if a flat top is added to the vertical portion of the antenna, it not only increases the radiation resistance of the vertical element but also increases the capacitance of the antenna. This results in decreasing the loss in the antenna loading inductor and in the transmission line thus increasing the power in the actual antenna. The current distribution in the vertical portion becomes more uniform thus increasing the radiation resistance of the antenna. Thus the power radiated from the antenna is increased not only by reducing the losses in the antenna loading coil and transmission line, but by increasing the radiation efficiency of the antenna.

10. The capacitance of the transmission line is proportional to its length. Thus the longer the transmission line the greater the current which will be shunted to ground. While the losses in the transmission line itself may not be great, by shunting current to ground in the transmission line, the losses in the antenna loading inductor are increased. The r-f power loss in the antenna loading inductor is proportional to the square of the current in the inductor. Thus the increase in current due to the transmission line may be effective in creating large losses. Conditions may arise where the losses in the antenna loading inductor, particularly at the low frequencies, may be as great as 90% of the power output of the transmitter.

11. Occasions will arise where it will be of interest and practical value to calculate or determine the capacitance of transmission lines and trunks. The curve in Plate 11 gives the static capacitance per foot of transmission line as a function of the ratio of the diameters of the outer and inner conductors. Knowing the ratio of the diameters of the outer and inner conductors and the length of the transmission line, the static capacitance can be readily calculated. When the length of the transmission line is a small fraction of a quarter wavelength, the capacitance of the transmission line is equal to the static capacitance; i.e., the effect of the inductance can be neglected. The curve in Plate 11 is based on air dielectric and does not take into account the added capacitance due to the insulators that are used to support the inner conductor. For large transmission lines (six inches or greater in diameter) this correction is negligible. In practical installations the capacitance to ground of the leads connecting to the inner conductor of the transmission line (such as the lead from the transmitter to the transmission line) will add to the actual transmission line capacitance. Thus the actual transmission line capacitance will be greater than the calculated value. This error will not be large if the leads are relatively short.

12. The following example will illustrate the use of the curve in Plate 11.

Example:

Length of transmission - 50 feet
Inside diameter of outer conductor - 10 inches
Outside diameter of inner conductor - 1/2 inch
Ratio of outer and inner conductors - 10 divided by .5 = 20

From Plate 11 for a ratio of 20, the capacitance per foot of transmission line is 5.64 μμf. The capacitance of the fifty foot transmission line is 50 x 5.64 = 282 μμf.

13. If the currents at both ends of the transmission line are known and the capacitance of the transmission line has been calculated or measured, then the antenna capacitance can be calculated from the following formula:

$$C_a = \frac{C\, I_a}{I - I_a}$$

where

C_a is the capacitance of the antenna in μμf.
C is the capacitance of the transmission line in μμf.
I is the current at the transmitter end of the transmission line.
I_a is the current at the antenna end of the transmission line.

This formula may prove useful when more elaborate measuring equipment is not available.

Antennas in the Clear

14. Occasions frequently arise where it is desirable to determine the radiation resistance of an antenna of any given height, with or without top loading, and at any given frequency in the desired range. Furthermore, since the horizontally polarized radiation is ineffective at low and low-intermediate frequencies, it is desirable to evaluate the effective radiation resistance; that is, the vertical component. To further simplify such calculations and to permit more or less universal use, means should be provided for determining the wavelength of an antenna when the dimensions are expressed in feet. Finally, it would be advantageous to provide some simple method of determining the field strength developed at any given point by any value of radiated power. The curves presented in Plates 1, 2, and 9 were developed to accomplish the above purpose.

15. Plate 1, wherein five curves are presented, plots radiation resistance in ohms as a function of antenna height in wavelength. The radiation resistance under consideration is that portion of the total radiation resistance which is due to the vertical portion of the antenna system, or that portion which produces vertically polarized waves. This is the portion of the total radiation resistance which is useful. The five curves shown in Plate 1 are designated "A" to "E" inclusive. Curve "A" is calculated for a simple vertical antenna with no top loading; i.e., no flat top portion. Curve "B" covers the case where a flat top of half the length of the vertical section has been added to the vertical radiator. Curves "C", "D", and "E" apply to systems wherein flat tops of lengths equal to, 3 times, and 7 times the length of the vertical section, respectively, have been added to the vertical element. The addition of the flat top sections has the effect of increasing the effective height of the vertical section. However, the curves show that, as far as the vertical component of radiation resistance is concerned, the continued increase in the length of the flat top becomes increasingly less effective. Hence, when the length of the flat top is 7 or 8 times that of the vertical height, no essential gain in the vertical component of radiation resistance would result. The curves in Plate 1 are so drawn that given the height of the antenna in wavelength and the length of the flat-top in wavelength, the vertical component of radiation resistance can be determined directly.

16. Plate 2 is a conversion chart which provides a simple and rapid means for determining the wavelength (or fraction thereof) of various heights of antennas at any frequency.

17. In Plate 9 the field strength of the ground wave over sea water is plotted as a function of distance, in miles, for a radiated power of one watt. The ground wave is here considered to be that portion of the wave received on the earth's surface which has not been propagated by conducting portions of the upper atmosphere. When the ground wave reaches values much less than those predicted by the inverse distance law, the sky wave may be effective in producing field strengths much greater than those indicated in the attached curves, especially at night. There will be intervals of time when the values given in these curves will represent the maximum field strength which will be observed. These conditions will generally exist during the daylight hours. In the region of frequencies and distances herein discussed, the contribution of energy of the sky wave during the daytime is considered negligible in comparison to the energy of the ground wave. It will be noted that the field strength is given in millivolts per meter (mv/m) for distances up to 60 miles. Beyond this distance field strength is plotted in microvolts per meter (μv/m). The curves cover frequencies of 150, 300, 550, and 1,000 kilocycles. Field strengths for other frequencies within this range may be obtained by interpolation.

18. As stated above, the curves in Plate 9 are based on a radiated power of 1 watt. In order to apply these curves to cases wherein the radiated power is of greater or smaller magnitude, it is necessary to multiply the field strength as read on the graph by the square root of the radiated power (in watts) for the particu-

lar case under consideration. To illustrate the application of these curves a few examples are given.

Example "A"

To determine the field strength at 50 miles and at 300 miles, when:

Antenna height - 80 feet vertical
Length of flat top - 80 feet
Frequency - 200 kilocycles
Transmitter connected directly to base of antenna; no transmission line used.
Current at base of antenna - 3.5 amperes

From Plate 2 it is found that the wavelength of an 80 foot antenna at 200 kilocycles is 0.016. From Plate 1, Curve "C", it is found that the vertical component of radiation resistance of a 0.016 wave length antenna with a flat top of equal length is 0.22 ohm. Squaring the current at the base of the antenna (3.5^2) gives 12.25, which multiplied by 0.22 gives the radiated power as 2.695 watts. Since the field strength is proportional to the square root of the power, the field strength per watt must be multiplied by the square root of the power. The square root of 2.695 is 1.64. From Plate 9 it is found that the field strength for 1 watt radiated power at 50 miles (at 200 kilocycles) is 0.12 mv/m. $1.64 \times 0.12 = 0.196$ mv/m, which is the field strength at 50 miles for a radiated power of 2.695 watts. At 300 miles the field strength from Plate 9 is 12.5 μv/m. $1.64 \times 12.5 = 20.5$ μv/m, which is the field strength at 300 miles for a radiated power of 2.695 watts.

Example "B"

To determine the field strength at 50 miles and 300 miles. Same conditions as listed under Example "A", except antenna is connected to transmitter through transmission line of such constants as to reduce the current at the base of the antenna to 2.5 amperes.

From Plate 2 the wavelength of an 80 foot antenna is 0.016. From Curve "C" of Plate 1, the vertical component of radiation resistance of a 0.016 wavelength antenna with a flat top equal in length to the vertical height is 0.22 ohm. Squaring the current at the base of antenna (2.5^2) gives 6.25, which multiplied by 0.22 equals 1.375 watts. The square root of 1.375 is 1.17. From Plate 9 it is found that the field strength for 1 watt of radiated power at 50 miles (at 200 kilocycles) is 0.12 mv/m. $1.17 \times 0.12 = 0.14$ mv/m, which is the field strength at 50 miles for a radiated power of 1.375 watts. At 300 miles the field strength, from Plate 9, is 12.5 μv/m. 1.17×12.5 equals 14.6 μv/m, which is the field strength at 300 miles for a radiated power of 1.375 watt.

Example "C"

To determine the field strength at 500 miles when:

Antenna height - 90 feet vertical
Flat top - none
Frequency - 500 kilocycles

Trunk - None
Current at base of antenna - 3.5 amperes

From Plate 2: wavelength of a 90 foot antenna is 0.046 at 500 kilocycles. From Curve "A" of Plate 1: vertical component of radiation resistance due to vertical element of a 0.046 wavelength antenna is 0.8 ohm. Squaring the current at the base of the antenna (3.5^2) equals 12.25, which multiplied by 0.8 equals 9.8 watts. The square root of 9.8 is 3.12. From Plate 9 it is found that the field strength for 1 watt radiated power at 500 miles (at 500 kilocycles) is 2 μv/m. $3.12 \times 2 = 6.24$ μv/m, which is the field strength at 500 miles for a radiated power of 9.8 watts.

19. It should be realized that the degree of accuracy which can be obtained through the use of these curves will not be of an exact nature. The curves, to some extent, are based upon ideal conditions which may not be completely fulfilled by a Naval shipboard installation. However, the curves will serve the purpose of arriving at generally useful results in connection with the problem of shipboard antenna systems in the frequency range below 600 kilocycles.

Shielded Antennas

20. As mentioned above, it has been realized that stacks, masts, and other grounded superstructure on board ship have affected the radiation characteristics of antennas. In general, the effect of shields or screens near a vertical radiator is to make the antenna partially directive, to increase the antenna capacity and to decrease the radiation resistance of the antenna. Directivity in vertical radiators is a very undesirable characteristic, especially if the ratio of the maximum field strength to the minimum field strength is high. A decrease in radiation resistance results in a decrease in the radiated power and a consequent decrease in field strength at any given distance from the antenna. A nearby shield does not increase the field strength in one direction, but decreases the field strength in all directions. However, this decrease is greater in some directions than in others. These facts have been pointed out in the past. The tendency toward shorter antennas and the concentration of the antennas in small areas on board ship in the vicinity of grounded superstructure has increased the detrimental influence of such shields or screens upon the radiation properties of antennas to such an extent that the magnitude of these effects should be known.

21. The radiation characteristics of an antenna are affected by the surrounding antennas as well as by the superstructure. To attempt to take into account all of these influences would result in extremely difficult mathematical calculations which would not lend themselves to a practical solution. However, in the case under consideration; namely, at frequencies below 600 kilocycles, all of the surrounding antennas are only a small fraction of a wavelength in height and thus will not be resonant. The effect of any shield will be proportional to the square of the distance between the shield

and antenna. In most cases one shield or screen will be predominant and the effect of all others may be neglected. Thus the problem will reduce in a majority of cases to the one antenna under consideration and a single shield or screen.

22. The simplest case to treat mathematically is that of a grounded vertical radiator that is close to an infinite shield or screen. The screen may be considered infinite if the screen is considerably higher than the antenna and the angle α is nearly 180°. (See Fig. 1) D must be only a small fraction of a wavelength. Then the effect of the infinite screen and the ground can be replaced by image currents as shown in Fig. 2. The infinite screen is the y z plane in Fig. 2. Thus the effect of the screen and ground are replaced by three image currents. This antenna can radiate only above the x y plane and to the left of the y z plane. If the screen were not infinite, but of height h and of width c and $\alpha' = \alpha''$ (see Fig.3), then the image currents i_z'' and i_z''' would not be equal in magnitude to the antenna current, but would be $K\, i\, z$ where $i\, z$ is the current at a height z in the antenna and $K \leqq 1$. K is a function of z, the height h and the width C of the screen and the distance the screen is from the antenna. In order to simplify the calculations K is taken as independent of the height z and depends only upon the width of the screen and the distance the antenna is from the screen. Thus for a particular antenna and screen K is a definite constant. This simplification holds fairly accurately if the screen is at least twice as high as it is wide.

23. The following example will illustrate the low efficiency when an antenna is near an infinite screen. This condition may be compared to the case where an antenna is only a short distance from a stack, say, secured to the stack by means of stand-off insulators, and no part of the antenna is in the clear. Such an antenna may be likened to a 50 foot vertical antenna 30 feet distant from an infinite vertical screen. The radiation resistance of this antenna at 600 kilocycles is less than 0.0001 ohm. Thus for a current of 10 amperes at the base of the antenna, less than 0.01 watt of power will be radiated. The antenna cannot radiate through the screen so the antenna will be directional. If the above antenna were in the clear it would have a radiation resistance of 0.34 ohm and for a current of 10 amperes at the base of the antenna, 34 watts of r-f power would be radiated. This example illustrates the great loss in radiated power due to a screen or shield.

24. The shields or screens on board ship are not large enough to be considered infinite except when the antenna is only a few inches distant from the screen or when the angle α is nearly 180°. (See Fig.3) Thus the more complex problem of a finite shield next to the antenna must be considered. The diagram in Fig. 3 illustrates the problem. The antenna is of a height h_1 and has top loading h_3. The length of the antenna ℓ is equal to $h_1 + h_3$. This antenna is at a distance D from a shield or screen of height h and width C . The antenna is assumed to be symmetrical with respect to the shield; that is, the angles α' and α'' are equal in Fig. 3. This

case is sufficiently general to be applied to a large number of shipboard antennas for frequencies below 600 kilocycles.

25. The assumptions made for this problem are tabulated below:

(a) The heights h_1 and h are assumed to be small compared to λ .

(b) The distance D is less than h and is also small compared to λ .

(c) The height of the screen h is at least twice the width C . This restriction is necessary in order to neglect the end effect at the top of the screen, or to assume that K is independent of z .

(d) The current distribution in the antenna is assumed to be sinusoidal and to be given by:

$$i_z = I' \sin \frac{2\pi}{\lambda} (\ell - z) \sin \omega (t - \frac{r}{c}) \qquad (1)$$

where

I' is the current at the current loop
ℓ is the length of the antenna
z is the height above the ground at which the current is i_z.

(e) The radiation from the horizontal section or flat top of the antenna is neglected.

(f) The ground or counterpoise is assumed to act as a perfect conductor.

(g) The effect of the earth may be replaced by an image antenna with a current distribution given by

$$i'_z = -I' \sin \frac{2\pi}{\lambda} (\ell + z) \sin \omega (t - \frac{r}{c}) \qquad (2)$$

(h) The effect of the screen may be replaced by the image antennas (see Fig.4) with current distributions

$$i''_z = -K I' \sin \frac{2\pi}{\lambda} (\ell - z) \sin \omega (t - \frac{r}{c}) \qquad (3)$$

$$i'''_z = K I' \sin \frac{2\pi}{\lambda} (\ell + z) \sin \omega (t - \frac{r}{c}) \qquad (4)$$

These image antennas are at a distance 2D from the actual antenna.

(i) K is equal to the magnitude of the ratio i''_z / i_z. This ratio for a finite screen will vary with z. However, if the screen is at least twice as high as it is wide K will be approximately constant, except near the very top of the screen. This end effect will be small for high narrow screens and is neglected. Then K depends only upon the width of the screen and the distance the screen is away from the antenna.

(j) The angles α' and α'' in Fig.3 are assumed to be equal. It can be shown that if the angles α' and α'' are both positive, the radiation resistance given by $R_1 + R_2 + R_3$ (as defined in paragraph 26 below) can still be used with a negligible error.

26. The equivalent antenna of Fig.3 is given in Fig. 4. The antenna system in Fig. 3 or the equivalent antenna system in Fig.4 can not radiate in all space. The top section h_2 of the antenna can radiate in all space above the surface of the earth or above the xy plane. The h section of the antenna of Fig. 3, or the equivalent h section of Fig. 4, can radiate in the space above the surface of the earth that is not in the angle α. Let E_2 be the field at the point P in space produced by the h_2 section of the antenna. Let E_1 be the field at the point P in space produced by the current distributions i_z and i'_z in the h section of the antenna. Let $-E'_1$ be the field produced at the point P in space by the current distributions i''_z and i'''_z. Then the electric field E at the point P is

$$E = (E_1 - E'_1) + E_2$$

The total energy S in ergs per second that is radiated by the antenna is

$$S = \frac{c}{4\pi} \iint E^2 r^2 \sin\theta \; d\theta \, d\phi \tag{5}$$

$$= \frac{c}{4\pi} \iint \left[(E_1 - E'_1) + E_2\right]^2 r^2 \sin\theta \, d\theta \; d\phi \tag{6}$$

$$S = \frac{c}{4\pi} \iint (E_1 - E_1')^2 \, r^2 \sin\theta \, d\theta \, d\phi$$

$$+ \frac{c}{4\pi} \iint E_2^2 \, r^2 \sin\theta \, d\theta \, d\phi \tag{7}$$

$$+ \frac{c}{4\pi} \int 2 \, (E_1 - E_1') \; E_2 \, r^2 \sin\theta \, d\theta \, d\phi$$

Let

$$S = S_1 + S_2 + S_3 \tag{8}$$

Then one obtains

$$S_1 = \frac{c}{4\pi} \iint (E_1 - E_1')^2 \, r^2 \sin\theta \, d\theta \, d\phi \tag{9}$$

$$S_2 = \frac{c}{4\pi} \iint E_2^2 \, r^2 \sin\theta \, d\theta \, d\phi \tag{10}$$

$$S_3 = \frac{c}{4\pi} \iint 2 \, E_2(E_1 - E_1') \, r^2 \sin\theta \, d\theta \, d\phi \tag{11}$$

This is equivalent to saying that the total energy radiated per second by the antenna is equal to the energy that flows outward per second through a sphere surrounding the antenna. The energy that flows through every unit area of this sphere is equal to

$$\frac{c}{4\pi} E^2$$

and the total energy that flows outward through this sphere per second is equal to the sum of the energies that flow through each unit area of the sphere per second.

27. If one knows the energy S radiated per second and the current at the base of the antenna, then

$$S = I^2 R \tag{12}$$

or

$$R = \frac{S}{I^2}$$

where R is the radiation resistance of the antenna.

Since $$S = S_1 + S_2 + S_3$$

and letting $$R = R_1 + R_2 + R_3 \tag{14}$$

then $$S = S_1 + S_2 + S_3 = I^2 R = I^2 R_1 + I^2 R_2 + I^2 R_3 \tag{15}$$

and
$$R_1 = \frac{S_1}{I^2} \tag{16}$$

$$R_2 = \frac{S_2}{I^2} \tag{17}$$

$$R_3 = \frac{S_3}{I^2} \tag{18}$$

It can be shown that

$$R_1 = \frac{G(1-K)^2}{2} \quad M + KG\ 256\ \pi^4 \left(\frac{Dh}{\lambda^2}\right)^2 \tag{19}$$

$$\left\{ \frac{1 - \frac{11}{21}\pi^2\left(\frac{h}{\lambda}\right)^2 - \cos\left(\frac{4\pi\ell}{\lambda}\right)\left[1 - \frac{53}{21}\pi^2\left(\frac{h}{\lambda}\right)^2\right] - \frac{2\pi h}{\lambda}\ \sin\left(\frac{4\pi\ell}{\lambda}\right)}{\sin^2\ \left(\frac{2\pi\ell}{\lambda}\right)} \right\}$$

$$R_2 = N \quad \frac{\sin^2\left[\frac{2\pi}{\lambda}(\ell - h)\right]}{\sin^2\left[\frac{2\pi\ell}{\lambda}\right]} \tag{20}$$

$$R_3 = G\ (1-K)\ \sqrt{MN} \quad \frac{\sin\left[\frac{2\pi}{\lambda}\ (\ell - h)\right]}{\sin\ \left(\frac{2\pi\ell}{\lambda}\right)} \tag{21}$$

$$+ G\ K\ 256\ \pi^4 \left(\frac{Dh}{\lambda^2}\right)^2 \quad L$$

or
$$R_1 = \frac{GS}{2} \quad M + K\ G\ B\ A \tag{22}$$

$$R_2 = J^2\ N \tag{23}$$

$$R_3 = GJ\,(1-K)\,\sqrt{MN} + G\,K\,B\,L \tag{24}$$

where

$$A = \left\{ \frac{1 - \frac{11}{21}\pi^2\left(\frac{h}{\lambda}\right)^2 - \cos\left(\frac{4\pi\ell}{\lambda}\right)\left[1 - \frac{53}{21}\pi^2\left(\frac{h}{\lambda}\right)^2\right] - \frac{2\pi h}{\lambda}\quad \sin\left(\frac{4\pi\ell}{\lambda}\right)}{\sin^2\left(\frac{2\pi\ell}{\lambda}\right)} \right\}$$

$$B = 256\,\pi^4\left(\frac{Dh}{\lambda^2}\right)^2$$

$G \cong 2 - K$ This approximation holds when the height of the screen is at least twice its width. G is a function of the limits of integration and depends upon the size and position of the screen.

$$J = \frac{\sin\frac{2\pi}{\lambda}\,(\ell - h)}{\sin\left(\frac{2\pi}{\lambda}\ell\right)}$$

$K \cong \dfrac{\alpha' + \alpha''}{180}$ (as defined in paragraph 22 above)

L The limits of L are:

$$H = \frac{(h_1 - h)^2\;(2h_1 - h)}{2\,h\,h_1^2}$$

for an antenna without top loading, and

$$F = \frac{2\,(h_1 - h)}{h}$$

for an antenna with uniform current distribution in the vertical element. (Other values of L must be interpolated from the two curves shown in Plate 8.)

M is the radiation resistance of an antenna of height h and with a top loading equal to $\ell - h$ or $h_2 + h_3$.

N is the radiation resistance of an antenna of height h_2 and with a top loading h_3.

$S = (1 - K)^2$

h is the height of the screen.

λ is the wavelength.

ℓ is the length of the antenna

h_1 is the height of the antenna

h_3 is the antenna flat top

h_2 is the height of the antenna above the shield

D is the distance the antenna is from the shield

$\alpha' + \alpha'' = \alpha$ is the angle the antenna makes with the screen (See Fig. 3)

C is the width of the screen

28. The Eq.(22), (23), and (24) apply only for short antennas; i.e., the height of the antenna is small compared to a wavelength ($\lambda/10$ or less). An analysis of the foregoing equations reveals that: (See Fig.3)

R_1 is the radiation resistance of an antenna of height h next to a screen of height h.

R_2 is the radiation resistance of the h_2 section of the antenna.

R_3 represents the radiation resistance due to the interaction between the h and h_2 sections of the antenna.

Thus it will be seen that the sum of these three resistances gives the total radiation resistance of the antenna. (The terms R_2 and R_3 are zero if the height of the antenna is less than or equal to the height of the screen.)

29. In order to simplify the calculations of R_1, R_2, and R_3, curves have been prepared so that the terma A, B, J, K, L, M, N, and S may be read directly therefrom. The term GKBA in R_1 and the term GKBL in R_3 are negligible if K is less than 0.9 or if the antenna is 50% higher than the screen. Thus, except for very special cases, these two terms may be neglected when determining R_1 and R_3. It will be noted from the examples given below that the terms GKBL and GKBA are very small in most applications.

A is given as a function of ℓ/h in Plate 3.

B is given for various values of D/λ as a function of h/λ in Plate 4.

J is given as a function of ℓ/λ for various values of h/ℓ in Plate 5.

$K = K' + K''$ is given as a function of c'/D and c''/D in Plate 6.

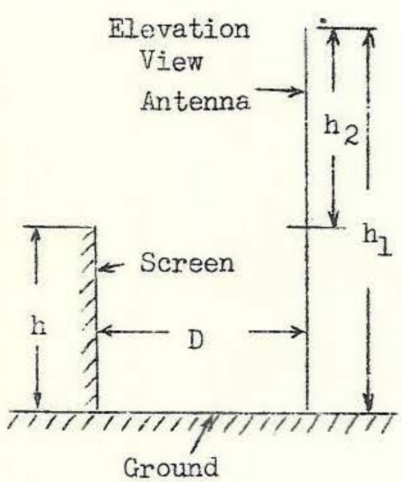
M and N. The radiation resistance of an antenna in the clear, with various amounts of top loading is given as a function of the antenna height in wavelengths in Plate 1.

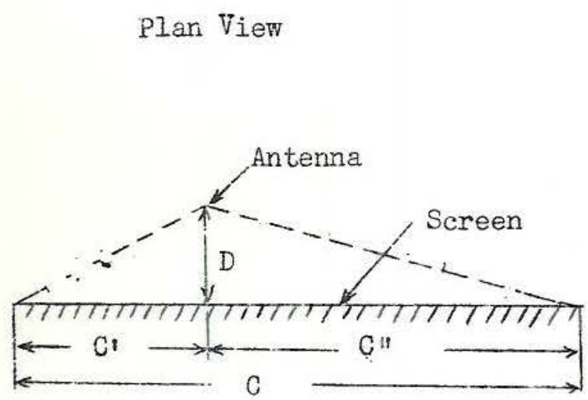
S is given as a function of K in Plate 7.

L can be interpolated from the values of F and H in Plate 8.

30. In order to illustrate the use of the attached curves for determining the radiation resistance of an antenna adjacent to a screen or shield, a number of examples are given below. An inspection of the examples reveals that quite a few operations are necessary to arrive at the desired result. However, it will be noted that all the calculations are simple problems in multiplication and addition. By following the methods outlined in the examples, little difficulty should be experienced in arriving at the correct result.

Example D





$D = 5$ feet	$C' = 10$ feet
$h = 50$ feet	$C'' = 20$ feet
$h_1 = 100$ feet	$C = 30$ feet
$h_2 = 50$ feet	$\ell = 100$ feet
$h_3 = 0$ (No flat top)	Frequency = 600 kilocycles

Problem: To determine the Radiation Resistance of the antenna illustrated above at a frequency of 600 kilocycles.

From Plate 2: Convert the linear measurements into wavelength.

$D = 0.003$

$h = 0.03$

$h_1 = 0.06$

$h_2 = 0.03$

$h_3 = 0$ (No top loading)

$\ell = 0.06$

Eq. (22) $R_1 = \frac{GS}{2} M + KGBA$

Eq. (23) $R_2 = J^2 N$

Eq. (24) $R_3 = GJ\ (1-K)\ \sqrt{MN} + GKBL$

$K = 0.775$ $(K = K' + K'')$

$K' = 0.355$ for $c'/D = 10/5 = 2$ from Plate 6

$K'' = 0.42$ for $c''/D = 20/5 = 4$ from Plate 6

$0.355 + 0.42 = 0.775$

$G = 2 - K = 2 - 0.775 = 1.225$

$S = 0.051$ as read from Plate 7 for $K = 0.775$

$M = 0.8$ as read from Curve C on Plate 1 for $\lambda = 0.03$

$B = 0.0002$ as read from Plate 4 for $D = 0.003\lambda$ and $h = 0.03\lambda$

$A = 1.13$ as read from Plate 3 for $\ell/h = 100/50 = 2$

$J = 0.51$ as read from Plate 5 for $\ell/\lambda = 0.06$ and $h = 50/100 = .5\ell$

$N = 0.35$ from Plate 1, Curve A for $h_2 = 0.03\lambda$ and $h_3 = 0$

$L = 0.4$ from Plate 8 for $h_1/h = 2$ for antenna with no top loading.

$$R_1 = \frac{1.225 \times 0.051}{2} \times 0.8 + 0.775 \times 1.225 \times 0.0002 \times 1.13$$

$$= 0.025 + 0.000214*$$

$R_2 = 0.51 \times 0.51 \times 0.35 = 0.091$

$R_3 = 1.225 \times 0.51 \times 0.225 \times \sqrt{0.8 \times 0.35} + 1.225 \times 0.775 \times 0.0002 \times 0.4$

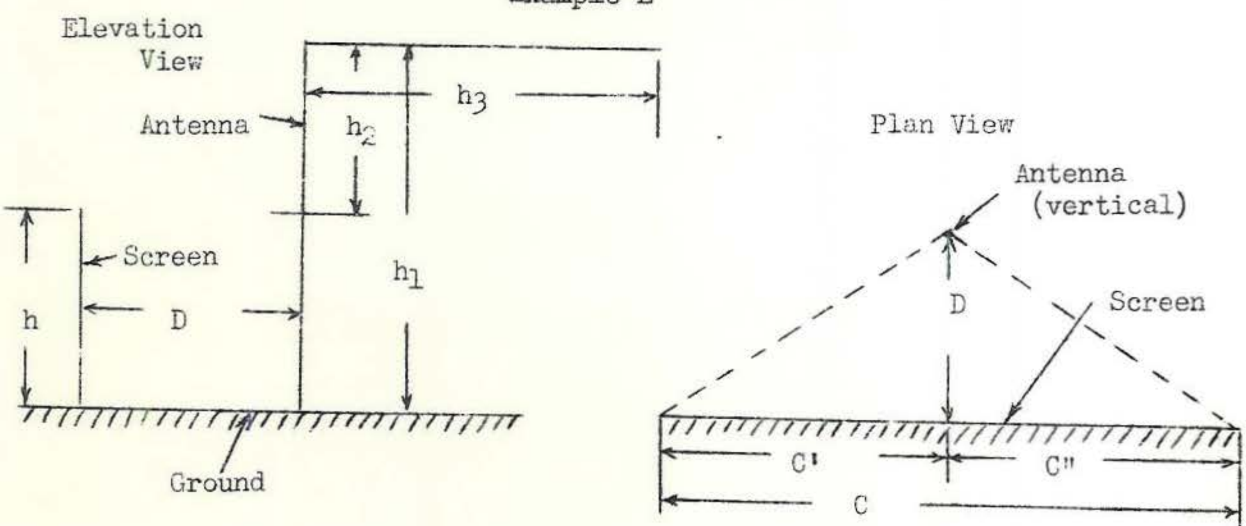
$= 0.0745 + 0.000076$*

$R = 0.025 + 0.091 + 0.0745 = 0.1905$ ohm, which is the Radiation Resistance of the antenna illustrated above.

*NOTE: As stated in paragraph 29 above, the terms GKBA in R_1 and GKBL in R_3 are negligible if K is less than 0.9 or if the antenna is 50% higher than the screen. The above example illustrates that these terms may be neglected without affecting the practical result.

The same antenna in the clear; i.e., screen removed, would have a radiation resistance of 1.5 ohms (as obtained from Plate 1, Curve A for an antenna 0.06λ).

Example E



$D = 10$ feet

$h = 50$ feet

$h_1 = 90$ feet

$h_2 = 40$ feet

$h_3 = 90$ feet

$C = 30$ feet

$\ell = h_1 + h_3 = 180$ feet

Frequency = 300 kilocycles

$C' = C'' = 15$ feet

Problem: To determine the Radiation Resistance of the antenna illustrated above at a frequency of 300 kilocycles.

From Plate 2: Convert the linear measurements into wavelength

$D = 0.003$

$h = 0.015$

$h_1 = 0.028$

$h_2 = 0.012$

$h_3 = 0.028$

$\ell = 0.056$

Eq. (22) $R_1 = \frac{GS}{2} \quad M + KGBA$

Eq. (23) $R_2 = J^2N$

Eq. (24) $R_3 = GJ\ (1-K)\ \sqrt{MN} + GKBL$

$K = 0.62 \qquad (K = K' + K'')$

$K' = 0.31$ for $c'/D = 15/10 = 1.5$ from Plate 6

$K'' = 0.31$ for $c''/D = 15/10 = 1.5$ from Plate 6

$K = 0.31 + 0.31 = 0.62$

$G = 1.38 \quad (2-K = 2 - 0.62 = 1.38)$

$S = 0.145$ as read from Plate 7 for $K = 0.62$

$M = 0.27$ as interpolated between Curve C and D on Plate 1 for $h = 0.015$ and top loading equal to 2.6

$B = 0.00004$ as read from Plate 4 for $D = 0.003\lambda$ and $h = 0.015$ (4×10^{-5}) Since this value is off scale read from 0.03 and multiply by 0.01.

$A = 1.48$ as read from Plate 3 for $\ell/h = 180/50 = 3.6$

$J = 0.72$ as read from Plate 5 for $\ell/\lambda = 0.06$ and $h/\ell = 50/180 = 0.28$

$N = 0.16$ from Plate 1 (Interpolation between Curves C and D.)

$L = 1.3$ from Plate 8 for $h_1/h = 90/50 = 1.8$ (Interpolation between limits F and H .

$R_1 = \frac{1.38 \times 0.145}{2} \times 0.27$ + (KGBA which term is neglected) = 0.027

$R_2 = 0.72 \times 0.72 \times 0.16 = 0.08$

$R_3 = 1.38 \times 0.72 \times 0.38 \times \sqrt{0.27 \times 0.16} +$ (GKBL neglected)

$= 0.078$

$R = 0.027 + 0.08 + 0.078 = 0.185$ ohm, which is the Radiation Resistance of the Antenna illustrated above.

The same antenna in the clear; i.e., screen removed, would have a radiation resistance of 0.75 ohm (as obtained from Plate 1).

31. In order to obtain actual experimental proof of the validity of the theoretical study of radiation characteristics as outlined in the foregoing paragraphs, a series of experiments were undertaken at the Naval Research Laboratory. A series of five different length antennas were operated at varying distances from a screen. The screen dimensions were as follows:

Height - 20 feet
Width - 10 feet

The screen consisted of an iron framework covered with copper gauze. The antennas consisted of straight vertical wires (#8) of the following lengths:

16 feet
19 feet
23.7 feet
28.5 feet
38 feet

32. The base of each antenna was one foot above the ground. Thus it will be seen that the 16 foot antenna was shorter than the screen; the 19 foot antenna was the same height as the screen, while the remaining antennas extended above the screen at varying distances. All transmissions were conducted at a frequency of 2004 kilocycles. This frequency was chosen in order that the dimensions of the screen and the antennas could be kept small enough to permit ease in handling. The 20 foot screen at 2004 kilocycles had the same effect as a 66 foot screen at 600 kilocycles or a 200 foot screen at 200 kilocycles. Each of the five different antennas was operated at varying distances from the screen; namely,

1 foot
2 feet
10 feet
20 feet

33. Relative field strength measurements were made at a point 1300 feet distant from the transmitting antennas. Measurements were made with a receiver equipped with an Electron-Ray Tube. The receiver was so adjusted that the signal under observation caused the shadow angle to reduce to exactly zero. A Standard Signal Generator was then connected to the input of the receiver and the output of the Standard Signal Generator adjusted to again reduce the shadow angle of the Electron-Ray tube to zero. By this means the relative field strengths of the various signals were determined.

34. The results of these experiments are plotted in the curves shown in Plate 12, wherein relative field strength is plotted as a function of the distance from the antenna to the screen in feet. The solid curves show the theoretical values calculated from the equations presented in the foregoing paragraphs of this report. The broken lines connect the points obtained by actual measurements. It will be noted that, in general, good agreement exists between the experimental and theoretical values. In all cases, however, the theoretical values range through a greater difference in field strength than was obtained during the actual experiments. These differences can be explained by the fact that unsuitable ground conditions existed at the point of transmission and it was necessary to resort to the use of a counterpoise. This counterpoise should have been centered directly under the antennas, but it was impracticable to accomplish this. The screen employed was not a perfect shield and various obstacles which were capable of causing partial reflection or shadows intervened between the transmitting and receiving locations.

35. Plate 13 presents curves wherein the experimental data obtained during the above testsare plotted in a different manner. In these curves Radiated Power (Relative) is plotted as a function of the distance from the antenna to the screen in feet. In all cases the current as measured at the base of the antenna was held constant. It will be noted that in all instances the power radiated by a given antenna close to the screen is far less than the power radiated by the same antenna when spaced 20 feet from the screen. In the case of the 16 foot antenna, the power radiated at the 20 foot distance is approximately 11 times that radiated by the antenna when within one foot of the screen. These curves also illustrate, to a marked degree, the loss in radiated power resulting from the use of short antennas.

36. From the results of these experiments it may be concluded that the theories upon which this study of short antennas and partially shielded antennas is based are valid and represent a practical method for analyzing the characteristics of Naval shipboard radiators.

37. Another form of antenna which is frequently encountered in shipboard installations is the type illustrated in Fig. 5. This antenna runs vertically to a height h_1 and then at an angle θ with the horizontal to a height h_2. This type of antenna can be changed to an equivalent vertical antenna with a horizontal flat top. Let $h = h_2 - h_1$. Then if d is at least three times h the following approximate method may be used. The equivalent flat top antenna is $(h_1 + h/2)$ in vertical height with a horizontal flat top of length d . Now the radiation resistance can be read from the curves in Plate 1.

38. <u>The effective height of an antenna</u>. Occasions arise where it is desirable to know the effective height of an antenna. If the antenna is short (vertical height is less than 0.1 wavelength), the effective height may be calculated by the following method. The flat top is restricted to lengths such that the total electrical length of the antenna is less than a quarter wave.

Let

$$\text{Effective Height} = \frac{h}{2}\sqrt{\frac{R_R}{R_r}}$$

where

Effective Height is in feet

h is the height of the vertical element of the antenna in feet.

R_r is the radiation resistance of an antenna, without top loading, of height h. (Antenna in the clear)

R_R is the radiation resistance of the total antenna.

If the antenna does not have top loading, then $R_R = R_r$ and the effective height of the antenna is $h/2$. The following example will illustrate the use of the Effective Height formula:

To find the Effective Height, at 200 kilocycles, of an antenna of 80 feet vertical height with an 80 foot flat top. From the curves in Plate 2 the antenna is 0.0163 wavelength in height at 200 kilocycles. The radiation resistance of a vertical antenna, without top loading, of height 0.0163 wavelength is 0.098 ohm. The radiation resistance of an antenna of height 0.0163 wave length and with an equal length of flat top is 0.23 ohm. These values of radiation resistance are taken from Plate 1. Substituting these values in the above equation, one obtains

$$\text{Effective Height} = \frac{80}{2}\sqrt{\frac{0.23}{0.098}}$$

$$= 40\sqrt{2.35} = 61.2 \text{ feet}$$

RADIATION SYSTEMS 2000 TO 20,000 KILOCYCLES

39. At 2000 kilocycles an 80 foot vertical antenna is 0.163 wavelength in height and would have a radiation resistance of about 10 ohms. At 3000 kilocycles, this antenna would be about one-quarter of a wavelength in height and would have a radiation resistance of 36 ohms. These values of radiation resistance are taken from the curves in Plate 1. Flat top loading would increase the radiation resistance, as can be seen from the curves. It should be noted that the curves in Plate 1 are for antennas which are in the clear. If the antennas are near masts or stacks or other obstructions, partial shielding will result and the radiation resistance will be lower than the values shown on the curves. In general, as the antenna height is increased on board ship, more of the antenna is in the clear and a greater radiation resistance will result. If the antenna is not as

high as the screen or shield, the radiation resistance can be calculated from the following equation:

$$R = \frac{GSM}{2} + \frac{GK\ 15\left(\frac{4\pi D}{\lambda}\right)^2}{\sin^2\left(360\frac{h}{\lambda}\right)^\circ}\left[1 + \frac{\cos\left(720\frac{h}{\lambda}\right)^\circ}{2} - \frac{3\sin\left(720\frac{h}{\lambda}\right)^\circ}{\frac{8\pi h}{\lambda}}\right]$$

where

R is the radiation resistance in ohms

D/λ is the distance in wavelengths the antenna is from the screen. D/λ must be a small fraction of a quarter wavelength.

h/λ is the height of the antenna in wavelengths.

M is the radiation resistance of an antenna of height h in wavelength without top loading. M is taken from Curve A of Plate 1.

G, S, and K are defined in paragraph 27 above.

or

$$R = \frac{GSM}{2} + GKVZ$$

where

$$V = 15\left(\frac{4\pi D}{\lambda}\right)^2$$

$$Z = \frac{1}{\sin^2\left(360\frac{h}{\lambda}\right)^\circ}\left[1 + \frac{\cos\left(720\frac{h}{\lambda}\right)^\circ}{2} - \frac{3\sin\left(720\frac{h}{\lambda}\right)^\circ}{\frac{8\pi h}{\lambda}}\right]$$

V is given in Plate 14 as a function of d/λ.

Z is given in Plate 15 as a function of h/λ.

The advantages of a radiation resistance of at least 10 ohms will be pointed out later. As the frequency is increased, the height of the antenna in wavelength increases and the radiation resistance reaches a maximum value of about 2000 ohms for an antenna one-half of a wavelength in height. At frequencies for which the antenna is a multiple of $\lambda/2$ the radiation resistance is a maximum, while at frequencies for which the antenna is an odd multiple of $\lambda/4$ the radiation resistance is a minimum value. The reactance of the antenna will vary from zero to 2000 ohms and may be either inductive or capacitive. A transmission line or trunk, if greater than 12 feet in length, will be over $\lambda/4$ in length at 20,000 kilocycles. The transmission line is no longer a small fraction of $\lambda/4$ in length, as was the case at frequencies below 600 kilocycles and therefore can no longer be treated as a lumped capacitance or condenser. Let us consider a few representative cases which are likely to exist on board ship.

40. Case (1). Where the transmitter is at the base of the antenna and no transmission line is used. For a fairly good antenna, 80 feet in height, the radiation resistance at 2000 kilocycles will be about 10 ohms and greater than this value for all higher frequencies. The loss resistance of the antenna will be relatively small. The effective resistance of the coupling and antenna tuning circuits is small compared to the antenna resistance so that the r-f power is efficiently transferred from the power amplifier tank circuit to the antenna. The overall efficiency of the antenna system is good.

41. Case (2). In the majority of cases the transmitter is not located at the base of the antenna and some means must be provided for transferring the power from the transmitter to the antenna. The most logical method of doing this would be by means of a matched transmission line. The antenna impedance would have to be matched to the transmission line. This would require a matching network. There would be no standing waves on the transmission line and the power losses in the transmission line would be a minimum. The input impedance of the transmission line would be equal to its characteristic impedance. This impedance, for a concentric transmission line, is at least 40 ohms and is a pure resistance. The antenna coupling and tuning circuits operate very efficiently when transferring r-f power from the power amplifier tank circuit into a pure resistance of 40 ohms or more. The overall efficiency of this system is about 70%; i.e., about 70% of the power output of the transmitter is radiated if the antenna radiation resistance is 10 ohms or more. These conditions would hold for a good transmission line that is not over 200 feet long.

42. There are some serious disadvantages to this method when considered for use on board a Naval vessel. A standard transmitter is required to cover the frequency range of 2000 kilocycles to 18,100 kilocycles. This requires that the antenna matching network be capable of matching the antenna to the transmission line at any frequency within the above range. The antenna reactance varies from zero to 2000 ohms and may be either inductive or capacitive. The antenna radiation resistance varies from about 10 ohms to 2000 ohms. The matching network must be capable of matching the antenna having this wide range of impedance to the transmission line. This matching network must be located at the antenna end of the transmission line and therefore must be tuned by remote control from the transmitter location. Consequently, simplicity in operation is of prime importance. A careful study of matching networks has shown that the networks illustrated in Fig. 6 and 7 are the simplest form of a practical installation. The matching network in Fig.6 is capable of matching the antenna to the transmission line except when the radiation

resistance of the antenna is less than the characteristic impedance of the transmission line and the antenna acts as a capacity reactance. This condition exists when the antenna is less than $\lambda/4$ in height. Although the antenna can not be matched to the transmission line, the inductance L_1 will resonate the antenna and thus the transmission line will be terminated in a pure resistance equal to the antenna resistance. Thus, even under this condition the antenna will be fairly well matched to the transmission line.

43. The matching network in Fig. 7 is capable of matching the antenna to the transmission line except when the antenna presents an inductive reactance and the antenna resistance is less than the characteristic impedance of the transmission line. This condition will exist when the antenna is between $\lambda/2$ and $\lambda/4$ in height, and the antenna resistance is less than the characteristic impedance of the transmission line.

44. The inductance L_1 or L_2 must be continuously variable from zero to 50 microhenries. The condensers C_1 and C_2 must be continuously variable from 5 to 400 micromicrofarads. The design of such a condenser would be difficult. Let us assume that we have designed the matching network shown in Fig. 6. Then the problem of operating the matching network from the transmitter location arises. Radio frequency ammeters must be inserted between L_1 and the transmission line and between L_1 and the antenna. The first ammeter, I_1, reads the current at the antenna end of the transmission line. The second ammeter, I_a, reads the current at the base of the antenna. A means must be provided for reading these meters at the transmitter. The current at the transmitter end of the transmission line will be called I_T. In order to match the antenna to the transmission line and the power amplifier tank circuit to the transmission line, the following conditions must be fulfilled simultaneously:

(1) The antenna current I_a must be a maximum.

(2) The transmission line current I_T and I_1 should be nearly equal, with I_T slightly greater than I_1.

(3) The transmitter must be tuned to operate into a pure resistance load equal to the characteristic impedance of the transmission line.

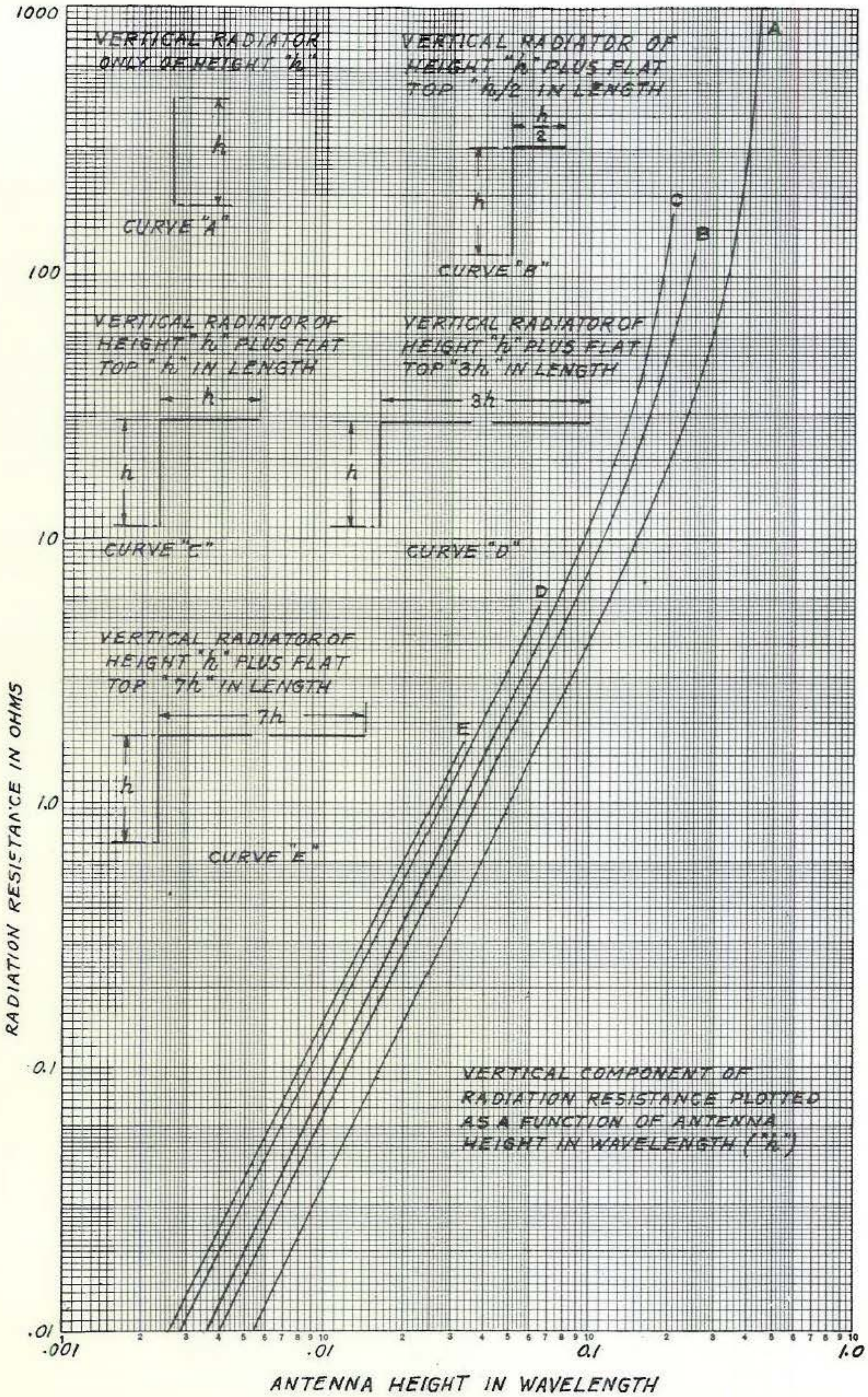
In order to obtain such a match the operator must first set all the dials on the transmitter to the previously calibrated values, including the antenna tuning dials. Then he must watch I_1, I_a, and I_T as well as the power amplifier plate current and vary L_1 and C_1 until he obtains the maximum value of I_a while simultaneously I_T must be slightly greater than I_1.

45. Thus it will be seen that the problem of matching a single antenna over a wide frequency range under the conditions which are encountered afloat results in a rather complicated installation, which is difficult to adjust. Extreme care must be exercised by the operator to obtain the proper adjustments or the advantages of using matching networks are lost. These adjustments are difficult to make since it is hard to determine exactly when the best match has been obtained. Furthermore, the impedance of the antenna would not remain constant due to the varying effects of booms, changes in humidity and the retuning of other antennas in the field of the antenna under discussion. Thus a calibration would not be useful over any extended period of time.

46. Case (3). In order to avoid the difficulties of using the antenna matching networks discussed under Case (2), an unmatched transmission line can be used to transfer the power from the transmitter to the antenna. The antenna reactance varies from zero to 2000 ohms and may be either inductive or capacitive. The radiation resistance of the antenna varies from about 10 ohms to 2000 ohms. It is readily seen that, except for special frequencies as when the antenna is $\lambda/4$, a very bad mismatch will exist at the antenna end of the transmission line. Therefore, there are standing waves upon the transmission line. Due to these standing waves, the voltage at certain points along the transmission line may be several hundred times the value for a matched transmission line. Thus a larger transmission line must be used in order to prevent voltage breakdown. The use of the larger transmission lines makes it possible to also have higher impedance lines. The advantages of higher impedance lines will be shown later.

47. In general, for unmatched transmission lines the current at the antenna end of the line is less than the current at the transmitter end. However, the current at the antenna end may, in some cases, be greater than the current at the transmitter end of the line. In either case there are standing waves on the transmission line. It can be shown mathematically, and has been confirmed experimentally, that increasing the characteristic impedance of the transmission line reduces the standing waves on the line, thus reducing losses in the transmission line and in the antenna tuning and coupling circuits of the transmitter. It should be borne in mind that this is true only in the case where matching networks are not used.

48. Plate 10 gives the power radiated from an antenna as a function of antenna height at frequencies of 2004, 3070 and 4155 kilocycles. The different antennas were connected to the transmitter by means of a transmission line 115 feet long having a characteristic impedance of 120 ohms. A 500 watt transmitter was used, operated at full power output. From the curves it will be noted that at 2004 kilocycles the antenna must be 100 feet high in order to radiate 15% of the power output of the transmitter. This corresponds to an antenna height of 0.2 wavelength. Such an antenna has a radiation resistance of 19 ohms. At 2004 kilocycles a 20 foot antenna radiates about 0.03% of the power output of the transmitter. This antenna has a radiation resistance of 0.63 ohm. The above figures show the disadvantages of short antennas with a correspondingly low radiation resistance. Conversely, the curves show very clearly the advantage of using high antennas when transmission lines are used.



VERTICAL RADIATOR ONLY OF HEIGHT "h"
CURVE "A"
VERTICAL RADIATOR OF HEIGHT "h" PLUS FLAT TOP "h/2" IN LENGTH
CURVE "B"
VERTICAL RADIATOR OF HEIGHT "h" PLUS FLAT TOP "h" IN LENGTH
CURVE "C"
VERTICAL RADIATOR OF HEIGHT "h" PLUS FLAT TOP "3h" IN LENGTH
CURVE "D"
VERTICAL RADIATOR OF HEIGHT "h" PLUS FLAT TOP "7h" IN LENGTH
CURVE "E"
VERTICAL COMPONENT OF RADIATION RESISTANCE PLOTTED AS A FUNCTION OF ANTENNA HEIGHT IN WAVELENGTH ("h")
RADIATION RESISTANCE IN OHMS
ANTENNA HEIGHT IN WAVELENGTH

PLATE I

CONVERSION CHART

ANTENNA HEIGHT

TO WAVE LENGTH

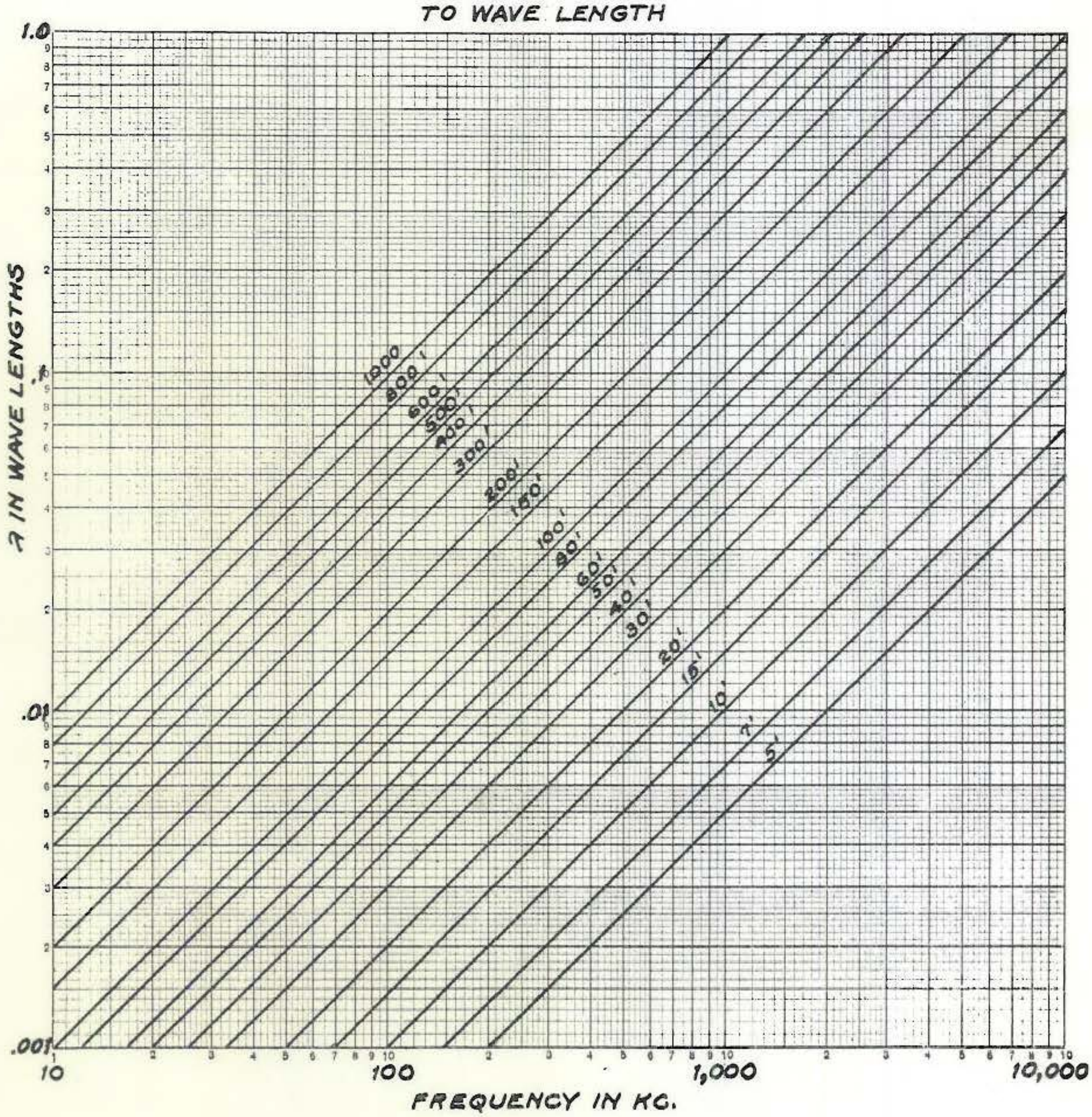


PLATE 2

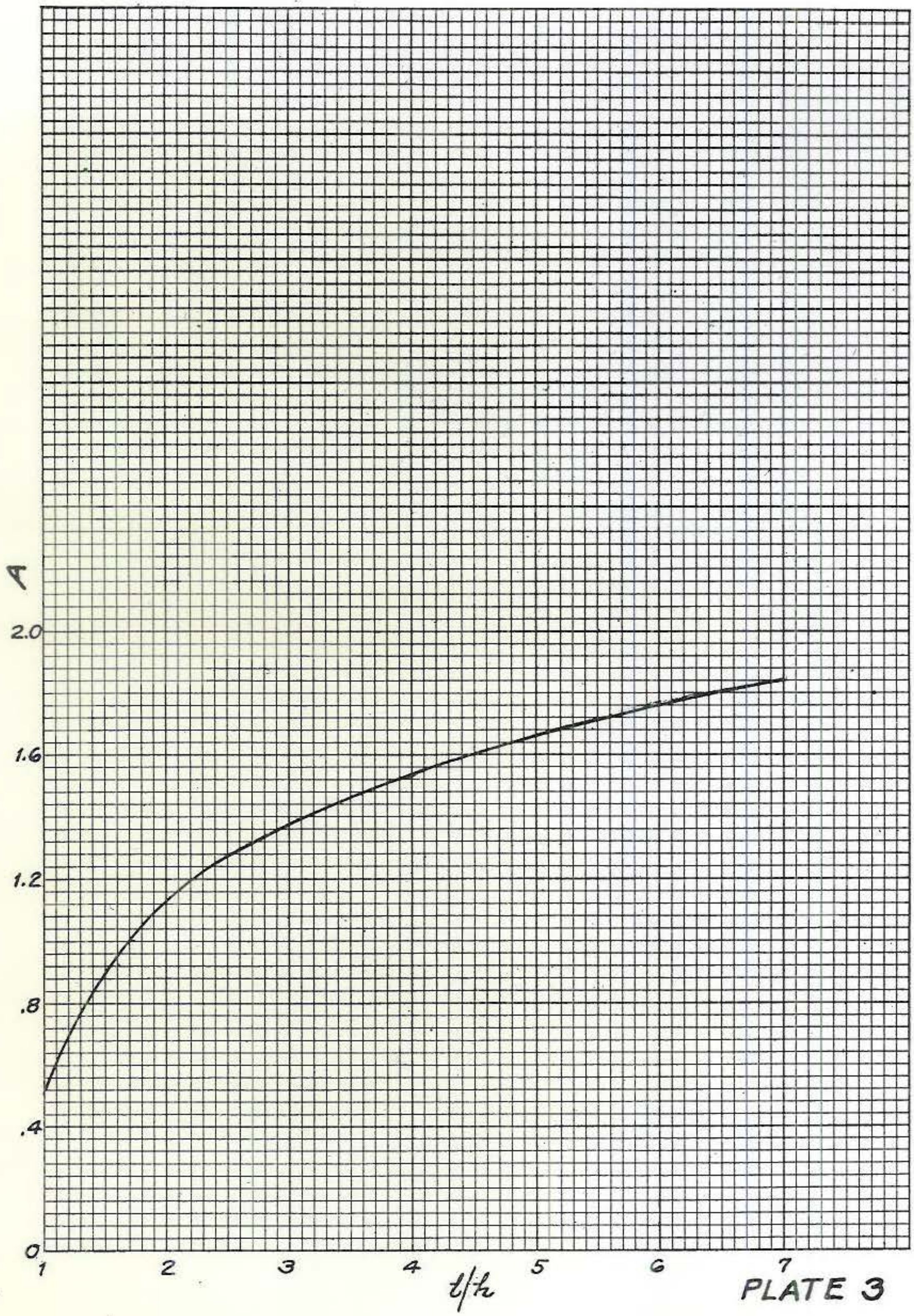
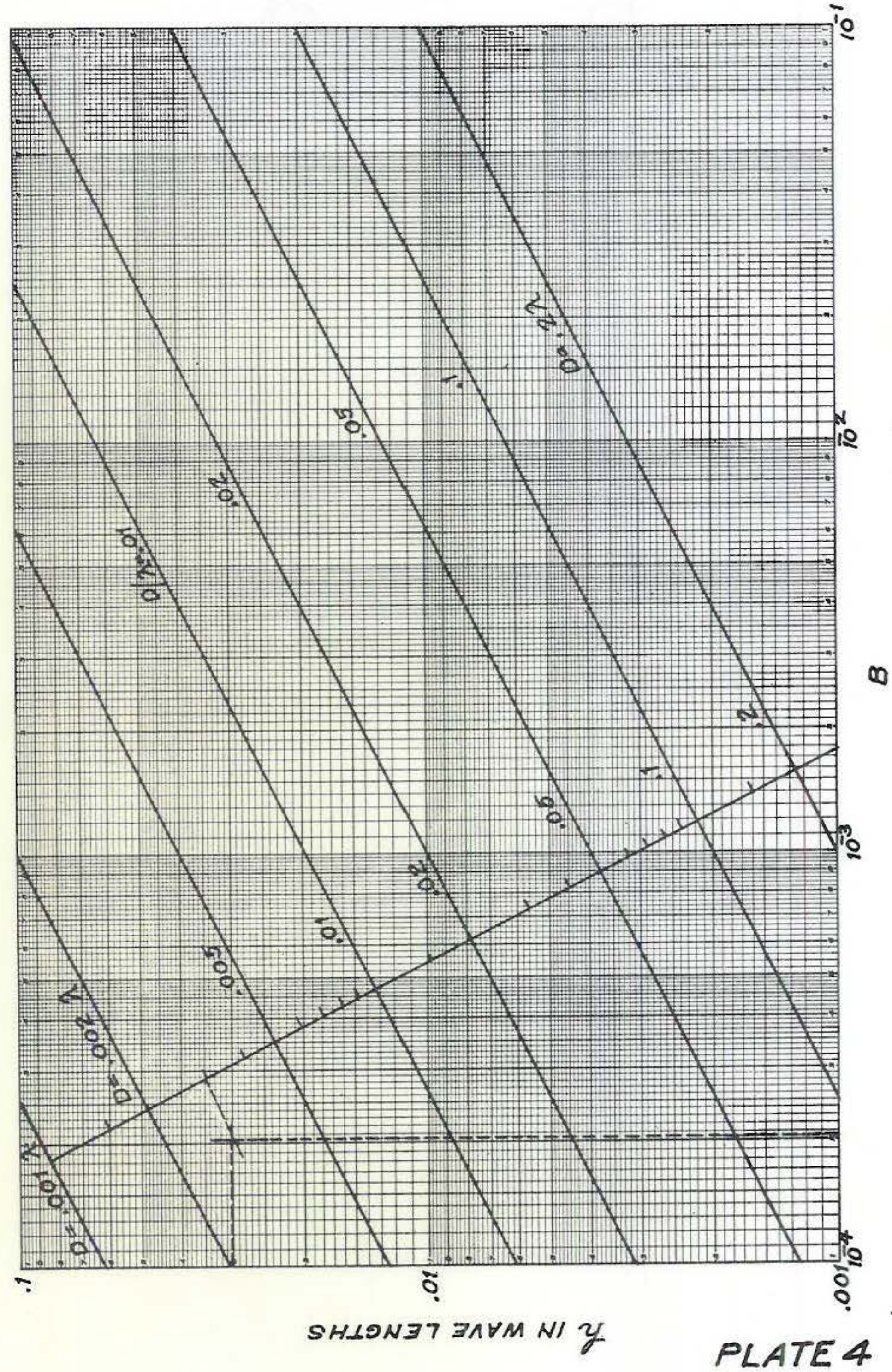
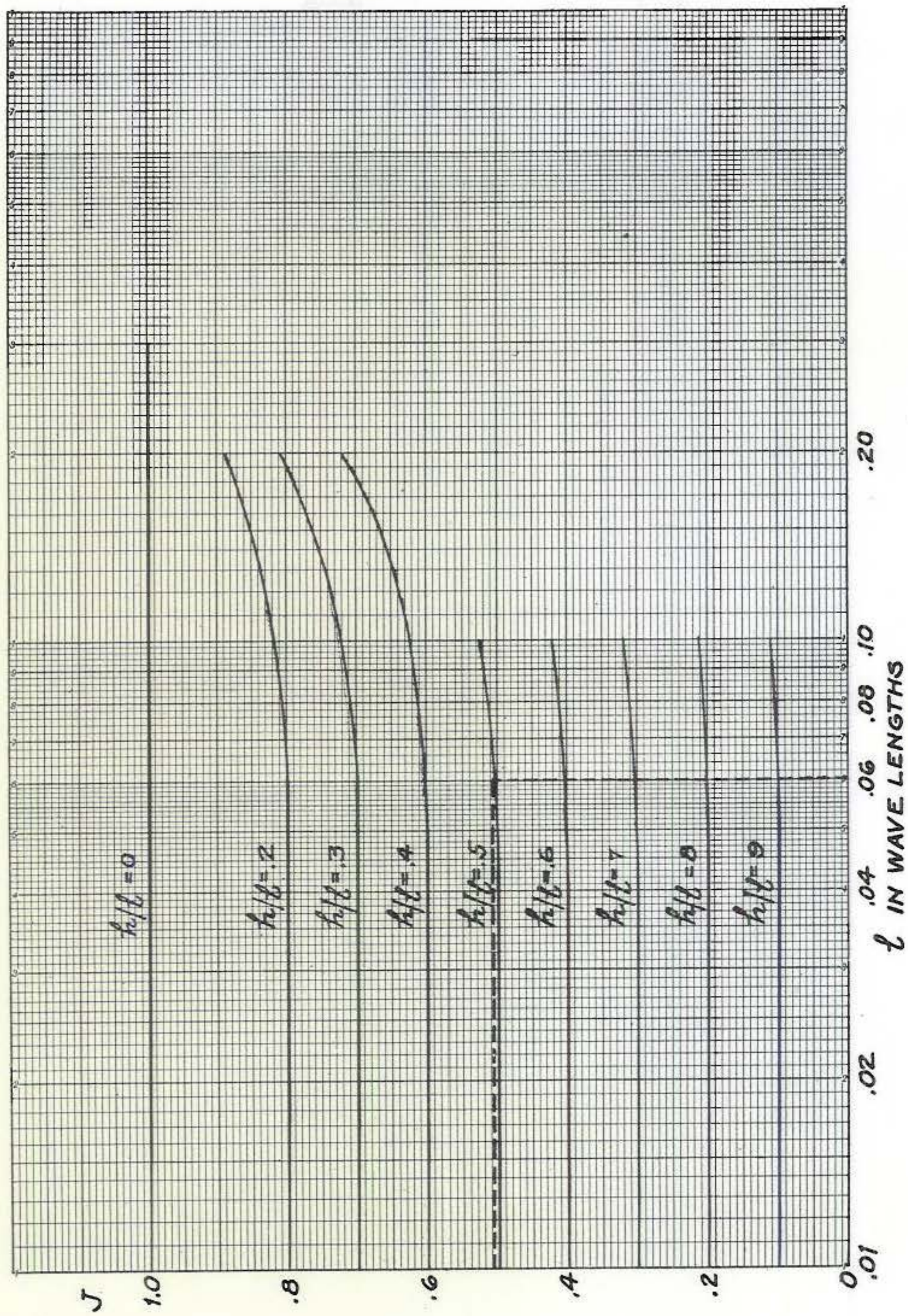


PLATE 3



B
.1
.01
.001
r IN WAVE LENGTHS
D = .001 λ
D = .002 λ
D/λ = .01
.02
.05
.1
D = .2 λ
.005
.01
.02
.05
.1
.2

PLATE 4



J
1.0
.8
.6
.4
.2
0
.01
.02
.04
.06
.08
.10
.20
l IN WAVE LENGTHS
h/l = 0
h/l = .2
h/l = .3
h/l = .4
h/l = .5
h/l = .6
h/l = .7
h/l = .8
h/l = .9

PLATE 5

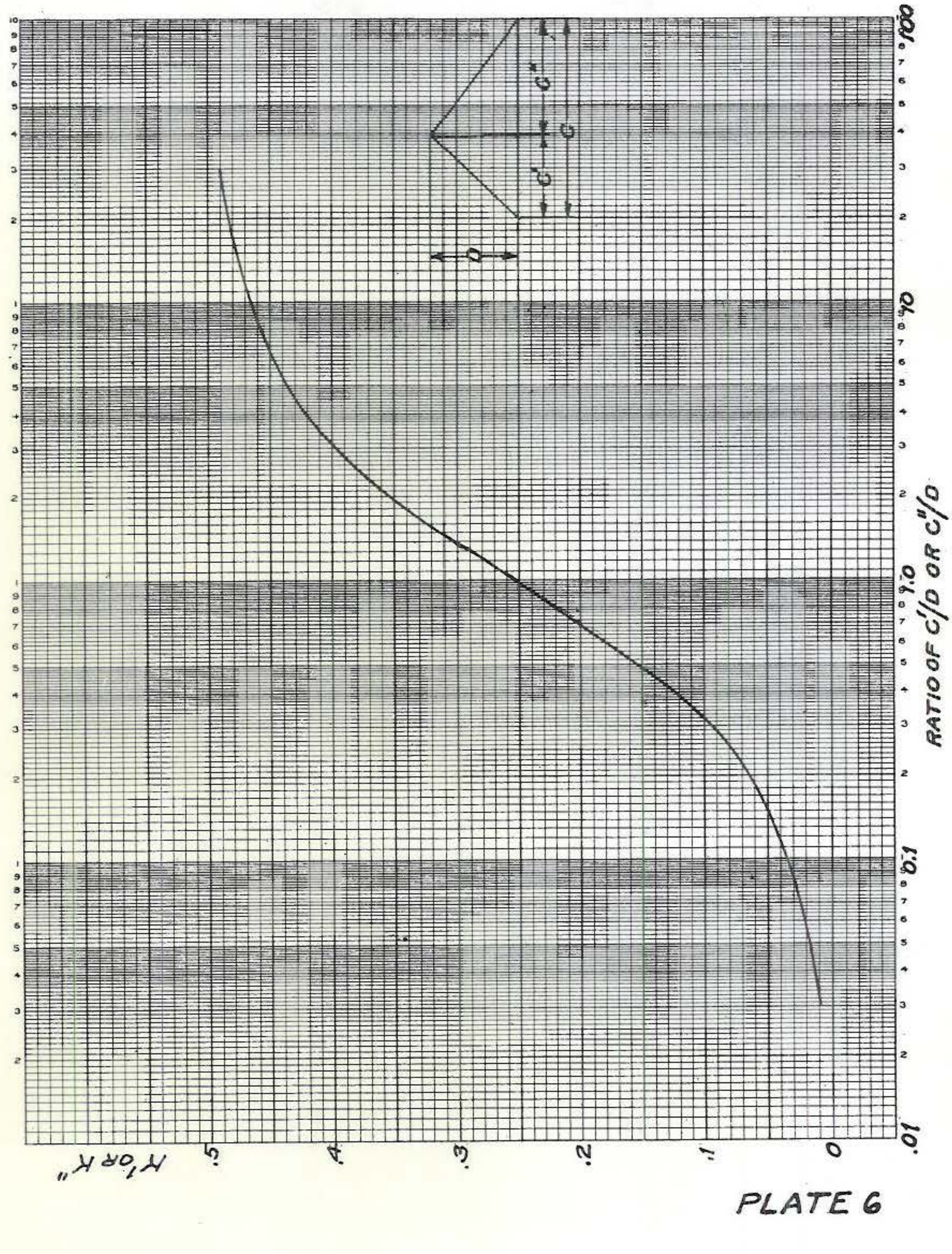


PLATE 6

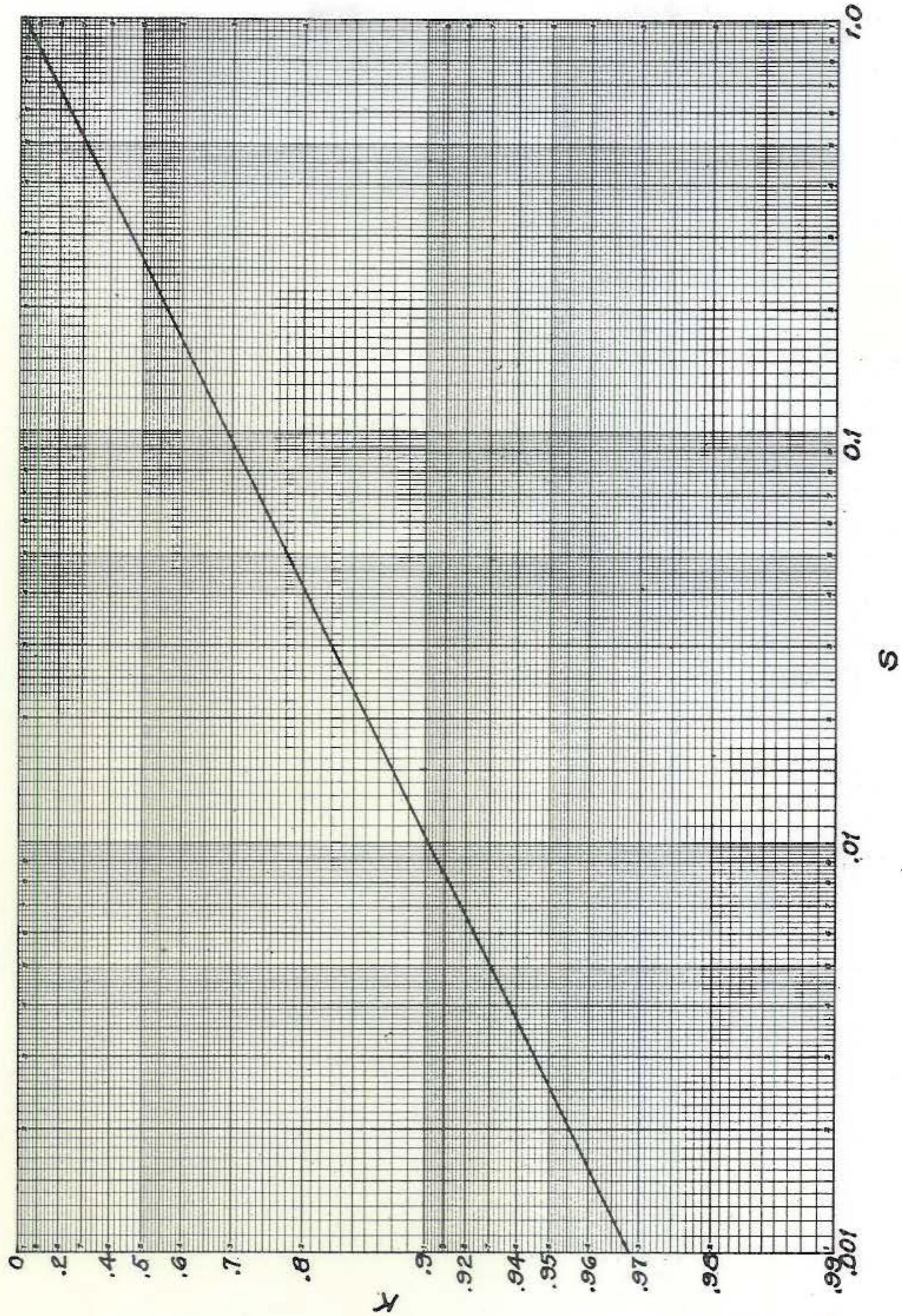


PLATE 7

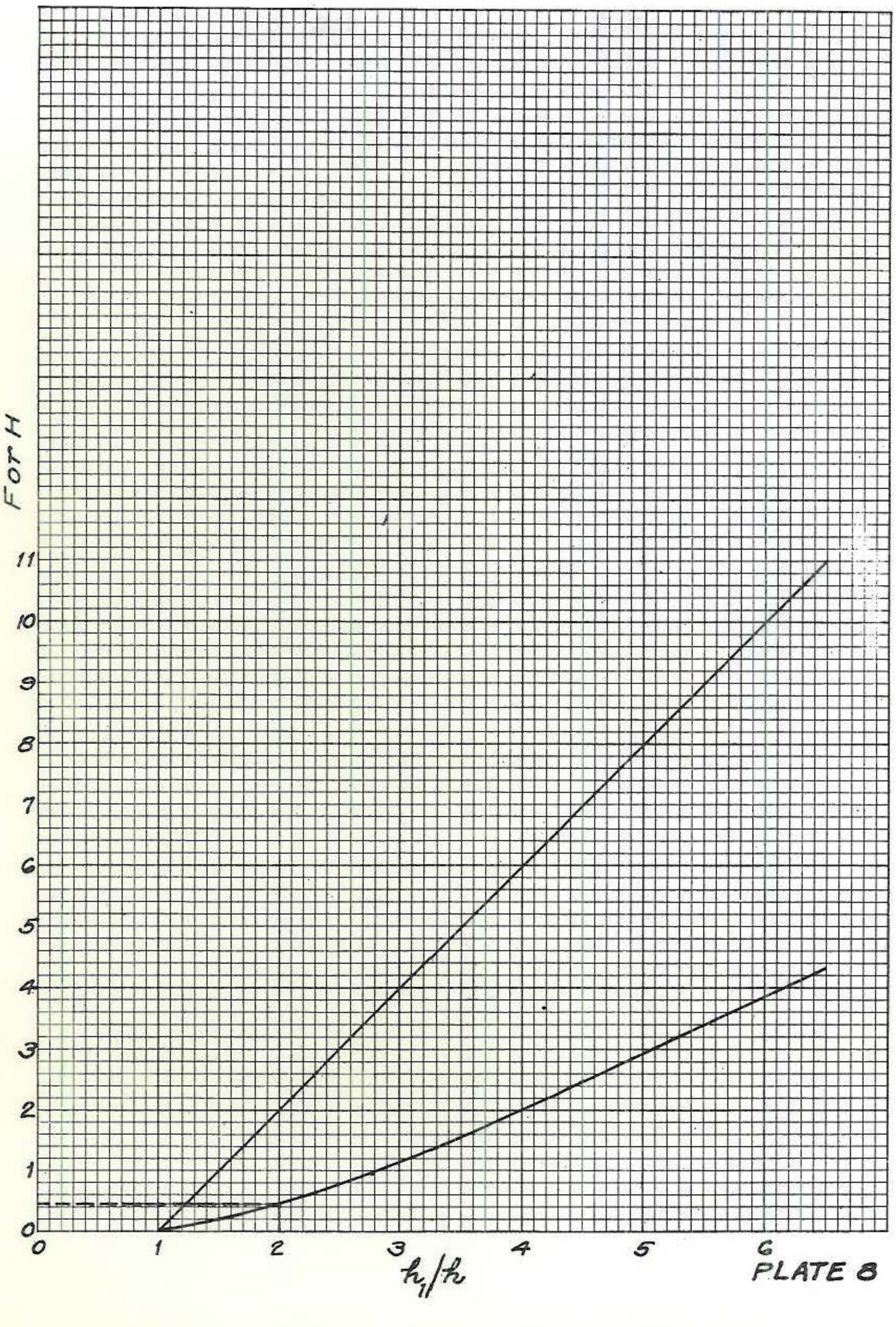
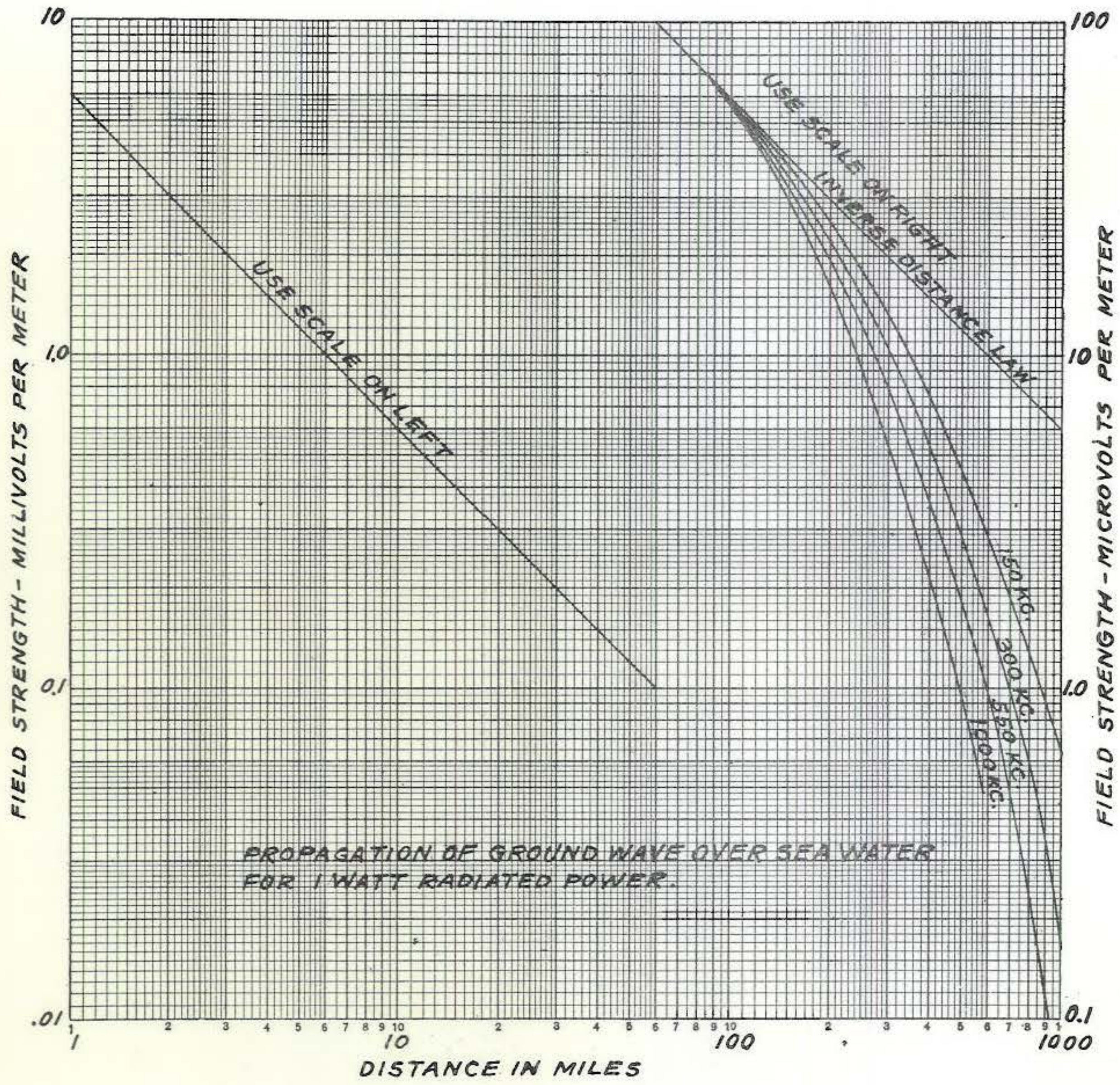


PLATE 8



USE SCALE ON RIGHT
INVERSE DISTANCE LAW
USE SCALE ON LEFT
150 KC.
300 KC.
550 KC.
1000 KC.
PROPAGATION OF GROUND WAVE OVER SEA WATER
FOR 1 WATT RADIATED POWER.
FIELD STRENGTH - MILLIVOLTS PER METER
FIELD STRENGTH - MICROVOLTS PER METER
DISTANCE IN MILES
10
1.0
0.1
.01
100
10
1.0
0.1
1
10
100
1000

PLATE 9

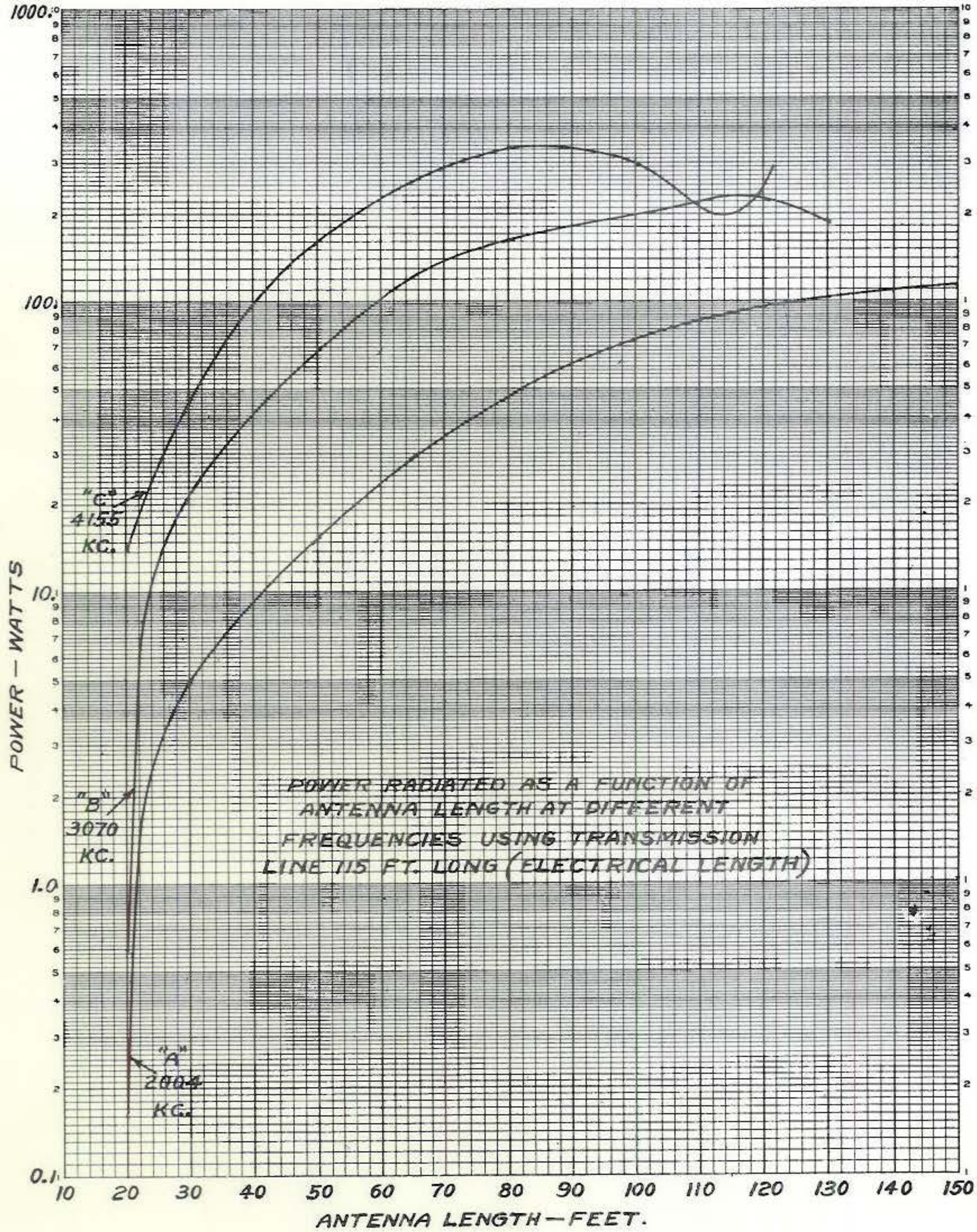

POWER RADIATED AS A FUNCTION OF ANTENNA LENGTH AT DIFFERENT FREQUENCIES USING TRANSMISSION LINE 115 FT. LONG (ELECTRICAL LENGTH)
"C" 4155 KC.
"B" 3070 KC.
"A" 2004 KC.
POWER — WATTS
ANTENNA LENGTH — FEET.
1000.
100.
10.
1.0
0.1
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

PLATE 10

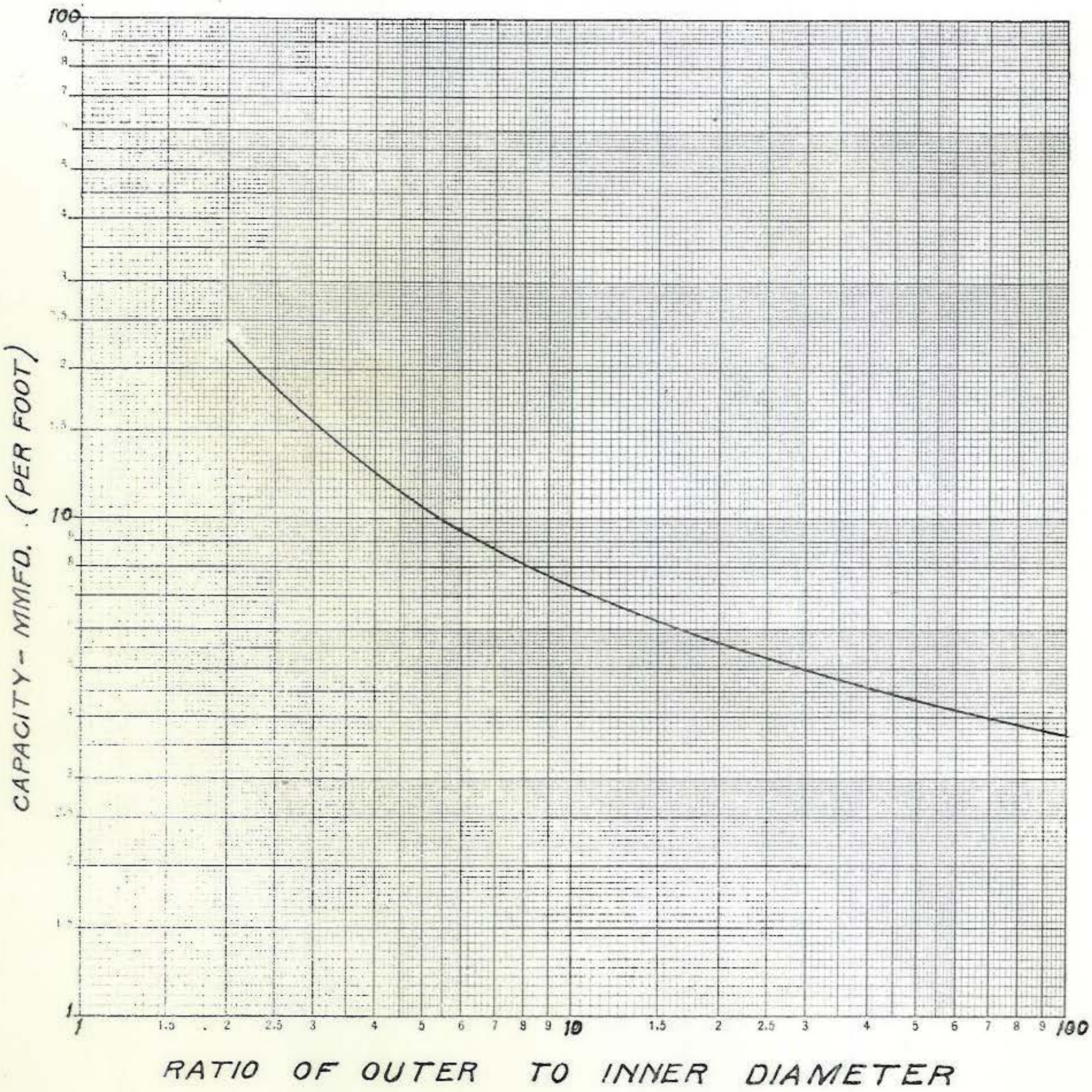
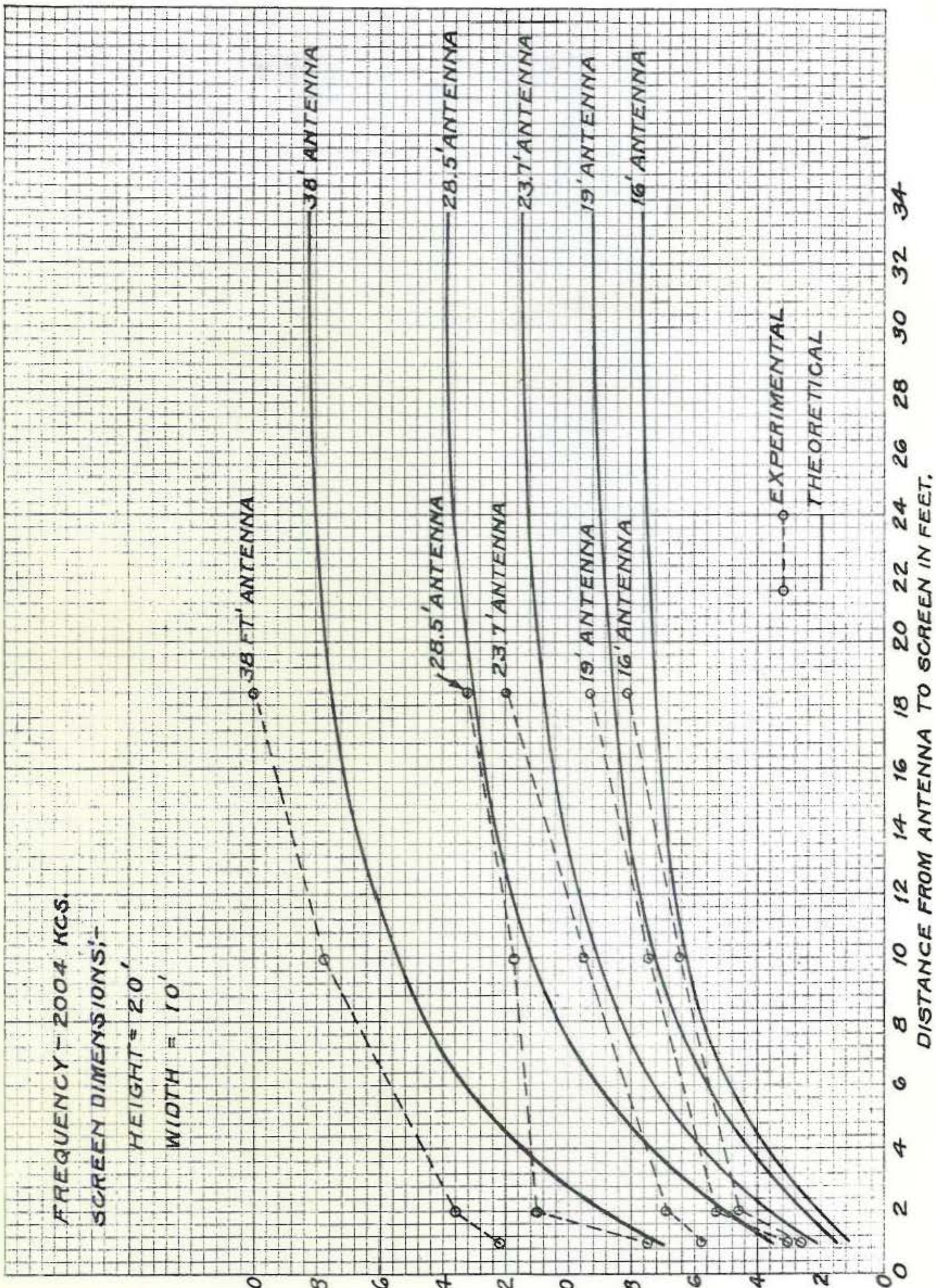


PLATE 11



FREQUENCY - 2004 KCS.
SCREEN DIMENSIONS:-
HEIGHT = 20'
WIDTH = 10'
38 FT' ANTENNA
28.5' ANTENNA
23.1' ANTENNA
19' ANTENNA
16' ANTENNA
38' ANTENNA
28.5' ANTENNA
23.1' ANTENNA
19' ANTENNA
16' ANTENNA
EXPERIMENTAL
THEORETICAL
FIELD STRENGTH
1.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34
DISTANCE FROM ANTENNA TO SCREEN IN FEET.

PLATE 12

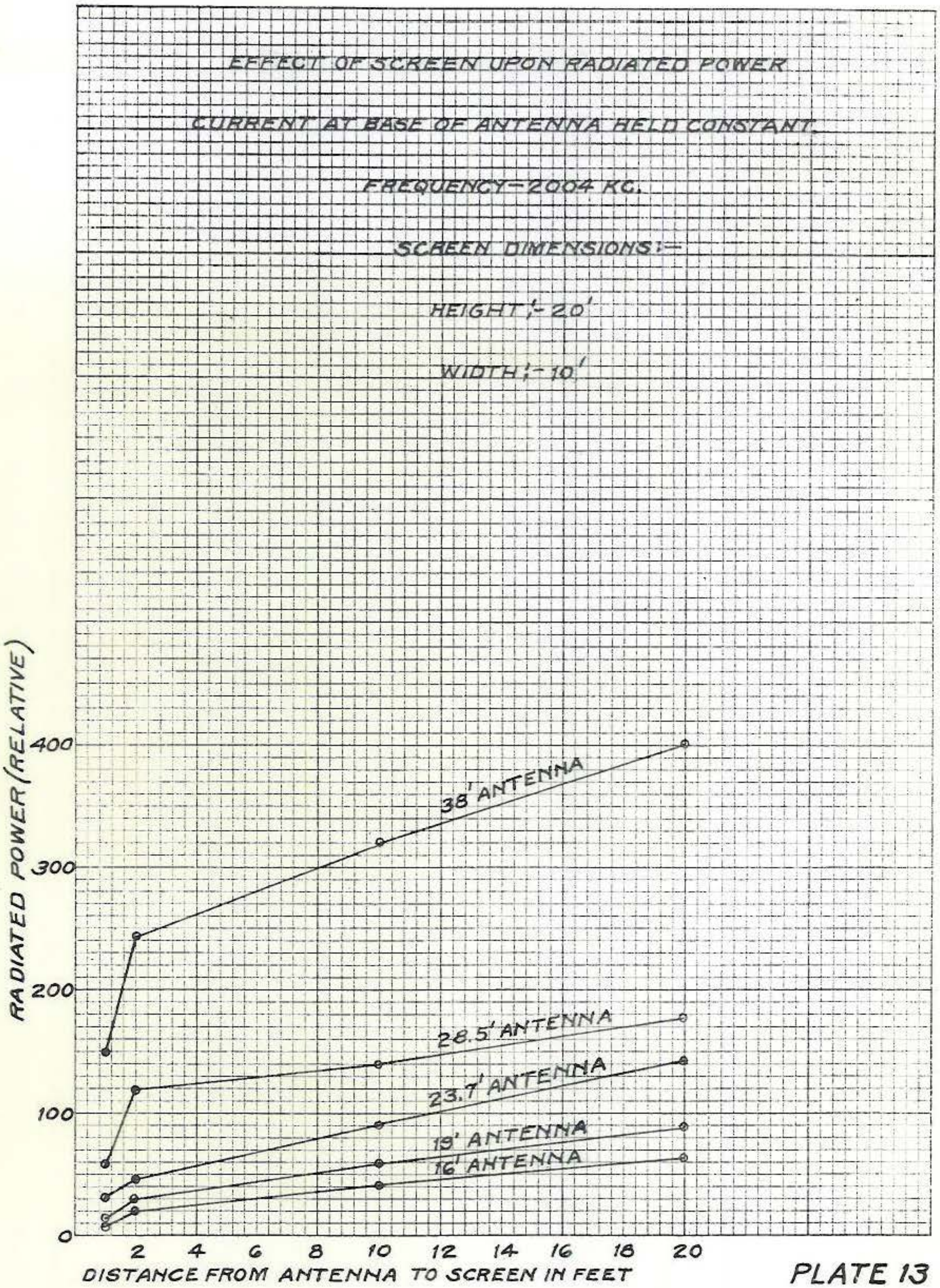

EFFECT OF SCREEN UPON RADIATED POWER
CURRENT AT BASE OF ANTENNA HELD CONSTANT.
FREQUENCY—2004 KC.
SCREEN DIMENSIONS:—
HEIGHT:- 20'
WIDTH:- 10'
38' ANTENNA
28.5' ANTENNA
23.7' ANTENNA
19' ANTENNA
16' ANTENNA
RADIATED POWER (RELATIVE)
0
100
200
300
400
2
4
6
8
10
12
14
16
18
20
DISTANCE FROM ANTENNA TO SCREEN IN FEET

PLATE 13

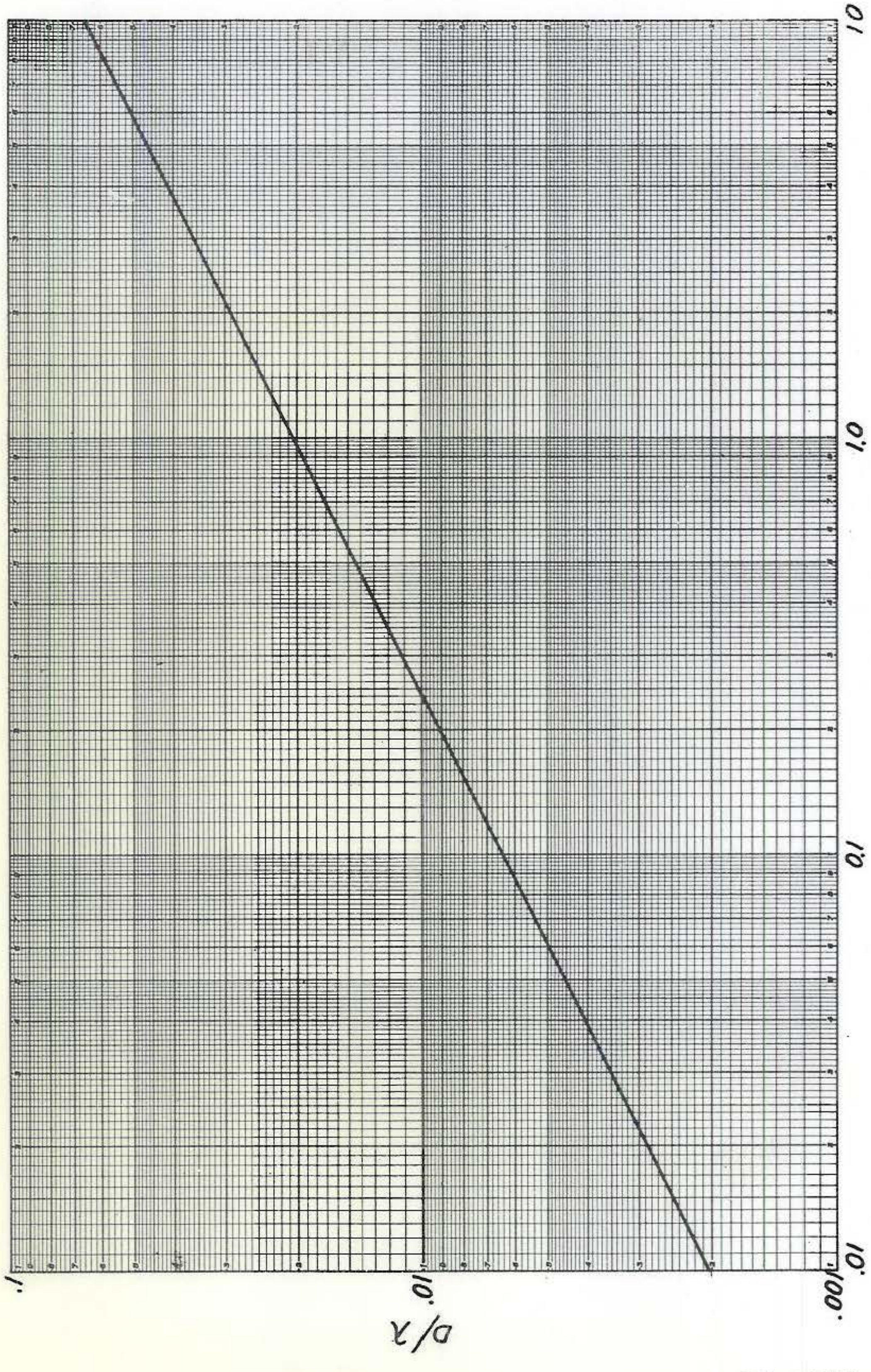


PLATE 14

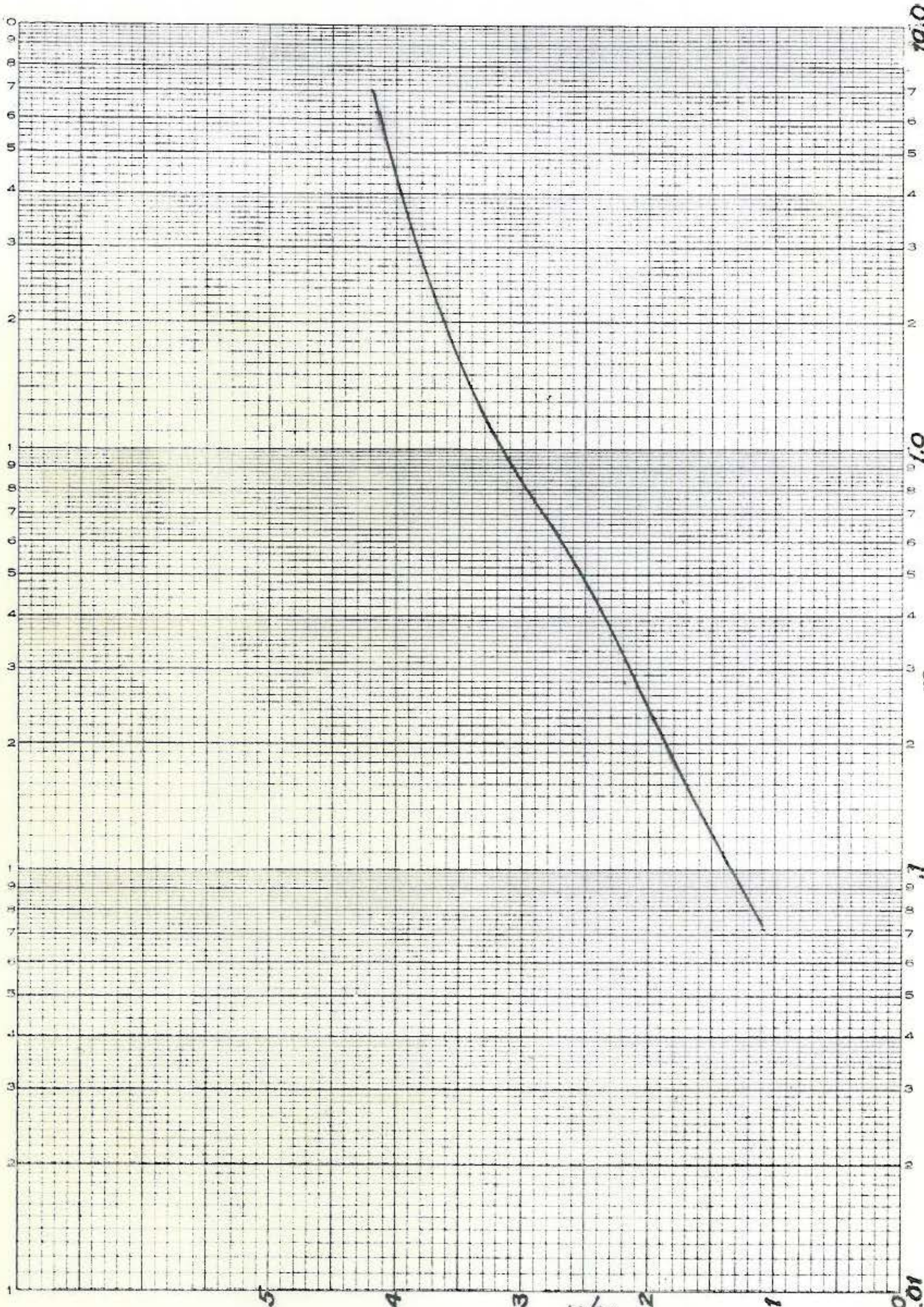


PLATE 15

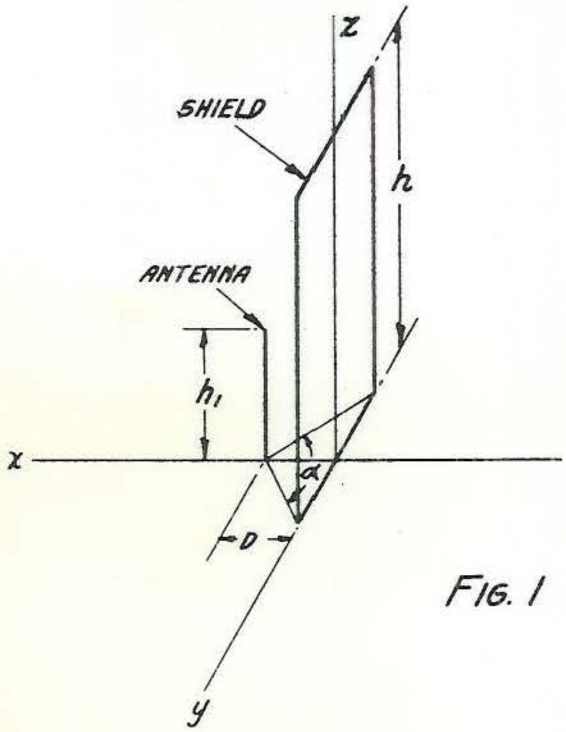


FIG. 1

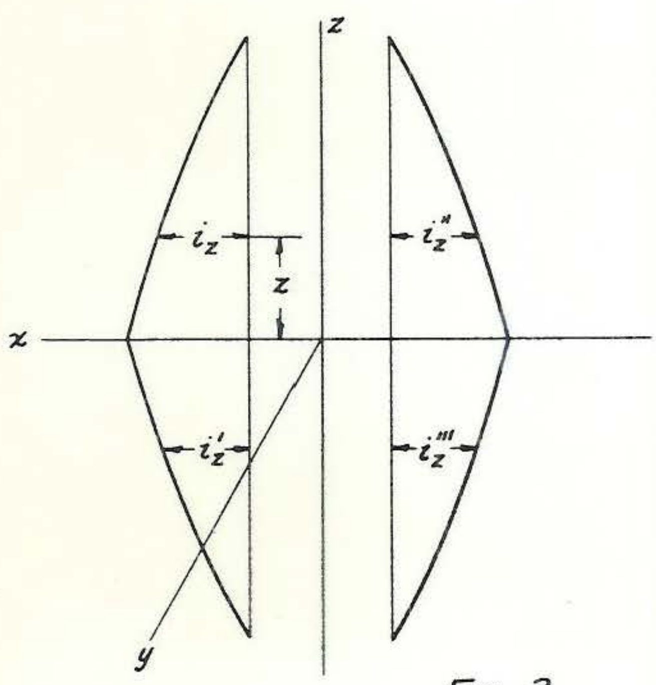


FIG. 2

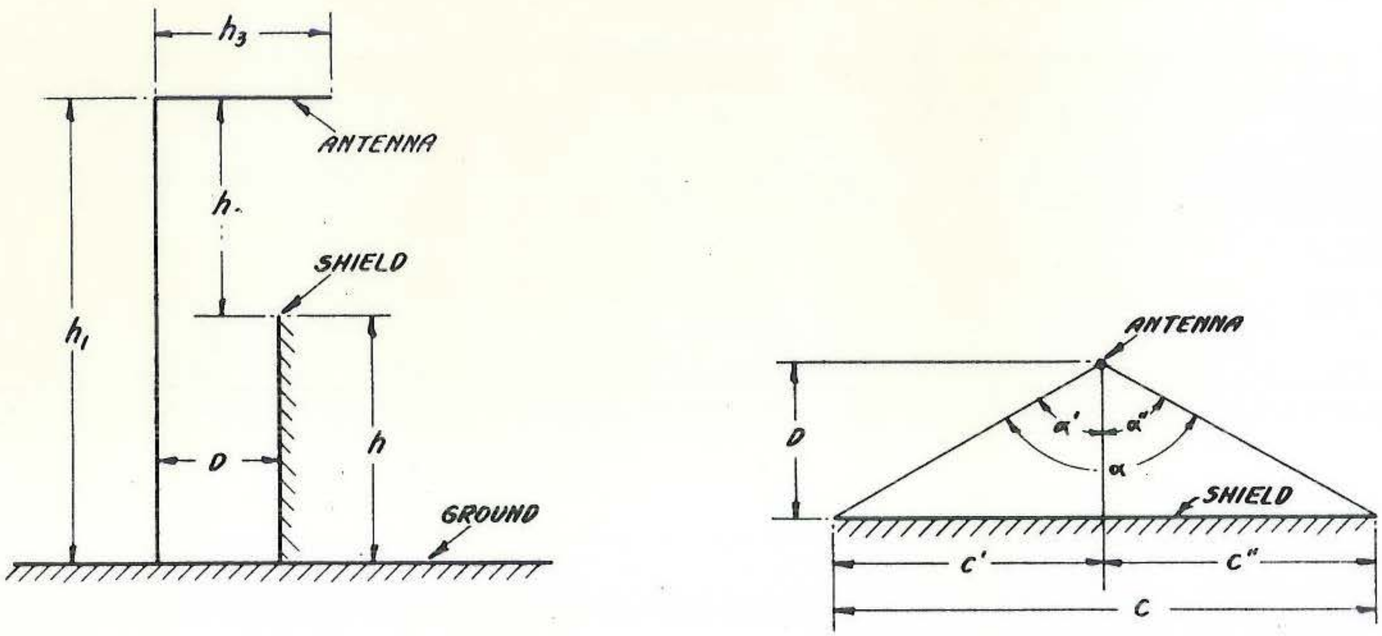


FIG. 3

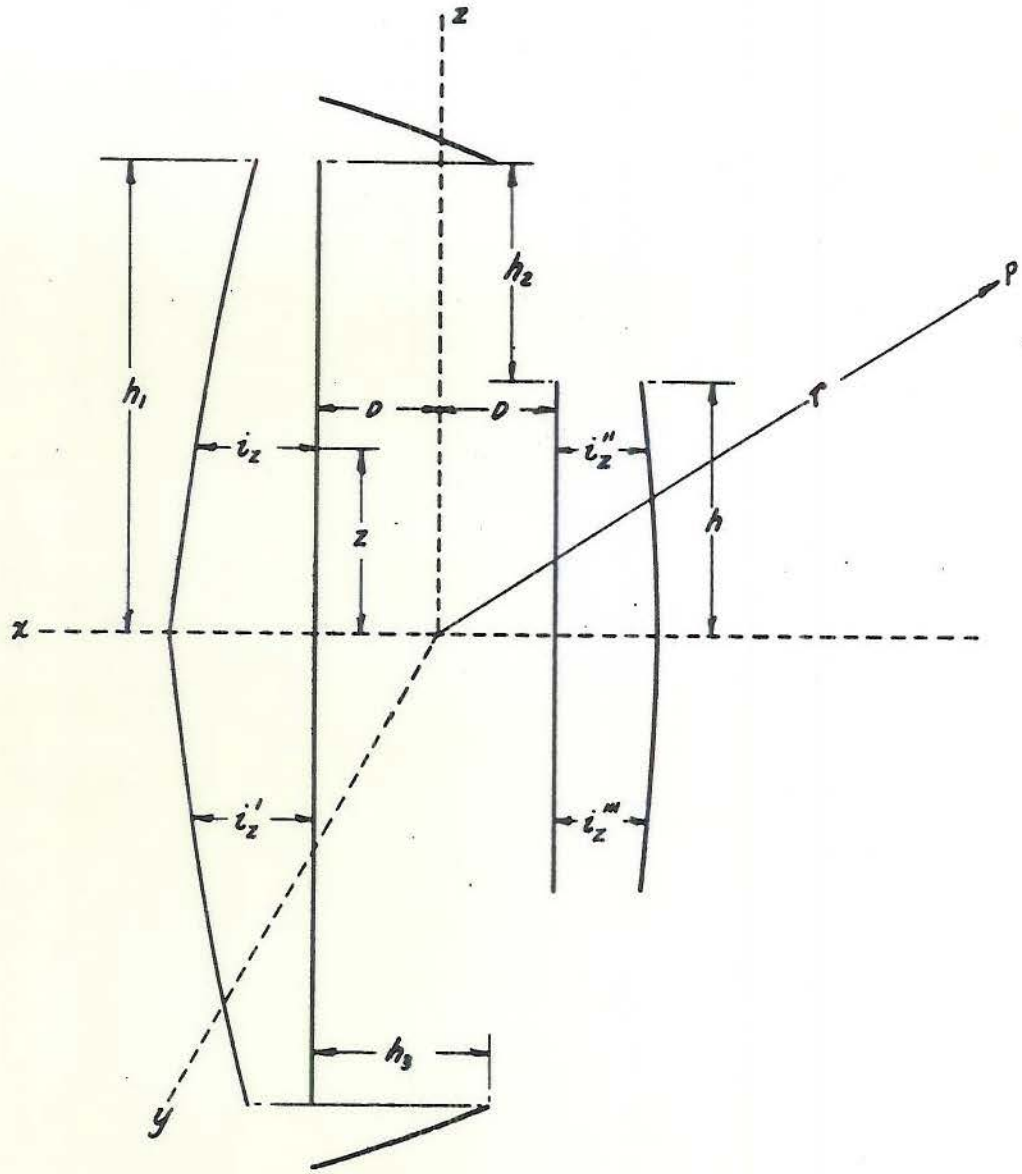


FIG. 4

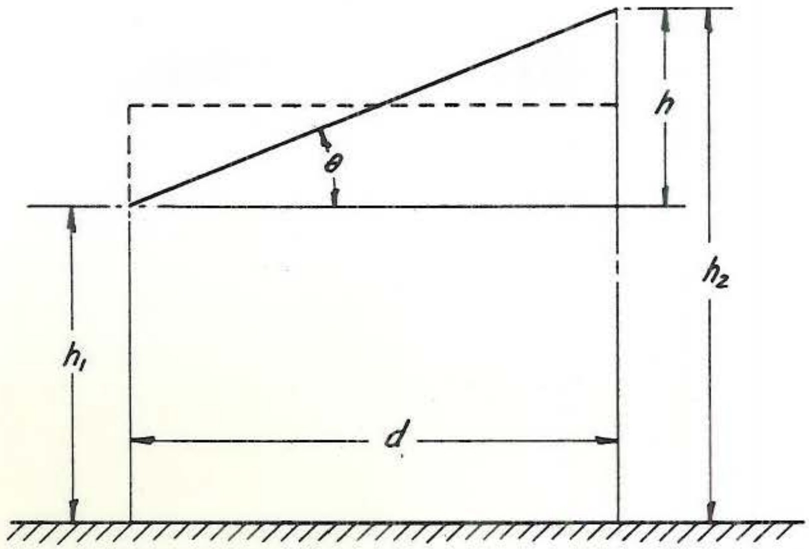


FIG. 5

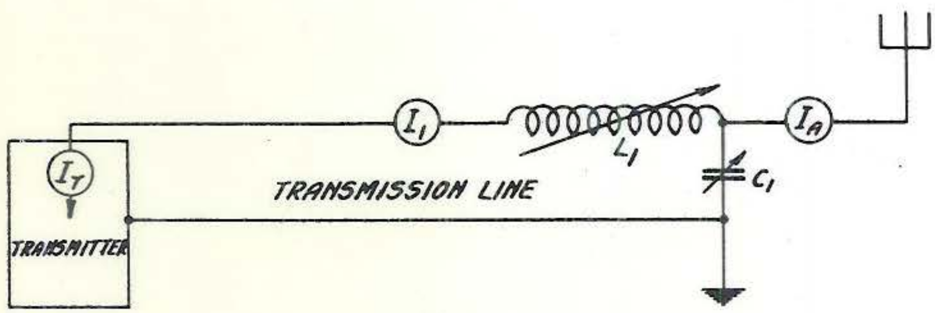


FIG. 6

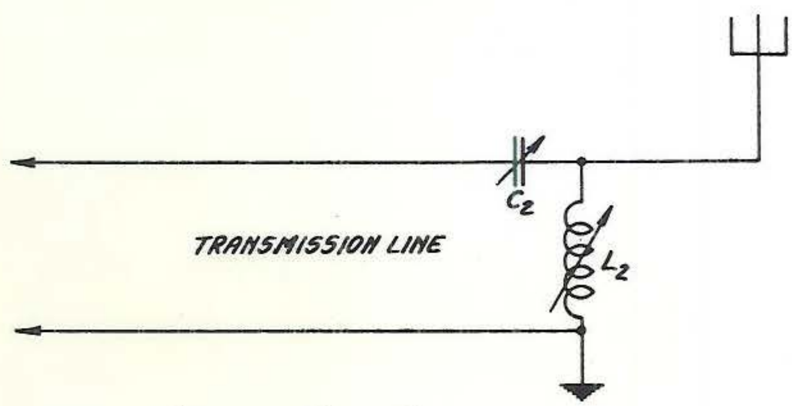


FIG. 7