U. S. DEPARTMENT OF COMMERCE
CIVIL AERONAUTICS ADMINISTRATION

Technical Development Division
Washington, D. C.

[redacted]

Technical Development Note No. 30

INTERFERENCE BETWEEN RADIO AIDS TO AIR NAVIGATION AND MARITIME RADIO BEACONS

By
H. W. Kohler
Radio Development Section

December 1942

CONTENTS

ILLUSTRATIONS

-22664

INTERFERENCE BETWEEN RADIO AIDS TO AIR NAVIGATION AND MARITIME RADIO BEACONS

SUMMARY

In order to establish a sound basis from which to work out solutions of interference cases between radio aids to air navigation and maritime radio beacons, curves of field intensity versus distance from radio range stations have been computed and are appended to this Note. Curves of carrier ground wave field intensity versus distance are presented for SBRA and MRL radio ranges, at frequencies of 200, 300, and 400 kilocycles and for five ground conductivities. At 300 kilocycles a curve for propagation over sea-water is also presented. Further, field intensity versus distance curves for airport traffic control transmitters operating at 300 kilocycles and adjusted to 1500 microvolts per meter at one mile are given. Sky wave field intensities which are exceeded during five per cent and 95 per cent of the time, respectively, based on data supplied by the Federal Communications Commission are also presented.

An example is given to show the application of the curves when interpolation of frequency and current is required to obtain field strength at a given distance. Another example is presented to demonstrate the application of the curves and theory to a hypothetical interference case between an ML radio range and a maritime radio beacon.

5-22664

INTRODUCTION

The frequency bands allocated to radio aids to air navigation and to maritime radio beacons extend from 200 to 400 kilocycles and from 285 to 315 kilocycles, respectively. Stations in the aeronautical services are permitted to share frequencies in the radio beacon band at locations where harmful interference will not result. Most direction finders of ships at sea are of the loop type and make use of the figure-of-eight field pattern of the loop in conjunction with the circular pattern of the sense antenna. Direction finding thus being based on a null method is very susceptible to interfering signals on the same frequency, especially if the disturbance comes from a direction at right angles to that of the maritime beacon signals.

In order to arrive at a firm basis from which mutually satisfactory solutions of interference cases can be worked out, the field intensity versus distance of the interfering radio aids must first be determined. The purpose of this Note is to give carrier field intensity curves versus distance for radio ranges of the loop type (MRL) and the simultaneous Adcock type (SBRA) for both ground wave and sky wave, and to analyze the interference probabilities.

BASIS OF FIELD INTENSITY CURVES

The curves of ground wave field intensity given in this Note are based on those presented by K. A. Norton in a paper entitled

"The Calculation of Ground Wave Field Intensity Over a Finitely Conducting Spherical Earth," FCC Publication No. 39920, or Proceedings of the I.R.E., 29, 623, December, 1941.

Briefly, the calculations in the above reference assume a homogeneous spherical earth surrounded by a medium whose dielectric constant decreases uniformly with height. In the present problem the surface wave is polarized vertically. The graphic determination of the field intensity given by Norton is done in two parts. The first covers the field near the antenna, wherein the earth's surface can be considered plane. Determination of the radiation field at one mile gives a point on the inverse-distance curve, of a plot of intensity versus distance. Using the same size of logarithmic paper as Norton, one point of the near-field intensity curve (at numerical distance 1) is determined and the appropriate curve is traced. The following constants enter into the selection of the curve to be traced: conductivity and dielectric constant of the ground, and frequency.

At distances beyond the line of sight (second part of Norton's presentation) the curvature of the earth's surface and the effect of air refraction are accounted for by taking a value of effective earth radius, 4/3 the actual radius. Again one point on the intensity-versus-distance curve is determined, the appropriate curve traced and joined smoothly with the near-field curve.

The curves giving field intensity of the sky wave versus distance were taken from "Standards of Good Engineering Practice Concerning Standard Broadcast Stations", published by the Federal

Communications Commission. The FCC curves are for a vertical antenna having a height of 0.311 wave length (112°) and hold for the second hour after sunset at the receiver location. A single reflection from the E-layer of the ionosphere is assumed. In order to illustrate the fluctuations of the sky wave, two intensity-versus-distance curves are shown. The upper curve represents the field strength which is exceeded during five per cent of the time, and the lower curve the field strength exceeded during 95 per cent of the time.

At distances over 600 miles multiple reflections between ionosphere and earth may take place. A sky wave undergoing multiple reflections suffers greater attenuation than one which is reflected but once, provided both waves travel the same distance along the earth's surface.

During daytime the sky wave disappears for all practical purposes, as the reflection coefficient of the ionosphere is reduced to an average value of 0.005 at the frequencies in question here. During nighttime the average reflection coefficient is 0.25. (See A. Ross, "Ground and Ionospheric Rays", Wireless Engineer, 14, 306, June, 1937).

DATA UNDERLYING THE CALCULATIONS

Calculations of field intensities were made for frequencies of 200, 300, and 400 kilocycles, and for ground conductivities of 1, 2, 5, 10, and 20 x 10^{-14} electromagnetic cgs units. For the dielectric constant of the ground (ϵ) the value 15 referred to free space as unity was taken throughout. At 300 kilocycles field intensities for propagation over sea water also were calculated, with values of $\epsilon = 80$ and $\sigma = 5 \times 10^{-11}$.

TYPE SBRA RANGES

In the SBRA ranges provision is made for simultaneous range operation and voice communication. Four towers nominally 125 feet high are located in the corners of a square whose diagonals measure 600 feet, and the fifth tower is in the center of the square. The towers are insulated from the ground and have no top loading. The currents in each pair of diagonal towers are assumed to be equal in magnitude and opposite in phase. The range operates on the single sideband principle viz., the corner towers are excited at a frequency $f_c + 1020$ cycles, where f_c denotes the carrier frequency; the center tower radiates the carrier, which may also be modulated by voice. On the range course the carrier is modulated 30 per cent, and at 45 degrees off-course the carrier is modulated 42.4 per cent at 1020 cycles.

To find a value of center-antenna resistance which could be considered as representative, a number of measurements were plotted and an average curve of center antenna resistance versus frequency was drawn (curve A of figure 1). Measured center-antenna currents were adjusted to an input power for the center-antenna of 400 watts and were also plotted versus frequency, see figure 2. Curve A of figure 2 is the average current. The radiation resistance of a single tower was computed for a filamentary vertical wire whose lower end is near the surface of a perfectly conducting plane earth.

Table I gives numerical data pertaining to SBRA ranges.

TABLE I

QUANTITY	UNITS	FREQUENCY 200 kc	300 kc	400 kc
Average center-antenna resistance	Ohms	5.0	5.3	5.75
Radiation resistance	Ohms	0.25	0.57	1.04
Effective height	Meters	19.2	19.2	19.2
Average center-antenna current	Amperes	9	8.7	8.35
Carrier field strength at 1 mile	Microvolts / Meter	27,000	39,100	50,000
Input power (P_i)	Watts	400	400	400
Radiated power (P_r)	Watts	22.7	43	72.5
Radiation efficiency (P_r/P_i) x 100	Per cent	5.7	10.8	18.2

TYPE MRL RANGES

The dimensions of the standard loop are 300 feet by 35-1/2 feet average, giving an area of 990 square meters. The loop currents are modulated 100 per cent at 1020 cycles (double sideband). The two figure-of-eight patterns are assumed to give two pairs of reciprocal courses normally at right angles to each other. The field intensity E (Θ) at Θ degrees off-course is related to the maximum field strength E_{max} by

$$E(\Theta) = E_{max} \cos (45^\circ - \Theta)$$

the angle Θ is between 0° and 45° and is measured from the nearest course. E (Θ) varies between E_{max} and 0.707 E_{max}.

It is worth noting that with a perfect goniometer the total power input into the two loops is independent of goniometer setting, and that the maximum field strength also is independent of goniometer setting as long as the length of the loop is small compared to the wavelength.

Table II gives numerical data on MRL ranges.

TABLE II

Quantity	Units	FREQUENCY		
		200 kc	300 kc	400 kc
Average loop resistance	Ohms	6.65	11	18
Radiation resistance of one loop	Ohms	0.00605	0.0307	0.0973
Effective height	Meters	4.14	6.215	8.29
Average loop current with goniometer set to 0° or 90°	Amperes	4.5	3.5	2.75
Maximum carrier field strength at 1 mile	Microvolts / Meter	2,910	5,040	6,970
Input power	Watts	135	135	135
Radiated power	Watts	0.122	0.377	0.735
Radiation efficiency	Per cent	0.091	0.28	0.545

RESULTS

Figures 3, 4, and 5 show the calculated carrier ground wave and sky wave field intensity versus distance for an average SBRA range, for five ground conductivities and three frequencies, with an input power of 400 watts into the center antenna. To find the field strength for other input powers P_n (SMRA ranges) multiply the values derived from the curves by $\sqrt{\frac{P_n}{400}}$, where P_n is another antenna input power in watts. If the current in the center antenna is known and different from that indicated by these curves, multiply the field strength by the ratio of these currents. Field strengths for frequencies and conductivities, other than those used in the attached curves, are found by interpolation. The sloping straight line on each of the figures gives field strength, assumed to vary as the inverse distance from the antenna. This line can be used as an upper limit of field strength to be expected with high-conductivity ground, for distances less than about 50 miles.

Comparing the ground wave field strength curves for 200, 300, and 400 kilocycles, it will be observed that close to the range station the field strength for a fixed input power increases with frequency due to increased radiation efficiency of the antennas. At greater distances, depending on the ground conductivity, the ground wave field strength is greater, the lower the frequency; because of lower losses in the ground at these frequencies. The sky wave field intensity is greater within the frequency range considered, the higher the frequency.

The sky wave suffers relatively little attenuation and may be as strong as the ground wave at distances as close as approximately 100 miles for the lowest ground conductivity and the highest frequency considered in this work. At great distances the sky wave, if present, predominates.

Figures 6, 7, and 8 show the maximum carrier ground wave and sky wave field strength versus distance from the station for an average MRL type range. The same ground conductivities and frequencies, as for the simultaneous range, are used. For different input powers (as in ML and RL stations), or different loop currents from those given in the headings of the figures, the same procedure as outlined for simultaneous ranges is used for determining field strength. The same remarks regarding wave propagation hold for both loop and tower stations.

Figure 9 shows field intensity versus distance curves for airport traffic control transmitters. As no standardized antennas are used for this service, input power and antenna currents vary considerably for different installations. The curves presented are, therefore, based on the maximum permissible field strength of 1,500 microvolts per meter at one mile from the transmitter.

In order to show the intensity of the sky wave beyond the distance of 2000 miles from the range station, figures 10 and 11 have been plotted. Figure 10 shows the sky wave, exceeded five per cent and 95 per cent of the time, produced by SBRA ranges with a power input of 400 watts into the center antenna, corresponding to radio frequency currents of 9, 8.7, and 8.35 amperes at frequencies of 200, 300, and 400 kilocycles, respectively. Figure 11 shows similar curves for MRL radio ranges with loop currents of 4.5, 3.5, and 2.75 amperes for a power input of 135 watts.

A large number of field strength measurements have been checked against the appended curves and have shown, in general, satisfactory agreement between theory and measurements. The field intensity meters used for these measurements were made by the Federal Telegraph Company (Type 101-B) and consist essentially of a superheterodyne receiver with an attenuator and a calibration oscillator. Both detectors are linear, making the output meter reading independent of modulation. The meter readings, therefore, represent carrier field strengths. According to the calibration report for a particular instrument checked by the National Bureau of Standards, the accuracy after calibration is within six per cent.

INTERFERENCE PRODUCED BETWEEN RADIO RANGES AND MARITIME RADIO BEACONS

Under this heading no attempt is made to analyze the detection problem in detail. Assuming the interfering frequencies to be so close together that they are all amplified equally by the receiver, we shall confine our attention to the amplitudes of the fundamental frequencies produced by linear detection. Regarding single sideband and double sideband modulation it should be recalled that if the percentage modulation m of the carrier is the same for both cases, the amplitudes of modulation frequency are substantially equal, and proportional to m. The definition of per cent modulation in the single sideband case is such that m per cent modulation means that the single sideband amplitude is m per cent of the carrier amplitude, whereas with double sideband modulation the amplitude of each sideband is m/2.

Let the range carrier field strength be E_1, modulated m_1 per cent and let the maritime beacon have a carrier field intensity E_2 modulated to a degree m_2. Assume first, that the range signal and the maritime beacon signal come from the same direction as seen from the receiver. After linear detection the amplitude of the beat frequency of the two carriers is approximately proportional to the amplitude of the weaker carrier. The carrier beat note will give the strongest audio frequency signal.

The amplitudes of the desired and the undesired signals, respectively, are

m_2E_2 (maritime beacon, $m_2 = 100$ per cent)

and m_1E_1 (ranges)

where $m_1 = 42.4 \cos (45^\circ - \theta)$ per cent for the simultaneous range. θ is the azimuth angle measured from the nearest course ($0 \leqslant \theta \leqslant 45^\circ$). In case of loop-type ranges $m_1 = 100$ per cent. The proportionality factor in all cases is the same, depending on the detector characteristic.

If the location of the two transmitters and of the receiver is such that the interfering signal comes from a direction α with respect to the beacon signal, figure 12, account must be taken of the directivity of the direction finder loop. This is done by multiplying the radio range field intensity at the receiver by sin α, and the beacon field intensity by $\sin \Delta\alpha$, where $\Delta\alpha$ is one-half of the no-signal arc of the direction finder. With the lowest usable field strength for the direction finder, $E_2 = 50\ \mu v/m$, a value for $\Delta\alpha$ of 3° is given, in which case $\sin \Delta\alpha = 0.0523$. Assuming that for satisfactory direction finder operation the beacon carrier voltage at the output terminals of the loop must be N times the carrier voltage of the interfering range, the following relation is obtained:

$$E_2 \times 0.0523 = NE_1 \sin \alpha$$

$$E_1 = E_2 \frac{0.0523}{N \sin \alpha}$$

In the case of simultaneous ranges, E_1 can be assumed constant for all azimuth angles and therefore follows directly from the field strength versus distance curves. For loop stations the field strength given in the curves must be reduced as follows:

$$E_1 = E_1 \max \cos (45^\circ - \theta)$$

where θ is the angle between the nearest range course and the direction to the receiver.

The value of N depends on the per cent modulation, the modulation frequency and the frequency separation between the interfering carriers.

ILLUSTRATIVE EXAMPLES

(a) Given an SBRA range operating at 350 kilocycles with a current in the center antenna of eight amperes. Find the carrier field strength at a distance of 600 miles over ground with an average conductivity $\sigma = 10^{-13}$ c.g.s. units, both for day and night conditions, using for the latter the intensities exceeded five per cent of the time. By interpolation the following approximate values of carrier field strength are obtained from the curves of figures 4 and 5.

	Frequency	Day	Night
	300 kc	2.5	46
	400 kc	0.75	58
Average values	350 kc	1.62	52

To adjust the above values to a center-antenna current of eight amperes, find the current for the average range at 350 kilocycles from figure 2. This is approximately 8.5 amperes. For final result multiply average field strength above by 8/8.5, giving

Day field intensity = 1.5

Night field intensity = 49

(b) Given an ML radio range with an antenna carrier power of 40 watts, at 300 kilocycles. Assuming an average ground conductivity of 5×10^{-14} c.g.s. units find the field strength at 20° off-course at a distance of 300 miles. At this location a direction finder on a ship at sea receives a beacon signal of 100 microvolts per meter from a direction $\alpha = 60^{\circ}$ with respect to the range signal. Disregarding that a part of the ground-wave path is over sea water, find the ratio of the emf's induced in the direction finder loop by the two carriers if the loop is rotated $\pm 3^{\circ}$ off zero.

From figure 7 we find, for 135 watts carrier power, a field strength of 1.6 $\mu v/m$ for the ground wave and 12.3 $\mu v/m$ for the sky wave, the latter value being exceeded during five per cent of the time. Reducing these quantities to 40 watts carrier power gives

for day time $E = \sqrt{40/135} \times 1.6 = 0.87$

for night time $E = \sqrt{40/135} \times 12.3 = 6.7$

Taking account of the azimuth angle $\theta \approx 20^\circ$

multiply by $\cos (45^\circ - 20^\circ) = \cos 25^\circ = 0.906$

giving 0.79 and 6.06 $\mu v/m$, respectively.

The characteristic of the direction finder loop is accounted for by multiplying the beacon and range field intensity by $\sin 3^\circ$ and $\sin 60^\circ$, respectively. This gives

for day time $\dfrac{E_{beacon}}{E_{range}} = \dfrac{100 \times .0523}{0.79 \times 0.866} = 7.6$ and

for night time $\dfrac{E_{beacon}}{E_{range}} = \dfrac{5.23}{6.06 \times 0.866} = 1$

Interference will result in this case, inasmuch as the desired signal 3° off the null is equal to the undesired signal at night time.

CONCLUSIONS

The theoretical curves of ground wave field intensity versus distance presented in this Memo agree, generally, with measured values of field intensity. The accuracy of the ground wave field intensity curves is estimated to be ± ten per cent. No measurements of the sky wave field intensity of radio ranges are available, and, therefore, no checks of the sky wave curves are possible at this time. Due to the fact that radio ranges located near the coast operate on frequencies outside the 285 to 315 kilocycle marine band, most cases of interference between radio aids to air navigation and maritime radio beacons must be due to the sky wave at night. It would be desirable to collect data on sky wave field strength with recording field intensity meters at or near the location of alleged interference in order to check the applicability of the curves presented.

The degree of interference experienced by the operator of a direction finder is determined by factors other than the relative amplitudes of desired and undesired voltages induced in the loop. Other factors entering into the problem are: variation of the sky wave field intensity with time, frequency separation of desired and undesired carriers, sensitivity and selectivity of direction finder, modulation frequency of desired and undesired carrier, skill and psychology of the operator.

Laboratory and field tests should be made with a typical direction finder to ascertain the weight which should be given to the several factors mentioned above bearing on the interference problem.

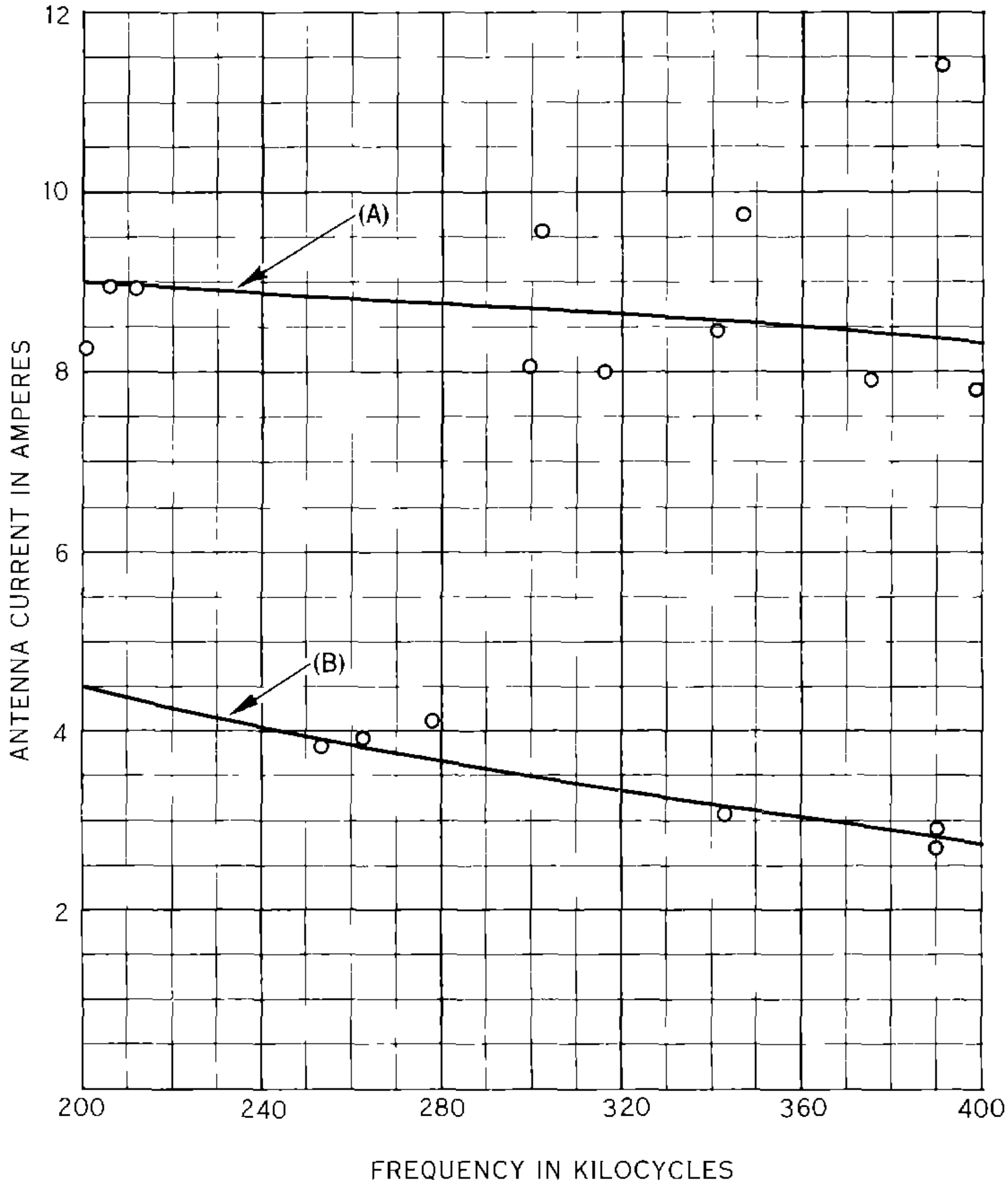

FIGURE 1. Antenna Current VS Frequency

A - Measured Current in Center Antenna of SBRA Radio Ranges for 400 Watts Input Power to Center Antenna

B - Measured Loop Current for MRL Radio Ranges for 135 Watts Input Power to Antenna and Goniometer Setting 0° or 90°.

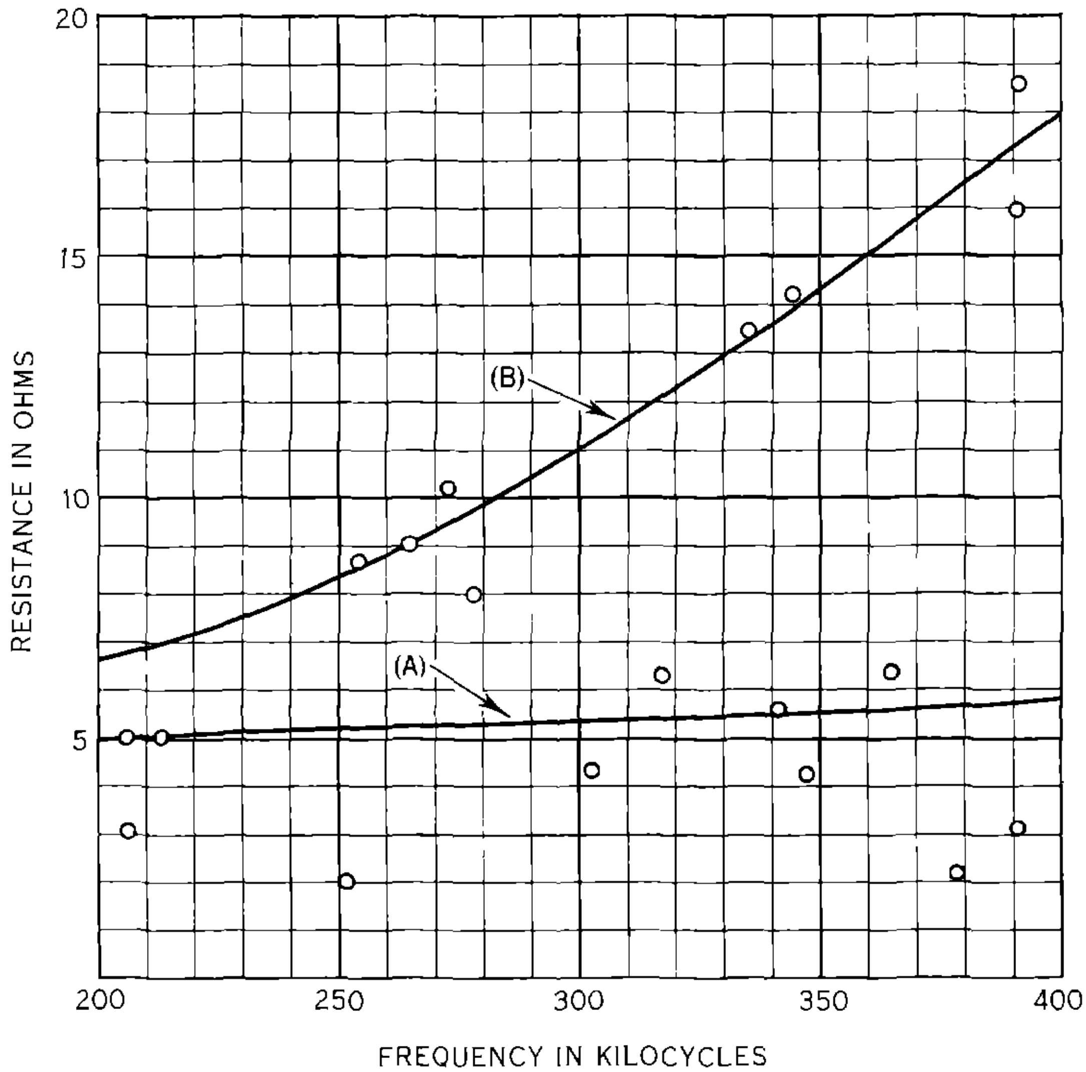

FIGURE 2. Antenna Resistance VS Frequency
A - Measured Resistance of Center Antenna of SBRA Radio Ranges
B - Measured Resistance of One Loop of MRL Radio Ranges

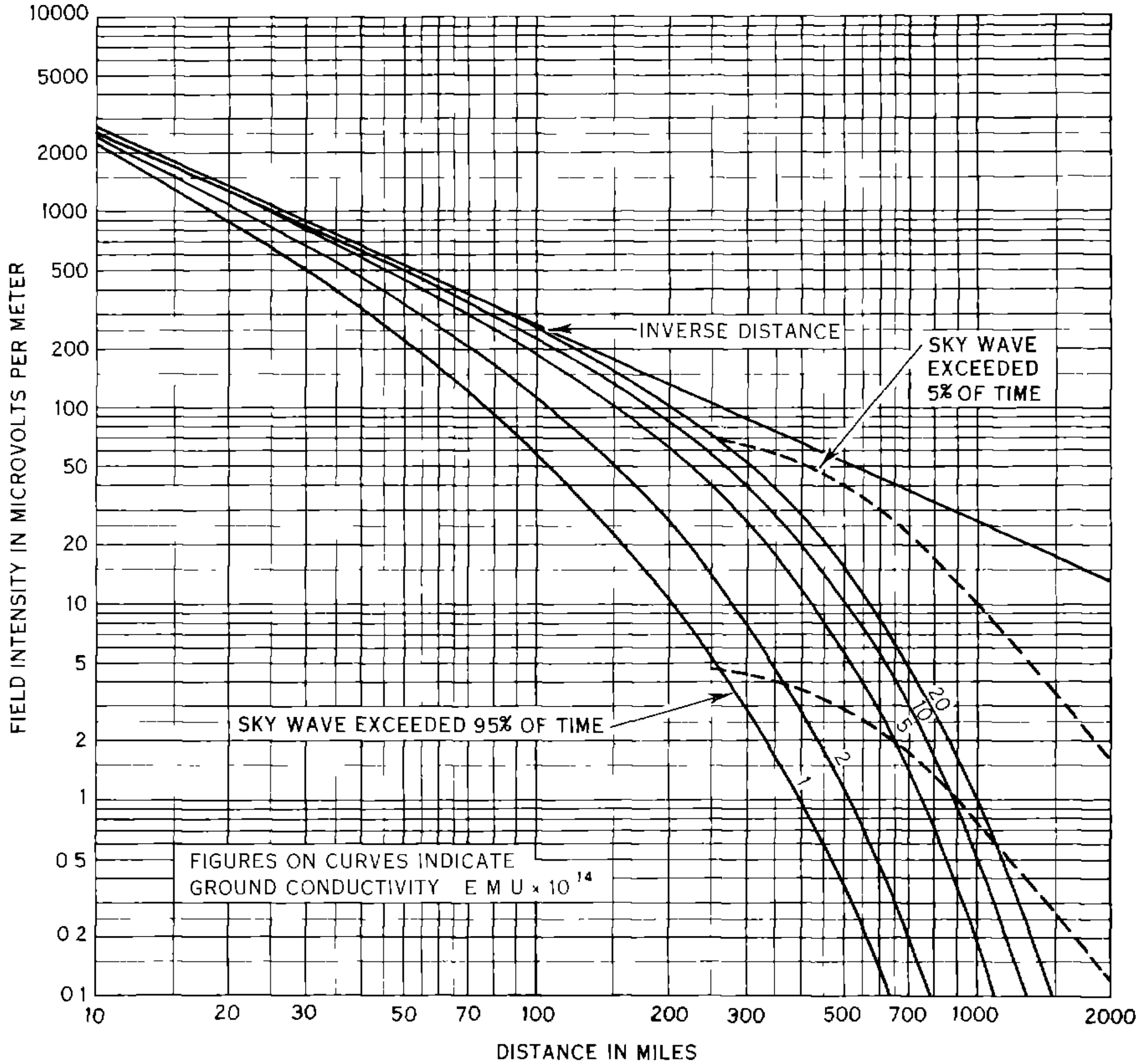

FIGURE 3. Field Intensity VS Distance for SBRA Radio Ranges
Input Power to Center Antenna = 400 Watts
Current in Center Antenna = 9.0 Amperes
Frequency = 200 Kilocycles

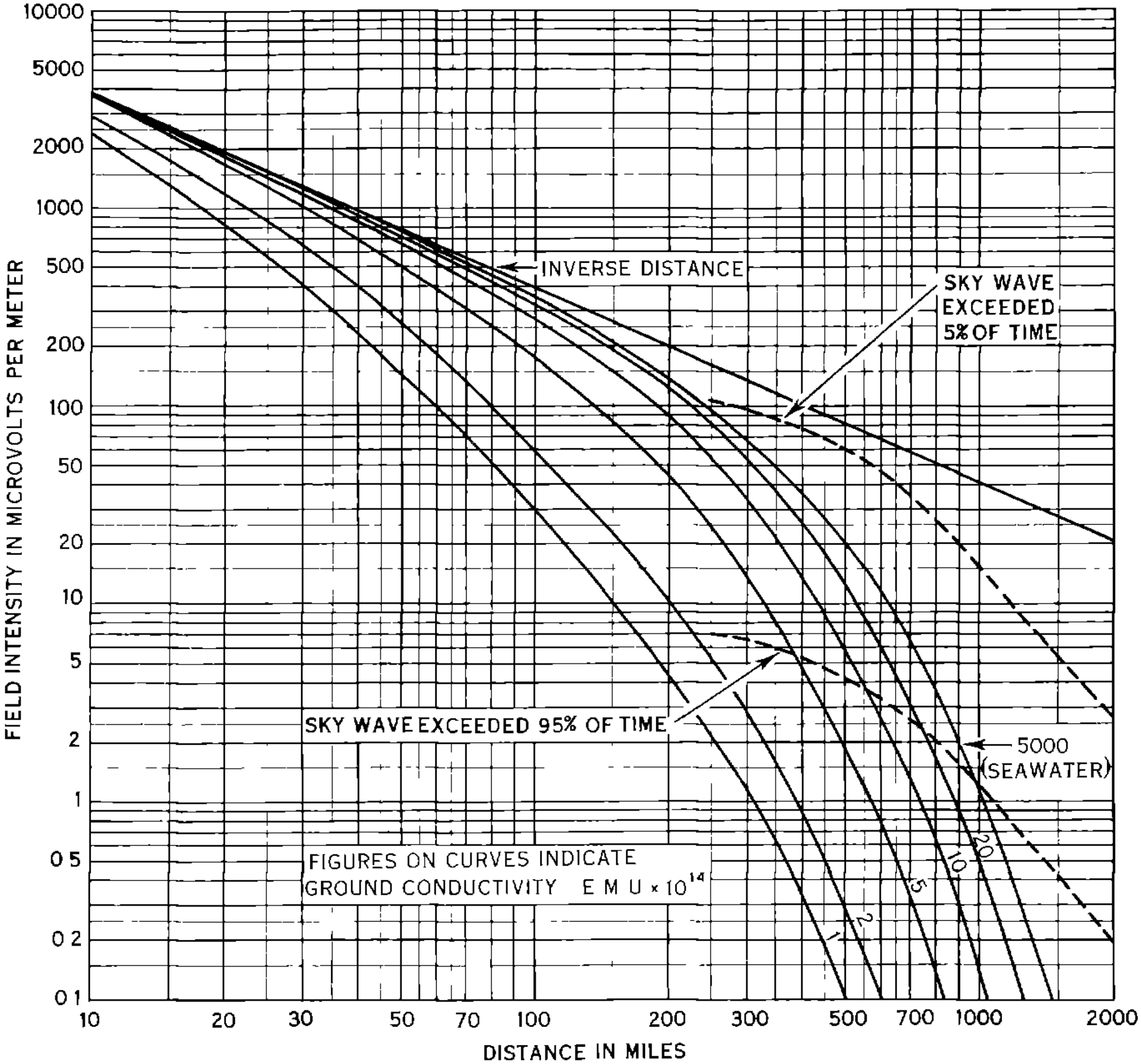

FIGURE 4. Field Intensity VS Distance for SBRA Radio Ranges
Input Power to Center Antenna = 400 Watts
Current in Center Antenna = 8.7 Amperes
Frequency = 300 Kilocycles

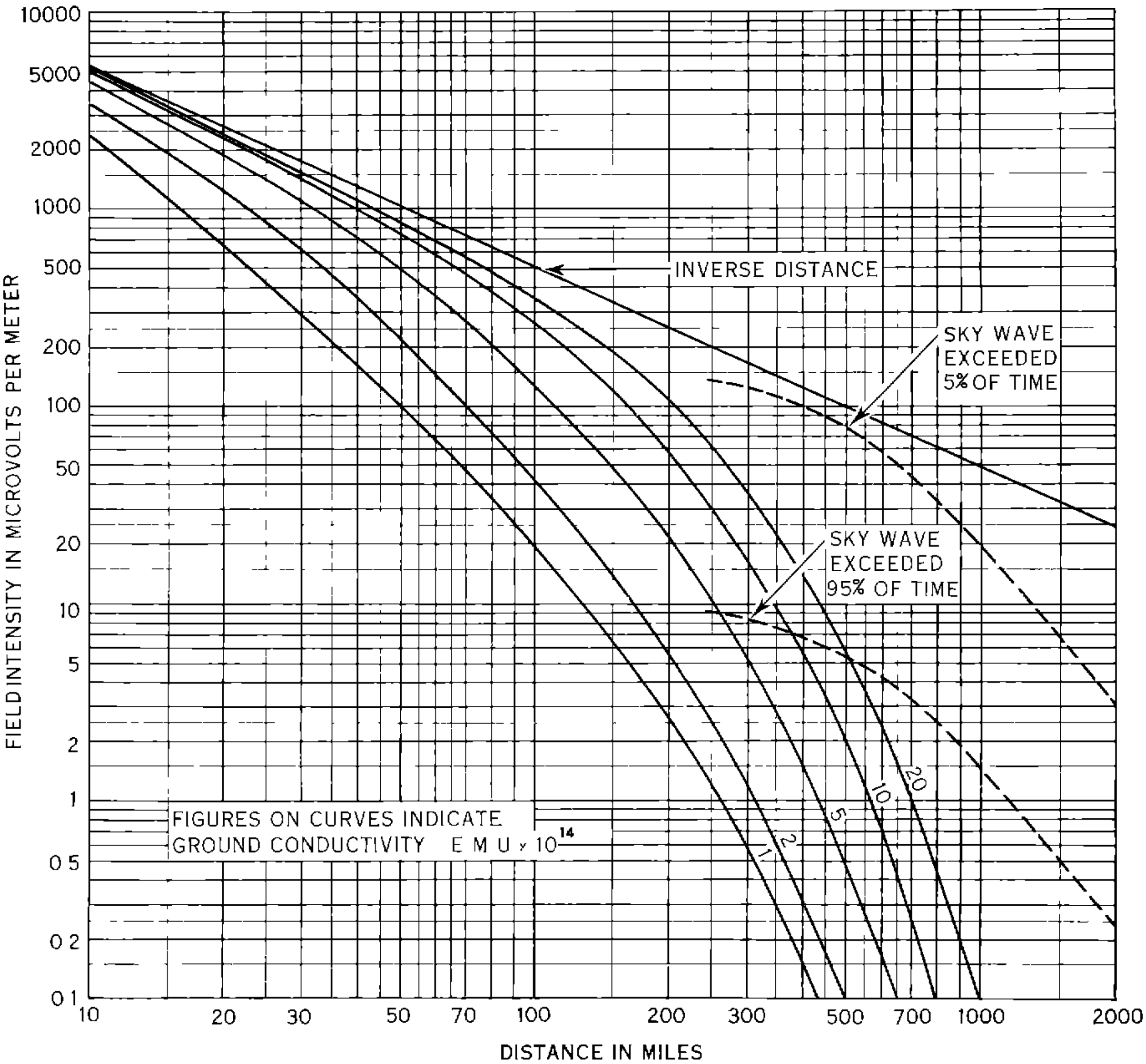

FIGURE 5. Field Intensity VS Distance for SBRA Radio Ranges
Input Power to Center Antenna = 400 Watts
Current in Center Antenna = 8.35 Amperes
Frequency = 400 Kilocycles

A-2349-0 (12)

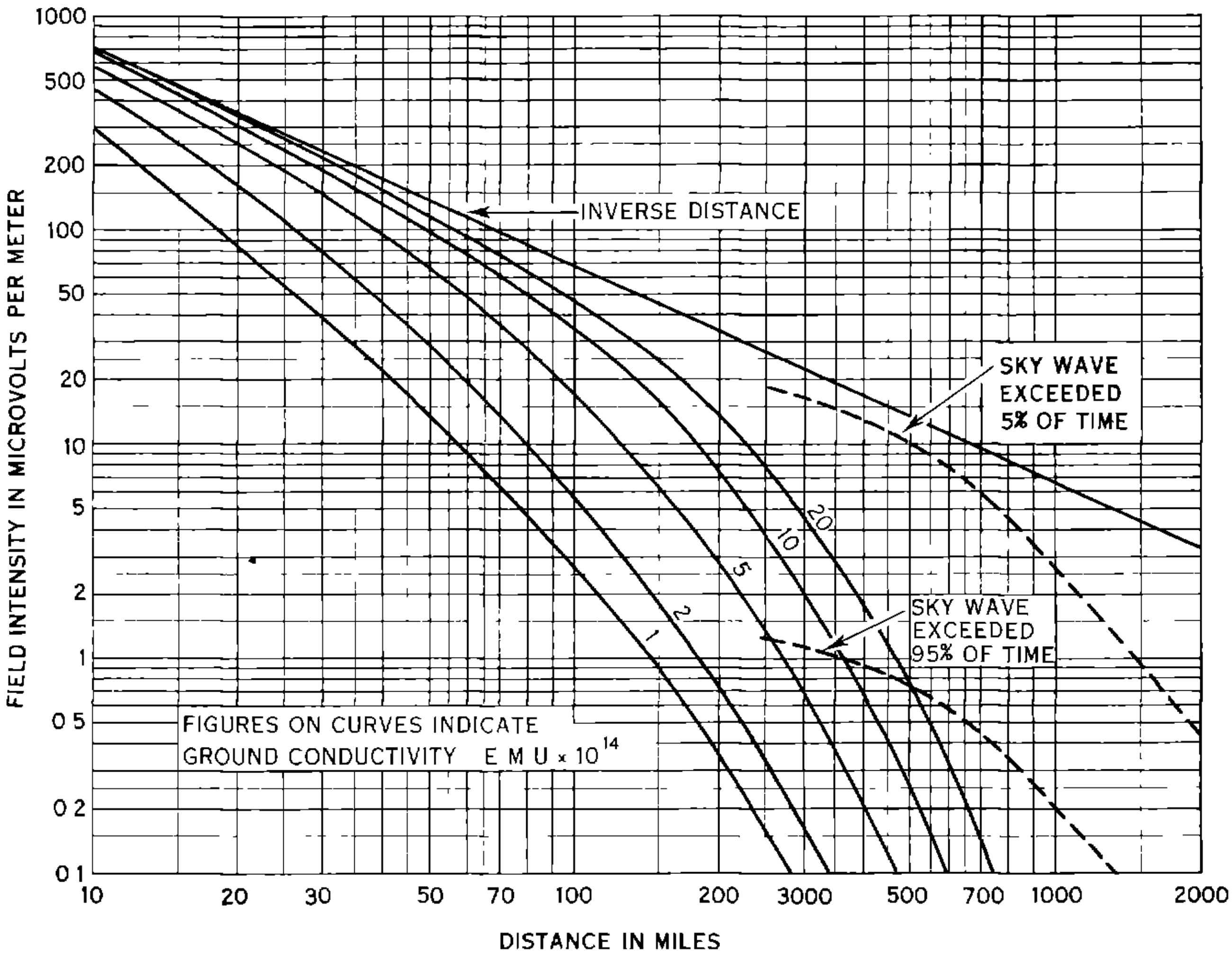

FIGURE 6. Maximum Field Intensity VS Distance for MRL Radio Ranges
Total Input Power to Two Loops = 135 Watts
Loop Current for Goniometer Setting 0° = 3.5 Amperes
Frequency = 200 Kilocycles

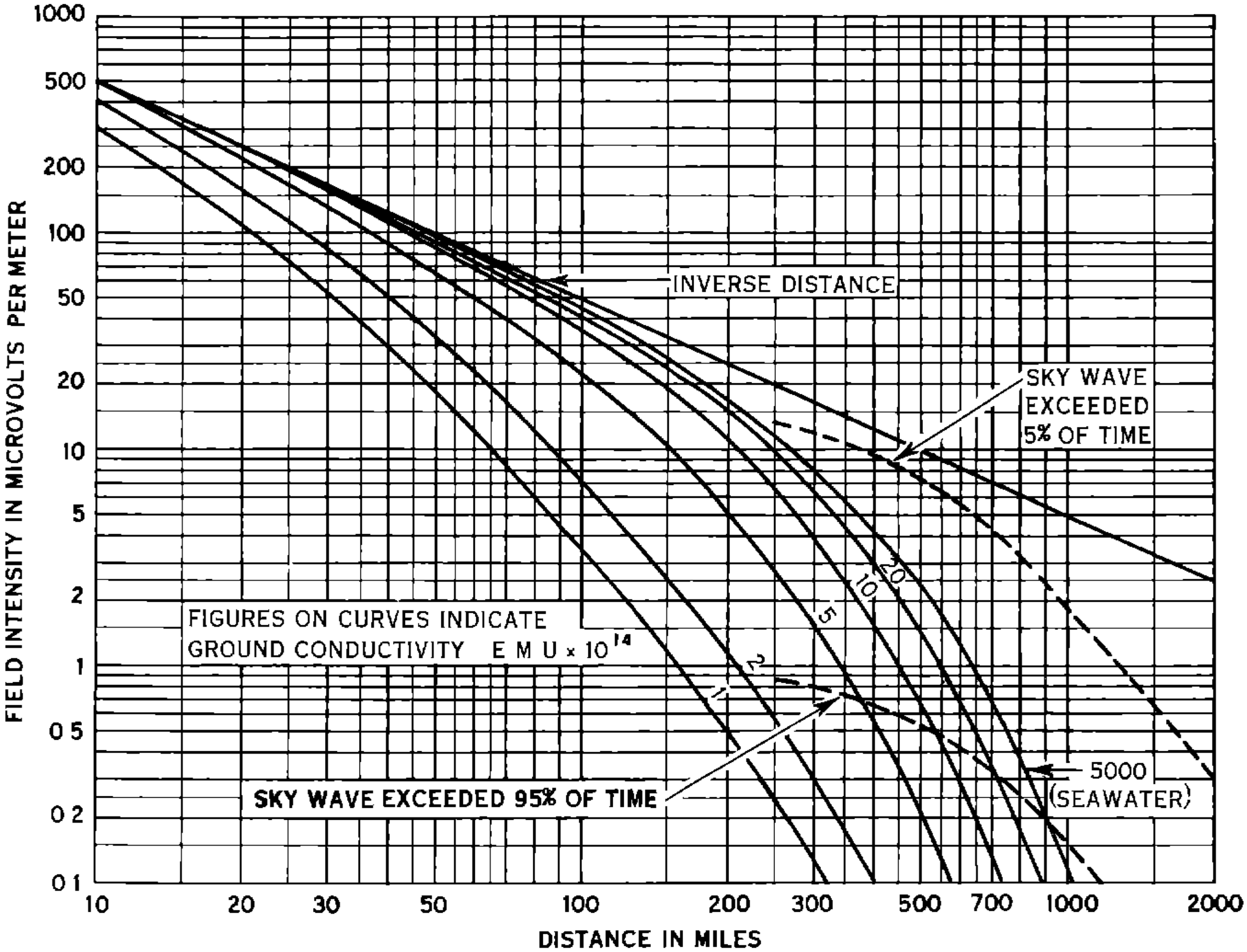

FIGURE 7. Maximum Field Intensity VS Distance for MRL Radio Ranges
Total Input Power to Two Loops = 135 Watts
Loop Current for Goniometer Setting 0° = 3.5 Amperes
Frequency = 300 Kilocycles

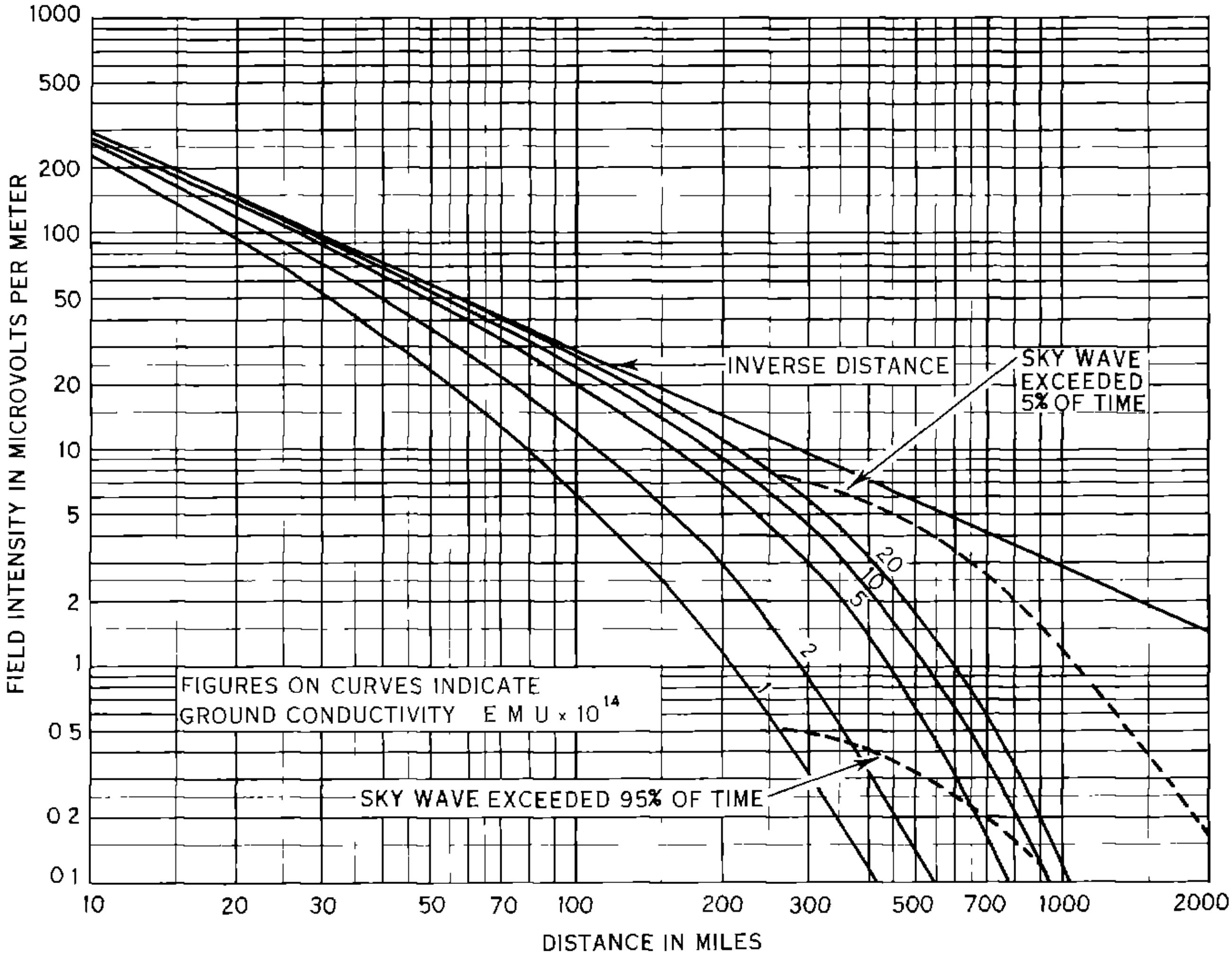

FIGURE 8. Maximum Field Intensity VS Distance for MRL Radio Ranges
Total Input Power to Two Loops = 135 Watts
Loop Current for Goniometer Setting 0° = 2.75 Amperes
Frequency = 400 Kilocycles

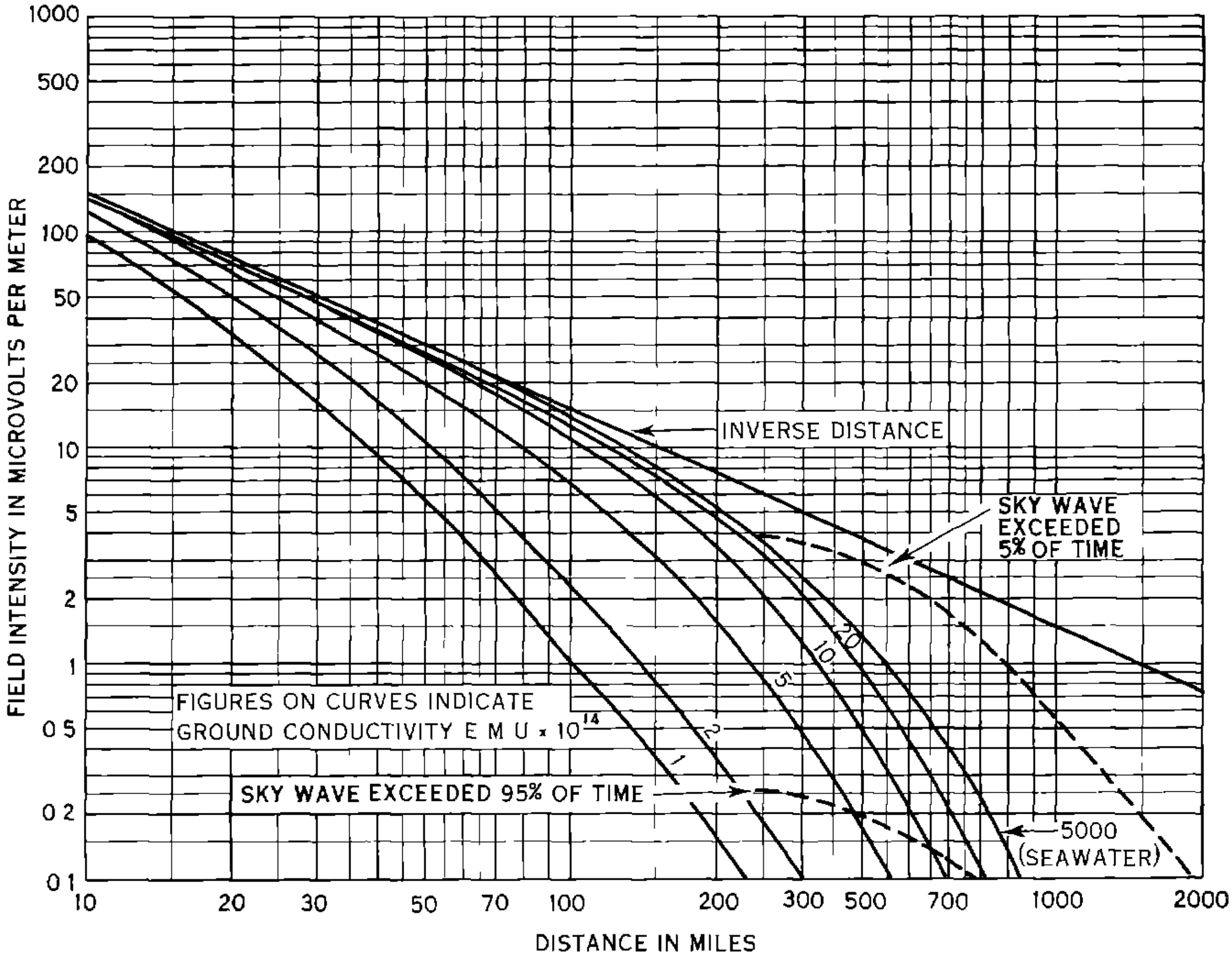

FIGURE 9. Field Intensity VS Distance for Airport Traffic Control Transmitters Adjusted to Give 1,500 Microvolts Per Meter at One Mile. Frequency = 300 Kilocycles

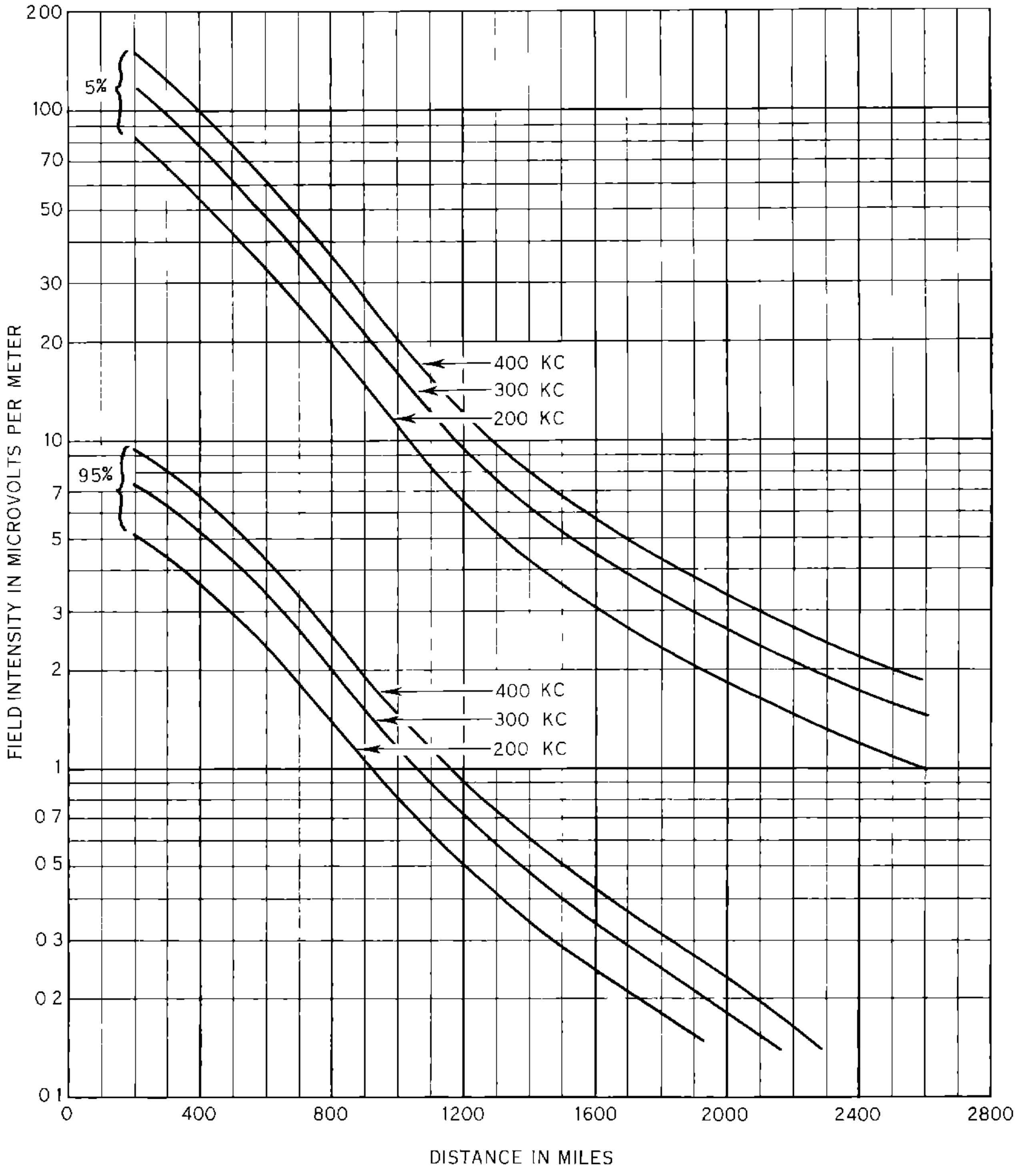

FIGURE 10. Sky Wave Field Intensity Exceeded 5 Percent and 95 Percent of the Time, VS Distance, for SBRA Radio Ranges With Power Input of 400 Watts to Center Antenna

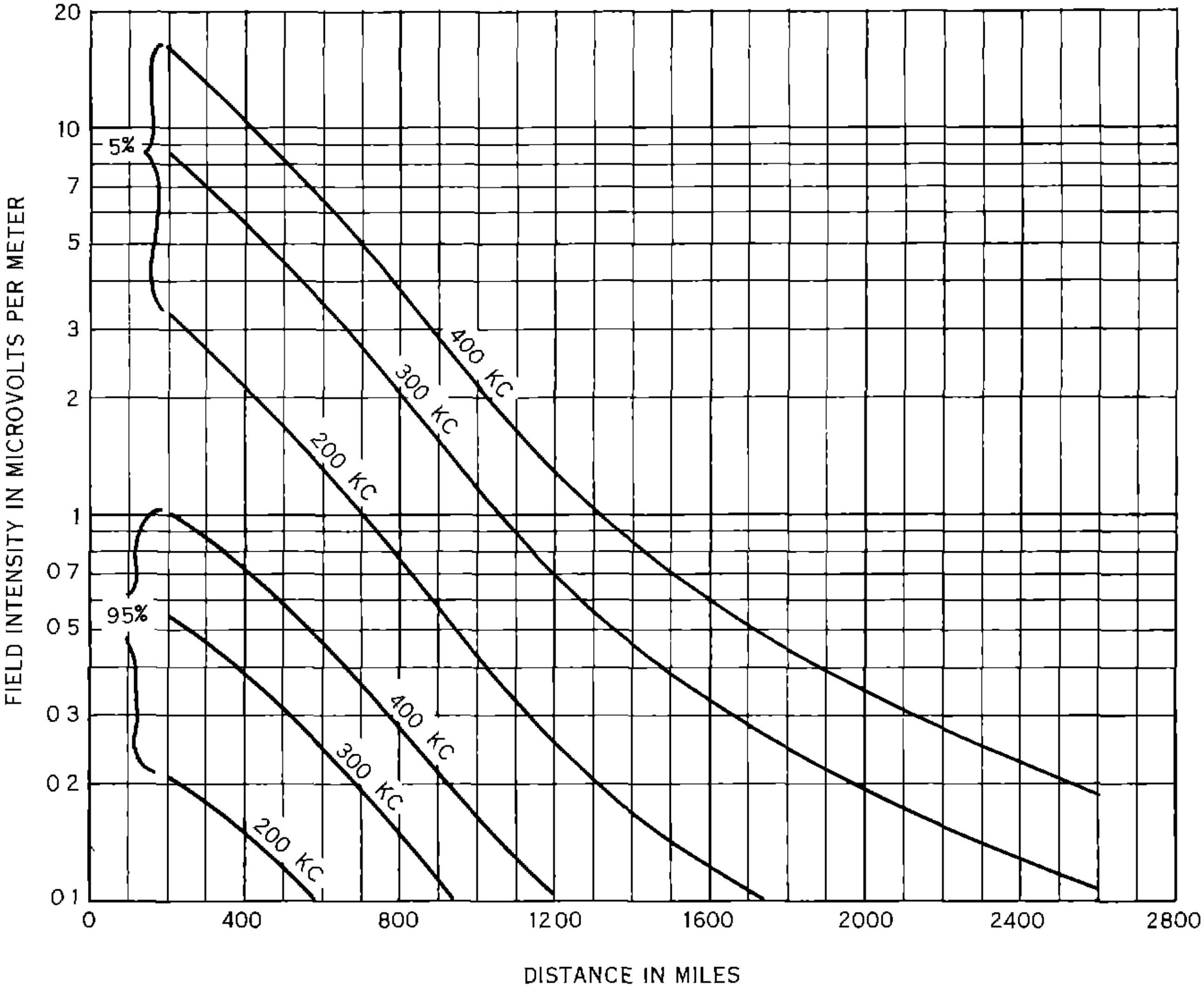

FIGURE 11 Sky Wave Field Intensity Exceeded 5 Percent and 95 Percent of the Time, VS Distance, for MRL Radio Ranges Total Power Input of 135 Watts to Two Loops

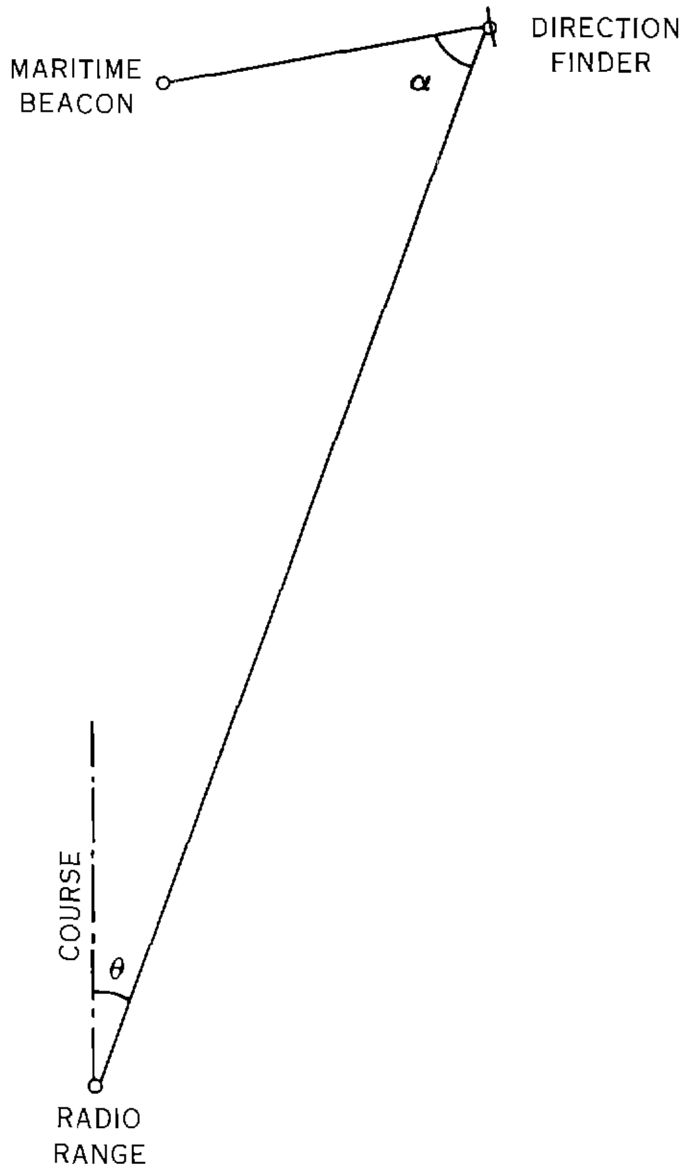

FIGURE 12. Layout of Transmitters and Direction Finder in Hypothetical Interference Case