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SHIP-SHORE RADIO DIVISION - TRANSMITTER SECTION

10 July 1946

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DIRECTIVE ANTENNA SYSTEM IN THE 6 TO 15 MC BAND FOR ESSEX CLASS AIRCRAFT CARRIERS

By Len G. Robbins and
Oscar Norgorden

- Report R-2738 -

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R. B. Meyer - Head, Transmitter Section

L. A. Gebhard, Superintendent
Ship-Shore Radio Division

Commodore H. A. Schade, Director
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DIRECTIVE ANTENNA SYSTEM IN THE 6 TO 15 MC BAND FOR ESSEX CLASS AIRCRAFT CARRIERS

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R. B. Meyer - Head, Transmitter Section

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ABSTRACT

This report describes a directive antenna system developed by the Naval Research Laboratory for use in conjunction with the Blanket system of communication in the 6 to 15 Mc band on Essex-class aircraft carriers. Radiation-pattern measurements conducted with this directive antenna installed on the starboard side of an Essex-class carrier (CV-39) have demonstrated that the proposed antenna system has the desired characteristics and fulfills the problem requirements. The radiation patterns indicate beam widths in the order of 50 to 60 degrees for ionosphere transmission and 65 to 80 degrees for free-space transmission; front-to-back field strength ratios greater than 3 to 1 are also indicated over the specified frequency range. The antenna system can be energized by standard Navy-type transmitters such as the Model TBK series, and offers no interference to topside fighting equipment.

Subsequent inspections of the aircraft carriers CV-33 and CV-15 have shown that this proposed directive antenna can be installed on both sides of this type of vessel. This fact greatly increases the usefulness of the antenna system for the intended service. Additional radiation-pattern measurements will be necessary however to determine the optimum spacing below the flight-deck level or above water for antennas in these proposed final locations, so that satisfactory radiation patterns will be assured.

For all practical purposes this directive antenna system radiates only horizontally polarized energy. This feature gives the communication circuit inherent security and anti-jam characteristics which are not possible with the usual shipboard communication antennas. In addition, this antenna has a number of other operational and electrical characteristics which are desirable for transmitting and receiving antennas, but which are lacking in most shipboard communication antennas. Therefore the antenna system described herein has definite possibilities for use as a general communication antenna in the 6 to 15 Mc band aboard ship.

The antenna system requires a balancing circuit and an impedance-matching network between the transmitter and the antenna. These circuits are incorporated into a single coupling unit, and two such units, designed for installation aboard ship, have been constructed. Each coupling unit includes a balance-indicator circuit which facilitates accurate adjustment of the system for highest operating efficiency. The system also includes an antenna-selector unit which permits switching r-f power to the desired antenna system; such a unit has also been designed and constructed.

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INTRODUCTION

1. Operational tests of the Blanket system of communication in the Naval service indicated the need for a directive antenna to operate within the frequency range of 6 to 18 Mc on several types of Naval ships. The operational requirements of this antenna are that it be excited by a regular Navy type transmitter, such as the Model TBK series, that the beam width be of the order of 120 degrees, and that the front-to-back ratio of field strength be not less than 3 to 1. Furthermore, it is required that the antenna offer no interference with topside fighting equipment.

2. Reference 1 authorized the development of such an antenna for large submarines and Essex-class aircraft carriers. In accordance with this authority, the Naval Research Laboratory has developed a directive antenna system for communications in the frequency range from 6 to 15 Mc on Essex-class aircraft carriers. Reference 2 describes a preliminary model of the proposed antenna system and shows the results of preliminary measurements. Reference 3 describes a test installation on the starboard side of the aircraft carrier CV-39 and shows representative radiation patterns obtained with this installation. The results of these measurements were satisfactory and led to an investigation of the possibilities of installing an antenna on both sides of the ship. This investigation, discussed in part in reference 4 but covered in detail herein, revealed that the proposed antenna system can be installed on both sides of the ship.

3. As indicated in References 2 and 3, the antenna is a horizontal, two-element, balanced collinear antenna, center-fed by an open, two-wire feeder line. The antenna system requires a balancing circuit and an impedance-matching network between the transmitter and the antenna in order that balanced r-f power will be delivered to the antenna. These circuits have been incorporated into a coupling unit which is relatively simple to adjust. Two coupling units, designed for installation aboard ship and which could remain a part of the ship's equipment have been constructed by the Naval Research Laboratory. Each coupling unit includes a balance-indicator for determining when the r-f voltages on the antenna-feeder lines are equal in magnitude but opposite in phase. These units thus serve to aid the operator in arriving at the correct adjustment of the antenna system. An antenna-selector unit is required at the transmitter. This unit permits switching the transmitter output to either of the two proposed directive antenna systems, to the regular non-directive antenna, or to a 50-ohm dummy antenna load; the dummy load is used in pre-tuning the transmitter before switching to one of the directive antennas.

4. This report covers the theoretical design considerations involved in the problem and points out certain inherent advantages of this antenna system over the usual shipboard communication antennas for the 6 to 15 Mc band. The desired locations of the

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antennas for a permanent installation aboard ship are pointed out, and a description of the various units required in the antenna system is given. A further discussion of the radiation-pattern measurements made aboard ship, which were previously reported in Reference 3, is also given.

5. Satisfactory locations from a physical viewpoint have been found for the installation of the proposed antenna system on both sides of the ship. However, the optimum location of the antennas from an electrical viewpoint cannot be determined by theoretical considerations alone. Further radiation-pattern measurements are necessary to determine the optimum compromise between a desirable radiation pattern in the vertical plane and an acceptable front-to-back ratio of field strength.

THEORETICAL CONSIDERATIONS

6. General. A number of types of directive antennas have been developed for operation within the frequency range of 6 to 20 Mc. The space requirements for most of these antennas however is too great for installation aboard ship. Consideration of the problem stated in Reference 1 showed that the most promising types of directive antennas for shipboard application would be a horizontal antenna with a reflecting screen, or an inverted "V" antenna. The inverted "V" antenna can be mounted on several types of Naval ships, but the required height of the apex of the "V" would probably make this antenna impractical for submarines. In most cases the antenna would have to be mounted along or near the centerline of the ship. This could offer interference to topside fighting equipment, and the ship's superstructure as well as other communication antennas would probably distort the directional radiation patterns. Furthermore, this type of antenna will radiate or receive vertically polarized energy and therefore does not possess the inherent security and anti-jam characteristics of a horizontal antenna.

7. The horizontal antenna is adaptable to Essex and Midway class aircraft carriers if the frequency range is limited to 6 to 15 Mc. The reflecting screen can be provided by arranging the antenna lengthwise along and outboard from the ship's hull. It may be possible to adapt this type of antenna to battleships and cruisers if the lower frequency limit is raised to about 12 Mc. When properly adjusted, only horizontally polarized energy is radiated, and for certain classes of military communications this feature offers several distinct advantages over the usual shipboard communication antennas for this frequency band. These advantages, some of which are discussed further in paragraphs 32 to 35, are listed below.

(a) For transmission:

(1) The inherent high attenuation of the ground wave in horizontal polarization and the use of ionosphere transmission provide security against direction finding and intercept within the skip zone, except at extremely close ranges.

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(2) By proper choice of frequencies the skip zone can be made 1000 miles and possibly up to 2000 miles wide, providing the communication range is sufficiently great.

(3) The directional characteristics of this antenna are not influenced by the ship's superstructure or by other antennas aboard ship. Thus the direction of maximum radiation is always known. This is not true for the usual shipboard communication antennas.

(4) The directional characteristics of this antenna in both the horizontal and vertical planes give it a power gain of several db over a vertical dipole in free space.

(5) Additional power gain is obtained as compared to the usual shipboard communication antennas as a result of the accurate impedance matching required in this antenna system. This gain is realized in both transmission and reception.

(b) For reception:

(1) It is impossible for an enemy located within the skip zone to jam signals received through this directive antenna because it is insensitive to vertically polarized radio waves.

(2) The power gain realized in this antenna tends to increase the signal-to-noise ratio at the receiver; thus the effective sensitivity of the receiver is increased.

(3) This increase in effective receiver sensitivity can produce a considerable increase in the communication range as compared to the usual shipboard communication antennas.

(4) Interference from any one source can be reduced by maneuvering the ship so that the antenna gain is minimum in the direction of the interfering signal.

8. As a result of these considerations, a horizontal antenna was chosen as the one having the greatest number of desirable characteristics for the intended service. A two-element, balanced collinear antenna, center-fed by an open, two-wire feeder line was selected because of the ability of this type of antenna to operate over a wide range of frequencies with no loss in efficiency. Reference 1 indicates 6 Mc to be the lower limit of the required frequency range. The maximum electrical length the antenna can have at any frequency within the required band and still produce the desired radiation pattern is $5\lambda/4$. This will be the length at the highest operating frequency. Consideration of such factors as an acceptable front-to-back ratio, radiation pattern in the horizontal and the vertical planes, radiation resistance, and range of impedances to be matched leads to the conclusion that the minimum length of the antenna should be about $\lambda/2$ at the lowest operating frequency. Such an antenna can thus be used over a 2.5 to 1 range of frequencies, or from 6 to 15 Mc. The antenna length then should be $5\lambda/4$ at 15 Mc, which is the equivalent of 82 feet (each element of the antenna would be 41 feet long)

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The outboard spacing of the antenna is governed by the radiation resistance at the lowest operating frequency (6 Mc). If this spacing is less than about $\lambda/10$ at this frequency the radiation resistance is seriously affected and the system would be difficult to adjust. The outboard spacing chosen is 15 feet which is approximately $\lambda/10$ at 6 Mc. The spacing of the antenna below the upper edge of the reflecting screen (or below the flight-deck level), must be about the same as the outboard spacing in order to obtain the desired front-to-back ratio (3 to 1). The height of the antenna above water governs the radiation pattern in the vertical plane; as this height increases, the vertical angle of radiation decreases. It is desirable that this vertical angle of radiation be as low as practicable, and should be in the order of 10 degrees for long range ionosphere transmission. The vertical height of the ship's hull from the water line to the flight deck is not sufficient to obtain the optimum pattern in the vertical plane. The optimum compromise between the height above water which will produce an acceptable vertical pattern and a distance below the flight-deck level which will produce a satisfactory front-to-back ratio can be determined approximately by calculation but must be determined finally be measurement of radiation patterns for the system installed aboard ship.

9. In order to maintain vertically polarized radiation at an absolute minimum, the currents supplied to the two elements of the antenna must be equal and must be 180 degrees out of phase; furthermore, the impedances presented by the antenna must be matched to the impedance of the transmission line from the transmitter. Thus a balancing circuit and an impedance-matching network are required between the antenna and the transmitter. A block diagram and a schematic diagram of the system are shown on Plates 1 and 2 respectively. These circuits are discussed in paragraphs 13 to 16 herein.

10. Desired Location of Antenna. In order to obtain the desired directional radiation pattern, a reflecting screen is necessary; this screen is provided by the side of the ship by installing the antenna parallel to and outboard from the hull, and somewhat below the flight-deck level. It is essential for the reflecting screen to present a vertical plane; i.e. the surface should be vertical and have little or no curvature. Furthermore, the reflecting screen should be relatively free from large, protruding obstructions. These factors play an important part in reducing vertically polarized radiation to an absolute minimum. In the test installation on the carrier CV-39 (see Plate 3) the island superstructure formed a part of the reflecting screen; thus it was possible to locate the antenna only 10 feet below the flight-deck level or 43 feet above the water and still have adequate reflecting surface to keep the back radiation within the problem requirements (front-to-back ratio at least 3 to 1). In the proposed final installations (see Plates 4 and 5), the island superstructure cannot be used as part of the reflecting screen; therefore the antenna must be mounted farther below the flight-deck level or closer to the water in order to provide the necessary height of screening surface. Normally the flight deck is 50 to

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55 feet above water. It can be shown that in order to maintain a vertical angle of maximum radiation in the order of 30 to 40 degrees over the frequency range of 6 to 15 Mc, the height of the antenna above water should not be less than 35 feet; this makes 20 feet the maximum spacing for the antenna below the flight-deck level. In addition, the antenna must not interfere with gun fire or any normal activities aboard ship. These various factors severely limit the number of suitable locations. The proposed locations discussed herein will require the use of a 50-ohm coaxial transmission line, 300 to 350 feet in length, between the transmitter and each antenna location.

11. <u>Antenna Impedance</u>. The outboard spacing of the antenna requires the use of an open, two-wire transmission line between the coupling unit and the feed point of the antenna. The antenna impedance at the feed point can be determined with the aid of available antenna-impedance charts.* These impedance charts are for antennas in free space, whereas the subject antenna has a reflecting screen; the addition of this reflecting screen, however, at the spacing used would not introduce an appreciable error in the calculations. The antenna impedance as it appears at the input end of the two-wire transmission, or feeder, line can be computed from the known values of antenna impedance, and the length and impedance of the feeder line. These calculations provide the data necessary for the design of the balancing and impedance-matching circuits. The calculations are based upon the following design factors:

(a) Antenna length - 82 feet (two elements 41 feet each)

(b) Feeder line length - 17.5 feet (includes lead-in connections)

(c) Feeder line impedance - 466 ohms

(d) Antenna cable size - 5/16-inch diameter (stranded)

The results of these calculations are tabulated in Table 1, and are shown graphically on Plates 6 and 7.

12. Consideration was given to the most practicable spacing for the two-wire feeder line. The sapcing chosen is 7-3/4 inches, for which standard, ceramic spacer insulators are commercially available. This spacing, with 5/16-inch cable, gives a surge impedance of 466 ohms. This impedance serves to transform the impedances at the feed point of the antenna to another range of values appearing at the input end of the feeder line; these impedances are of an order of magnitude such that they can be matched to the 50-ohm coaxial transmission line by the impedance-matching and balancing circuits. Plate 7 indicates a range of resistance from 35 to 2800 ohms and a range of reactance from plus 360 ohms to minus 640 ohms. The impedance ($R \pm JX$) over the frequency

* Harvard University "Notes on Antennas", Charts 7 and 8

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range varies from a minimum of 35 + J0 which occurs at 12.65 Mc, to a maximum of 2800 - J480, which occurs at 7.5 Mc. The impedance-matching network and the balancing circuit must be designed so as to match this range of impedances to the 50-ohm line from the transmitter.

13. <u>Balancing and Impedance-Matching System</u>. In this or any similar antenna system it is necessary to match the feeder-line input impedance to the transmission line impedance. From an electrical viewpoint the desirable arrangement would be to balance the system at the transmitter and match the impedances at the antenna. From an operational standpoint the desirable arrangement would be to perform both operations at the transmitter. Neither of these arrangements is practical, the former being difficult to adjust, while the latter results in a poor standing wave ratio on the transmission line, and in impedances which would be difficult to match. The most practical system investigated was to both balance the system and match impedances at the input end of the antenna-feeder line or as close as possible to the antenna. This arrangement also has the advantage of requiring but one coaxial transmission line.

14. The first consideration in the design of the balancing and impedance-matching circuits is that there are four conditions to be satisfied in order to present a 50-ohm load to the transmission line and provide a balanced input to the antenna. These conditions are as follows:

(a) The resistance presented to the transmission line must be 50 ohms.

(b) The reactance presented to the transmission line must be zero ohms.

(c) The feeder-line currents must be equal.

(d) The feeder-line currents must be 180 degrees out of phase.

In order to satisfy these four conditions it is necessary to provide a minimum of four variables in the balancing and impedance-matching circuits. From an operational viewpoint the first consideration in these circuits is simplicity and ease in tuning and adjustment. This requires that there be a minimum of interaction between the circuits. Theoretical considerations which were verified by actual operation of the antenna system have indicated that the circuits shown on Plate 2, Fig. 1 have the desired characteristics. No other arrangements were found during the investigation which had less interaction between the balancing and the impedance-matching circuits. It will be observed in this diagram that the circuits contain nine variable elements. However, in operation the balancing capacitors C_1 and C_2 are locked in one position and the capacitors of the pi-network are ganged in pairs. Thus four controls are eliminated during the process of tuning the system. It has been found experimentally that the inductances follow a definite curve over the frequency range and

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therefore they can be calibrated. The pi-network capacitors do not follow a curve, but observation of the meters provided in the system make proper adjustment of these capacitors unmistakable. Thus the adjustment of the system is made relatively simple and straight-forward by means of five controls.

15. Balancing Circuit. An analysis of this circuit is given in Appendix 1 herein. Briefly, the circuit serves to balance the output from the transmitter and thereby provides a balanced input to the impedance-matching pi-network. The balancing circuit also transforms the 50-ohm impedance of the transmission line to a higher impedance (about 200 ohms over the frequency range of 6 to 15 Mc.) and thus reduces the overall range of impedance which the pi-network must cover in order to properly match the feeder-line input and transmission-line impedances. It is shown in Appendix 1 that if the resistance of inductance L_1 is zero, then capacitors C_1 and C_2 will be equal. However, since the resistance of L_1 is not zero, the capacitive reactance of C_1 and C_2 must differ slightly in order to obtain a balanced output voltage from the circuit. The primary consideration in selecting the capacity of C_1 is that the capacitive reactance should be sufficiently high so that the capacitive reactance of C_2 will remain essentially constant over the required frequency range. Under these conditions capacitors C_1 and C_2 could be fixed values and the output voltage from the circuit would be approximately balanced. Slight corrections for any unbalance can be made by means of the inductances in the impedance-matching pi-network. Another factor to be considered in the choice of the capacity of C_1 is the output impedance of the balancing circuit. This impedance should be primarily resistive in order to simplify matching to the feeder-line input impedance by the pi-network. The numerical values of C_1, C_2, and L_1 have been computed from the design formulas at the end of Appendix 1 and are shown in Table 4. The resistance values R_1 for inductance L_1 were obtained by measurement. Approximate values for design computations can be obtained by assuming a reasonable value of "Q" for L_1. The data in Table 4 reveal the following points:

(a) The capacity of C_1 was assumed to be 53 mmf for the design of the circuit.

(b) The capacity of C_2 then varies from 46.5 mmf at 6 Mc to 48.7 mmf at 15 Mc. This represents a change of only 4.5 per cent over the frequency range.

(c) The range of inductance of L_1 is reasonable from a standpoint of coil design.

(d) The resistive component (R_a) of the balanced output impedance is about 200 ohms over the frequency range.

(e) The reactive component (X_a) of the balanced output impedance is small compared to the resistive component.

Thus the capacity of C_2 varies only a few per cent over the fre-

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quency range of 6 to 15 Mc and therefore it may be possible to use a fixed capacitor of approximately 47 mmf for C_2. It has been proven experimentally that the balancing circuit and the impedance-matching network are capable of matching the feeder-line input impedance to the 50-ohm transmission line over the frequency range when capacitors C_1 and C_2 are 53 and 47 mmf respectively.

16. <u>Impedance-Matching Network</u>. This circuit is shown on Plate 2, Figure 1. The pi-network type of impedance-matching circuit was selected because of its ability to match a wide range of impedances. The circuit consists of a balanced pi-network. As shown on the diagram, one network consists of capacitors C_3 and C_5 and inductance L_2, while the other consists of capacitors C_4 and C_6 and inductance L_3. Corresponding elements of each network are identical so as to provide a symmetrical system. Each side of the balanced pi-network is designed to match one-half of the feeder-line input impedance to one-half of the balancing-circuit output impedance.

17. <u>Beam Width of Radiation Patterns</u>. The beam width of the directional radiation patterns measured at a constant colatitude angle (see Plates 13 to 23) is primarily a function of the length of the antenna. The outboard spacing of the antenna and its height above water also affect the beam width, but these effects are only secondary. Radiation patterns were determined by calculation for three frequencies which were assigned by the Bureau of Ships as test frequencies for this project. From these patterns the theoretical beam widths were determined. These calculations were based upon the physical dimensions and spacing of the antenna in the shipboard test installation (see paragraph 19). Certain approximations were made, however, which affect the accuracy of these results to some extent. The results of these calculations are shown graphically on Plate 8; these patterns correspond to the vertical angles of maximum radiation indicated in paragraph 18. It can be shown that decreasing the length of the antenna tends to increase the beam width; increasing the outboard spacing, or decreasing the height of the antenna above water, or a combination of both tend to increase the beam slightly. These factors primarily govern the front-to-back ratio and the angle of maximum radiation in the vertical plane. Plate 8 shows half-power beam widths for 6275 kc, 9000 kc, and 14280 kc of 80, 72 and 65 degrees respectively, or an average of 72 degrees. This average beam width compares favorably with the 78 degrees which was obtained by actual measurement as discussed in paragraph 31 herein.

18. <u>Vertical Angle of Maximum Radiation</u>. The angle of maximum radiation in the vertical plane was determined by calculation for the shipboard test installation; the results are shown graphically on Plate 9. These calculations are based upon the reasonable assumption that the hull of the ship acts as an infinite reflecting screen; thus the curves on Plate 9, although only approximate, are sufficiently accurate for determining the general design of the antenna. It can be shown theoretically that

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the effect of the finite screen is to slightly increase the vertical angle of maximum radiation. Plate 9 shows vertical angles of radiation for 6275 kc, 9000 kc, and 14280 kc of 40, 35, and 25 degrees respectively. The results of actual measurement of these angles are discussed in paragraph 34.

INSTALLATION OF ANTENNAS

19. Test Installation Aboard Aircraft Carrier CV-39. This antenna installation is illustrated on Plate 3. A model TBK-17 transmitter located in Radio II was used to energize the antenna system. The output of the transmitter was first fed into a balancing circuit which was contained in a unit mounted on top of the transmitter. From this unit the r-f energy was fed into an impedance-matching unit, located in the Model SK-2 Radar room, by means of a pair of RG-18/U coaxial transmission lines. These lines were laid in existing wireways in the ship; actually 306 feet of this double line was required between the balancing and the impedance-matching units. In addition, a telephone line was installed to provide communication between the units to aid in tuning up the system. This coupling arrangement requiring two transmission lines, was used merely as an expedient in making the radiation-pattern measurements and did not represent a permanent part of the antenna system. Subsequently the coupling unit described in paragraph 23 has been designed, incorporating the balancing and the impedance-matching network into a single unit and requiring but one coaxial transmission line. The impedance-matching unit was mounted on a bench as near as possible to the bulkhead so that the connecting leads to the antenna-feeder lines were kept short. The location of the impedance-matching unit and the level of the antenna (10 feet below the flight deck) resulted in the antenna feeders assuming an angle of about 20 degrees with the horizontal. This is not a desirable condition but would be necessary in some installations. The feeder lines were brought through the ship's hull by means of standard bulkhead insulators and were held parallel throughout their length by ceramic spacer insulators. The antenna and the feeders were made of 5/16-inch standard antenna cable. Each of the two elements of the antenna was 41 feet long, and the total length of each feeder line was 17.5 feet. The antenna was suspended between a pair of strain insulators secured to the outboard ends of two outriggers. These outriggers were made of 3-inch pipe and were 15 feet in length. They were hinged at the point of attachment to the ship's hull so that the antenna could be hoisted up out of the way when not in use. The outriggers were guyed so as to hold the antenna taut in approximately a horizontal line; the sag at the center of the antenna was about 18 inches. These general features of construction were considered to represent reasonably well a final installation; therefore these details are shown on Plates 4 and 5.

20. Proposed Final Installation of Antennas. The most desirable locations for the directive antennas on both sides of the ship have been determined from an inspection of two other Essex-class aircraft carriers (CV-33 and CV-15). The proposed

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final installations are illustrated on Plates 4 and 5. It is suggested that these locations be used if possible for any future shipboard installations of the directive antennas. Antennas in these locations could be energized by a transmitter in Radio III and both would require about 300 to 350 feet of 50-ohm coaxial transmission line. The antenna installations are described as follows:

(a) Starboard Side: Location is limited to the space between Frames No. 110 and 140; this distance includes 82 feet for the antenna and 38 feet for guy lines and strain insulators. The center, or feed point, of the antenna should be at Frame No. 125 or 126. The coupling unit could then possibly be installed in the bomb-sight workshop and storage compartment on the gallery-deck level. In order to have adequate reflecting surface behind it, the antenna would have to be about 14 feet below the flight-deck level. The outboard spacing would be 15 feet. The ship's hull in this area is vertical and straight. In either direction from this space, outboard gun sponsons and other irregularities in the reflecting surface make any other location undesirable.

(b) Port Side: Location is limited to the space between Frames No. 138 and 173; this distance includes 82 feet for the antenna, and 58 feet for guy lines and strain insulators. Due to the overhand on this side, the antenna would have to be about 16 feet below the flight-deck level. The outboard spacing should be at least 15 feet, but could be 18 feet if irregularities in the reflecting screen make greater spacing necessary. Curvature in the ship's hull astern, and extreme irregularities forward of this space make any other location undesirable. It will be observed on Plate 5 that the supporting cable for the small-boat boom attached to the hull at Frame No. 159 would interfere with the antenna. In order to eliminate this interference it is suggested that, (1) the point of attachment of the supporting cable be lowered about 7 feet and the size of the cable be increased to overcome the increased strain thus caused; or (2) the point of attachment of the supporting cable and the pivot point of the boom both be lowered about 7 feet and a ladder be attached to the hull from the inboard end of the boom to the roller curtain as indicated by dotted lines on Plate 5. The coupling unit for this antenna could be installed in the unoccupied space over the entryway into the light labyrinth at about the forcastle-deck level at Frame No. 156.

21. Antennas installed in the above proposed locations will not interfere with topside fighting equipment or with gunfire from any outboard gun emplacements. Interference with any activities aboard ship would be kept at a minimum. The block and tackle proposed for lowering and hoisting the antenna outriggers and for maintaining tension on the antennas can be operated from existing walkways.

22. Summary of Important Factors in the Design and Location of Antennas. The various pertinent factors covered in the foregoing discussion, and which must be adhered to in any future

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shipboard installation in order to realize satisfactory operation of the antenna system, are summarized as follows:

(a) Each of the two elements of the antenna must be 41 feet long (equivalent electrical length = $5\lambda/8$ at 15 Mc.).

(b) The outboard spacing of the antenna must be at least 15 feet, but can be as much as 18 feet if irregularities in the ship's structure make greater spacing necessary; this spacing corresponds to an electrical length of approximately $\lambda/10$ at 6 Mc. The antenna must be paralled to the reflecting screen and must be horizontal.

(c) The antenna on the starboard side should be located about 14 feet below the flight-deck level between Frames No. 110 and 140 with the feed point at about Frame No. 125; the port side antenna should be located about 16 feet below the flight-deck level between frames No. 138 and 173 with the feed point at Frame No. 156. In no case should the antenna be less than 35 feet above the water level.

(d) The coupling unit should be located opposite the center or feed point of the antenna so that the antenna feeder lines will be perpendicular to the antenna and will be as nearly horizontal as possible.

(e) The coupling unit should be located within 1 foot of the bulkhead so that the connecting leads to the feeder lines will be kept short (in the order of 6 to 8 inches in length).

(f) The antenna and the feeder lines should be made of 5/16-inch standard antenna cable.

(g) The feeder lines should be spaced approximately 7-3/4 inches apart by means of ceramic spacer insulators secured to the line at 3-foot intervals along the line. This spacing and line size gives a surge impedance of 466 ohms.

(h) The antenna must be suspended between strain insulators attached to the outboard ends of a pair of outriggers; these outriggers must be at least 15 feet in length and must be properly guyed so as to maintain the antenna taut in approximately a horizontal line; an 18-inch sag at the center can be tolerated.

(i) The outriggers should be hinged at the point of attachment to the ship's hull so that the antenna can be hoisted up out of the way when docking or for maintenance.

(j) The supporting cable for the small-boat boom at Frame No. 159 on the port side will interfere with the antenna in the proposed location. Either of the following suggested modifications for the small-boat boom would eliminate this interference: (1) lower the point of attachment of the supporting cable by 7 feet and increase the cable size to overcome the resulting increase in strain; or (2) lower both the point of attachment of

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the cable and the pivot point of the boom by 7 feet and add a short ladder between the inboard end of the boom and the roller curtain (see Plate 5).

(k) Type RG-18/U coaxial transmission line should be used between the coupling units and the transmitter. This cable can, in general, be laid in existing wireways.

(l) A transmitter in Radio III should be used to energize the antenna systems since this radio room is the nearest to both of the proposed antenna locations.

(m) A means of telephone communication should be available between the transmitter and each coupling unit to aid the radio operators when adjusting the system.

OTHER MAJOR UNITS OF THE ANTENNA SYSTEM

23. Type RA-471375 Collinear Antenna Coupling Unit. The balancing circuit and the impedance-matching networks are incorporated into a single unit which has been assigned the above designation. The overall dimensions and the weight of this unit are as follows:

Height	32-1/2 inches
Width	22 inches
Depth	18-1/2 inches
Weight	100 pounds

The schematic diagram of this unit is shown on Plate 2, Figure 1, and the construction is illustrated on Plates 32, 33 and 34. The r-f ammeter M_1 indicates the input current to the unit, while r-f ammeters M_2 and M_3 indicate the current in each feeder line. Meter M_4 is a balance indicator which is described in the following paragraph. At the time the unit is calibrated the balancing capacitors are set to the proper capacity and locked (see paragraph 15); their dials are provided with a cover to prevent accidental manipulation of these controls which would nullify the calibration of all the other controls in the unit. All controls are adjustable from the front panel. Two pairs of output terminals are provided on the unit for ease in making connections to the feeder-line terminals, depending on the manner of mounting the unit on a bench or directly on the deck. This coupling unit has been designed and constructed so as to withstand the rigors of the Naval service and thus could remain a part of the ship's equipment when once installed aboard ship.

24. Balance Indicator. A circuit is included as part of the coupling units for indicating when the r-f voltages on the antenna-feeder lines are equal and are opposite in phase relationship. This circuit is described in Appendix 2 herein. Any r-f current flowing through this circuit as a result of a voltage unbalance between the feeder lines is rectified by a crystal detector and indicated by a microammeter. The circuit is sufficiently sensitive to show an unbalance in the feeder-line voltage

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as low as 6 volts. Over most of the frequency range the r-f voltage on the feeder lines for full power operation is in the order of 300 to 400 volts; the lowest line voltage encountered is about 100 volts. Thus the voltage (or current) balance on the feeder lines can be adjusted to within 2 to 6 per cent by observing the indication on the microammeter.

25. Type RA-23538 Antenna Selector Unit. A unit is provided by means of which the transmitter output can be switched to any one of three antenna systems or to a 50-ohm dummy-antenna load. This unit is intended to be mounted directly on top of the transmitter used with the antenna system. The schematic diagram of this unit is shown on Plate 2, Figure 2 and photographs are shown on Plates 37 and 38; other details are discussed in Appendix 3. The overall dimensions and the weight of this unit are as follows:

Height	9-3/4 inches
Width	16 inches
Depth	16-1/4 inches
Weight	28 pounds

The purpose of the 50-ohm dummy antenna load is to aid in tuning the directive antenna systems. By switching to this non-radiating load, the transmitter can be pre-tuned to approximately the correct dial settings to feed into the 50-ohm coaxial transmission lines before switching to one of the directive antenna systems. Almost all tuning can then be done at the coupling unit; only a slight trimming of the transmitter output controls should be necessary during the remainder of the tuning process.

TUNING OF ANTENNA SYSTEM

26. In its present design the system requires two operators for tuning to a desired frequency. For this reason it is necessary that telephonic communication be available between the transmitter and each of the coupling units. When the system has once been calibrated for several operating frequencies, operators who are familiar with the system can shift frequencies in approximately the same time normally allowed for shifting frequencies on a transmitter. A somewhat longer time, possibly 5 minutes, might be required for shifting to an uncalibrated frequency. The principal points to be born in mind in the adjustment of the coupling unit are that the antenna feeder-line currents should be equal and the balance indicator should read zero; this indicates that the currents in the two elements of the antenna are balanced and are 180 degrees out of phase. The transmitter output current should be about 3.1 amperes and the input current to the coupling unit should be about 2.9 amperes. This allows for about 0.6 db loss of power in the coaxial transmission line (assuming the line to be about 300 feet in length), and indicates proper impedance matching between the transmitter output circuit and the 50-ohm impedance presented by the coupling unit when correctly adjusted. The antenna system is then properly balanced and matched and should operate at maximum efficiency. The actual tuning procedure required for the system is fully described in

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Appendix 4.

METHOD OF MEASUREMENT

27. Calibration of Antenna System. When the shipboard test installation (see paragraph 19) had been completed, the transmitter, the balancing unit, and the impedance-matching unit were carefully calibrated for three test frequencies, namely, 6275 kc, 9000 kc, and 14280 kc. Adjustments were made until the unbalance voltage between the antenna-feeder lines, as indicated by a vacuum-tube voltmeter, was the lowest obtainable for that system; the greatest unbalance for any one of the three frequencies was 30 volts or about 7.5 percent. No attempt was made at the time to measure the actual r-f power in the antenna. The transmitter was operated at normal, full-power output (about 500 watts) during all of the tests and the only appreciable losses in the system would be in the balancing unit and in the transmission lines. The power loss in the two 306-foot lengths of Type RG-18/U coaxial transmission line would be approximately 0.6 db, or about 70 watts. The loss in the balancing unit was assumed to be in the order of 100 watts. Thus the power delivered to the antenna would be in the order of 300 watts.

28. Radiation-Pattern Measurements. Radiated energy from the directive antenna installed aboard ship was measured at several different receiving points in order to determine whether or not the antenna characteristics would fulfill the problem requirements. Measurements were made on, (1) a Naval blimp (K-92) which maneuvered in the vicinity of the carrier CV-39 while at sea, (2) at several distant shore receiving stations, and (3) at a local shore receiving station. The desired measurements to be made governed the operations of the carrier, and two distinct maneuvers were required. These operations were as follows:

(a) The ship turned a tight circle while the blimp hovered at some distance at low altitude to obtain the low-elevation pattern measurements. During this operation the distant receiving stations, in accordance with a prearranged schedule, were informed of the start of the test on a particular frequency and were warned to be on standby for the pattern measurements. This operation was carried out once for each test frequency.

(b) The ship maintained constant heading for several minutes for each successive 30 degrees of ship's heading so as to form 12 chords on a 5-mile diameter circle. Each 30 degrees of ship's heading was designated by a code letter (A = 0°, B = 30°, C = 60°, etc. as shown on Plates 13 to 31) and this code letter was transmitted to the various remote receiving stations so that readings of signal strength versus relative bearing could be made and thus obtain the desired radiation patterns. This operation was repeated three times for each test frequency so that the receiving stations could obtain an average radiation pattern for each frequency. During this operation the blimp circled the ship several times, maintaining constant altitude and range for each circle.

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and measured field intensity versus relative bearings at various colatitude angles from 87 to 45 degrees (or vertical angles from 3 to 45 degrees). Data as to range, elevation, and bearing of the blimp relative to the ship were transmitted to the blimp. At times navigational factors made accurate coordination in timing of readings of relative bearings and field strength difficult and introduced too great an error in the pattern data. At such times the field strength data were taken versus relative bearings estimated by personnel aboard the blimp by sighting on the centerline and crosslines on the flight deck of the ship.

29. These operations were carried out on 18-19 June 1945. The ship's position was approximately Latitude 36° 46' North and Longitude 74° 37' West. A log was kept on the ship of heading and position versus time, while at the local and remote receiving stations a log was kept of time and bearing code-letter versus field strength. Personnel aboard the blimp recorded relative bearings versus field strength and data on range and altitude. A Navy Model OF Field Strength and Noise meter was used for measurements of field intensity. The measurements at the local shore receiving station were made by means of equipment (RCA Model 308-A Field Intensity Meter and Navy Model OF Field Strength and Noise Meter) installed in a truck located in the vicinity of Weeksville, and Currituck, N. C. (about 60 miles from the ship). The distant receiving stations used Navy Model RBG or RBP receiving equipment with suitable antenna arrays. These stations, with their approximate distance from the ship in nautical miles are as follows: Washington, D. C. - 160 miles; Riverhead, Long Island - 300 miles; Great Lakes, Ill. - 600 miles; San Juan, Puerto Rico - 1200 miles; Point Gourde, Trinidad, B.W.I. - 1700 miles.

30. Polarization and Field Strength Measurements. Due to the effects of the blimp gondola it was found to be impractical under conditions of flight aboard the blimp to make independent measurements of the horizontally and vertically polarized radiation from the directive antenna. At the local shore receiving station the signal strength was measured at frequencies of 6275 kc and 9000 kc. The ratio of the intensity of the horizontally and vertically polarized signals could not be accurately determined, but the measurements indicated that very low intensity signals of both polarizations were present. These measurements are discussed in paragraph 36.

RESULTS OF MEASUREMENTS

31. Beam Width of Radiation Patterns. The radiation patterns shown on Plates 13 to 23 inclusive (measured on the Naval blimp) indicate half-power beam widths of 34 to 127 degrees (see Table 2). The average for the three frequencies is 78 degrees. This compares with an average of 72 degrees obtained by calculation (see paragraph 17). These measurements were subject to considerable error because of difficulties encountered in coordination and timing of readings of signal strength with respect to relative bearings. Such errors are especially evident in Plates

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13, 15, and 17 wherein the beam maximums, instead of being 90 degrees relative to the ship's heading, are distorted by as much as 30 degrees. The radiation patterns shown on Plates 24 to 31 inclusive (measured at the remote receiving stations) indicate half-power beam widths of 36 to 80 degrees, with an average of 52 degrees for the three frequencies used (see Table 3). In general, the results of the calculations and the actual measurements for the shipboard test installation are in reasonable agreement and show the general beam width to be in the order of 65 to 80 degrees for free-space transmission, and in the order of 50 to 60 degrees for ionosphere transmission. The conclusion may therefore be drawn that the beam-width requirements of the problem were fulfilled by the shipboard installation.

32. A point which deserves special attention here is the fact that in all of the radiation patterns measured, except those shown on Plates 13, 15, and 17 which are assumed to be in error, the beam maximum is consistently 90 degrees relative to the ship's heading. There is some slight distortion of the pattern in some cases but not beyond reasonable experimental error. Thus it can be concluded that with this directive antenna system the direction of maximum radiation is always known and can easily be controlled by merely maneuvering the ship. In many cases with the usual shipboard communication antennas for this frequency band, the radiation patterns are badly distorted by the ship's superstructure and by other adjacent antennas. The proposed directive antenna is therefore much superior to the usual antennas in this respect.

33. <u>Front-to-Back Ratios</u>. The front-to-back field strength ratios of the radiation patterns measured for the shipboard installation are tabulated in Tables 2 and 3. The minimum ratios obtained for the patterns measured on the Naval blimp and at the distant receiving stations are 3.6 to 1 and 10 to 1 respectively (see Plates 16, 24, and 28). These are voltage ratios and correspond to 11 db and 20 db respectively. Ratios as high as 100 to 1 or 40 db also are indicated (see Plate 31.) For this particular test installation therefore, the front-to-back ratios are well within the problem requirements. It is of interest to note that the front-to-back ratios for this antenna are comparable to that obtained with flat screen reflectors in the VHF band. It is emphasized here, however, that in this test installation the island superstructure served as part of the reflecting screen (see Plate 3). Because of this additional height of reflecting screen the antenna was located only 10 feet below the flight-deck level or about 43 feet above the water. This additional height of reflecting screen was favorable for reduction of back radiation and the additional height above water favored reduction of the vertical angle of radiation. In the proposed final locations for the antennas (see Plates 4 and 5), the island superstructure cannot be utilized as part of the reflecting screen, and thus the antennas must be farther down on the ship's side in order to obtain adequate screening surface. Actual pattern measurements will be necessary to determine the position of the antennas which will produce optimum radiation patterns in the

horizontal and vertical planes.

34. Vertical Angle of Maximum Radiation. Plates 10, 11, and 12 show the results of an attempt to determine the angles of maximum radiation in the vertical plane by measurement on the Naval blimp. Lack of time for these test operations and altitude limitations due to the pressure ceiling of the blimp prevented obtaining complete data for this test; as a result, these patterns are partially estimated. The extrapolations of these patterns indicate vertical angles of maximum radiation in the order of 30 to 45 degrees for the three test frequencies. This compares with 25 to 40 degrees obtained by calculation and thus the measurements support the theory discussed in Paragraph 18. The fact that excellent signals were received at the distant receiving stations can be used as evidence that the vertical angle of radiation was satisfactory for the intended service.

35. The rapid decrease in signal strength at the low vertical angles show that the ground wave would be extremely weak at any appreciable distance (50 miles or more) from the antenna or anywhere in the skip zone. This was demonstrated by the measurements discussed in the following paragraph and also by the fact that the distant receiving stations (Washington, D. C., Riverhead, L. I., and Great Lakes, Ill.), which were definitely in the skip zone for 14280 kc., could detect no signal at this frequency.

36. Field Strength of Vertically Polarized Radiation. The measurements of field strength made at the local shore receiving station at 6275 and 9000 kc showed signal strengths from about 1 microvolt per meter to a maximum of 10 microvolts per meter. Such signals are ordinarily just detectable. No signal was received at 14280 kc. The low intensity signal was fairly steady but the stronger signal showed a definite tendency to fade and thus could be attributed to ionosphere transmission. Accurate measurements of the ratio of intensity of the horizontally and vertically polarized signals could not be made, but the measurements did indicate that signals of both polarizations were present. It can be concluded from the data obtained that the ground wave was of very low intensity and that the field strength in any direction due to vertically polarized radiation from the directive antenna would be less than the field strength produced by a quarter-wave vertically polarized antenna with a radiated power of 0.1 watt and possibly with a radiated power as low as 0.001 watt. The rated power output of a Model TBK transmitter is 500 watts. It can be reasonably assumed that 400 watts are actually radiated from the directive antenna; then the ratio of the horizontally to vertically polarized radiation would be in the order of 4000-to-1, and possibly as high as 400,000-to-1. Thus the vertically polarized signal would be about 36 to 53 db down from the desired horizontally polarized signal.

CONCLUSIONS

37. The results of the radiation-pattern measurements made for the shipboard test installation show that all of the requirements specified in Reference 1 can be fulfilled by the antenna

system proposed herein for use on Essex-class aircraft carriers. The specified beam width is 120 degrees; the average half-power beam width measured over the frequency range for free space transmission was in the order of 65 to 80 degrees, while for ionosphere transmission the average beam width was in the order of 50 to 60 degrees. The specified front-to-back ratio is 3-to-1; the minimum front-to-back voltage ratio obtained for free-space transmission was 3.6-to-1, while the minimum ratio for ionosphere transmission was 10-to-1.

38. The problem specifies that the antenna be energized by a Navy Transmitter of the Model TBK series. Throughout the development and test of this antenna system, Model XTBK and Models TBK-12 and TBK-17 transmitters have been used as the source of excitation. No trouble has been encountered which could be attributed to failure of these transmitters to properly feed the antenna system. Although actual tests have not been conducted using Model TCK and TBL transmitters as the excitation source, available data make it reasonable to conclude that these transmitters also could be employed satisfactorily with this antenna system.

39. The antenna in the proposed locations will not interfere with topside fighting equipment or with gun fire from any outboard gun emplacements. This is also specified in Reference 1.

40. In order that the antenna will have the desired characteristics, certain fundamental factors with respect to design and location, as summarized in paragraph 22, must be adhered to in any future shipboard installations. The antenna system must also be carefully tuned and adjusted by the operators so that the power in the antenna will be balanced, thereby maintaining undesired vertically polarized radiation at an absolute minimum. Measurements indicate that the ratio of horizontally to vertically polarized radiation can be in the order of 4000-to-1 and possibly as high as 400,000-to-1 for this antenna system.

41. The beam width of the radiation patterns for this antenna does not change greatly with frequency. Furthermore, the directional characteristics are not influenced by other antennas aboard ship and the direction of maximum radiation is always known. This is not true for the usual shipboard communication antennas for the 6 to 15 Mc band; these antennas often have badly distorted patterns due to effects of other adjacent antennas and the ship's superstructure.

42. The inherent high attenuation of the ground wave for horizontal polarization and the use of ionosphere transmission provide security against direction finding and intercept within the skip zone except at extremely close range. By proper choice of frequencies the skip zone can be made 1000 miles and possibly up to 2000 miles wide providing the communication range is sufficiently great.

43. The directional characteristics of this antenna in

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both the horizontal and vertical planes give it a power gain of several db over a vertical dipole in free space. Additional power gain is obtained in this antenna as compared to the usual shipboard communication antennas as a result of the accurate impedance matching required in this antenna system. This gain is realized in both transmission and reception.

44. It would be impossible for an enemy located within the skip zone to jam signals received through this antenna system, because this antenna is insensitive to vertically polarized radiation.

45. The power gain realized in this antenna increases the signal-to-noise at the receiver and thus increases the effective sensitivity of the receiver. This results in a greater communication range for the system.

46. The various desirable characteristics inherent in this directive antenna system make it superior in many respects to the usual types of shipboard antennas used for communication in the frequency range of 6 to 18 Mc. Therefore this antenna has definite possibilities for use as a general communication antenna on Essex and Midway class aircraft carriers.

RECOMMENDATIONS

47. Further radiation-pattern measurements will be necessary in order to determine the optimum compromise between a satisfactory pattern in the vertical plane and an acceptable front-to-back ratio for the proposed final antenna installations. Therefore it is recommended:

(a) That the Bureau of Ships make the necessary arrangements in order that an Essex-class aircraft carrier can be made available for further radiation-pattern measurements on this directive antenna system.

(b) That the various fundamental factors in regard to design and location of the antenna as listed in paragraph 22 herein be closely adhered to in any future shipboard installations.

(c) That if this directive antenna is to be used as a general communication antenna, then additional development work should be done on the Type RA-471375 Collinear Antenna Coupling Unit to improve the ease and rapidity with which it can be adjusted for operation on any frequency in the 6 to 15 Mc band.

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4. NRL ltr C-S67-66(380-LGR), Serial No. C-380-552/45 of 26 October 1945 to BuShips: Third Intemim Report on Problem No. S1058R-C.

Original data recorded in NRL Log Book No. 5483.

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ANALYSIS OF BALANCING CIRCUIT

1. The function of this circuit is to convert the unbalanced output from the transmitter or transmission line to balanced output; this is the most important fundamental requirement for the proper operation of this antenna system. It is absolutely essential that the currents in the two elements of the collinear antenna be accurately balanced in both phase and magnitude. A schematic diagram of the balancing circuit is shown on Plate 39. This circuit consists of three elements, namely, capacitors C_1 and C_2, and inductor L_1. R_1 is the resistance of inductor L_1. The unbalanced output from the transmitter (or transmission line) is applied to the input of the balancing circuit. The input impedance of the balancing circuit is designated as Z_t. The output impedance (Z_a) is balanced with respect to ground. The resistance R_1 varies with frequency and with the inductance of L_1.

2. The two conditions to be satisfied by this circuit are that the output voltage between one side and ground be equal in magnitude and opposite in phase to the output voltage between the other side and ground. Thus there are only two conditions to be satisfied by three variables which leaves free choice of any desired fixed value for one of the three variables. The desired result can be expressed by two equations. One equation expresses one of the variables, say X_1, in terms of the quantities R_t, X_t, R_1 and X_2, while the other expresses X_3 in terms of these same quantities. The quantities X_1, X_2 and X_3 represent the reactance of inductance L_1 and capacitors C_1 and C_2 respectively. The resistance of inductor L_1, although small, is of sufficient importance in obtaining an accurately balanced system that it cannot be neglected in this analysis. The final results of this analysis are obtained by a method of approximation since it is not practical to solve the equations directly. However, the results are sufficiently accurate for this practical application.

3. The following equations are obtained from the fundamental laws of electrical circuits (see Plate 39):

$$i_1 = i_2 + i_3 \quad (1)$$

$$E_{ac} = E_{abc} \quad (2)$$

$$Z_t = R_t + jX_t = E_{ag}/i_1 \quad (3)$$

$$E_{ag} = -jX_2\, i_2 + (R_1 + jX_1)\, i_1 \quad (4)$$

$$E_{bg} = -jX_3\, i_3 + (R_1 + jX_1)\, i_1 \quad (5)$$

$$E_{ac} = -jX_2\, i_2 \quad (6)$$

$$E_{abc} = \left[R_a + j(X_a - X_3)\right] i_3 \quad (7)$$

where, $$X_1 = \omega L_1 \quad (8)$$

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$$X_2 = 1/\omega C_1 \tag{9}$$

$$X_3 = 1/\omega C_2 \tag{10}$$

$$\omega = 2\pi f \tag{11}$$

f = frequency in cps

4. The output voltage from the balancing circuit must be balanced to ground, therefore:

$$E_{ag} = -E_{bg} \tag{12}$$

When equations (4) and (5) are substituted in equation (12) one obtains

$$jX_2\, i_2/i_1 + jX_3\, i_3/i_1 = 2(R_1 + jX_1) \tag{13}$$

5. From equations (1), (2), (7), and (8) one obtains

$$\frac{i_3}{i_1} = \frac{X_2}{X_2 + X_3 - X_a + jR_a} \tag{14}$$

$$\frac{i_2}{i_1} = \frac{X_3 - X_a + jR_a}{X_2 + X_3 - X_a + jR_a} \tag{15}$$

6. Substituting equations (14) and (15) in equation (13) and equating the real and imaginary parts gives

$$2X_1 = X_2 + 2\beta(X_2 + X_3 - X_a) \tag{16}$$

and

$$2X_1\,(X_2 + X_3 - X_a) = X_2\,(2X_3 - X_a) - 2\beta R_a^2 \tag{17}$$

where, $\beta = R_1/R_a$ (18)

7. In any practical circuit R_a will be the order of R_o and R_1 will be only a few ohms (see equation 34). Thus β will be small compared to unity. If R_1 or β is assumed to be zero for the moment, then one derives the following interesting results from equations (16) and (17):

$$2X_1 = X_2 \tag{19}$$

and

$$X_2 = X_3 \tag{20}$$

8. For the condition $\beta = 0$, the inductive reactance of L_1 must be equal to the capacitive reactance of C_1 and C_2 in parallel. The balancing circuit would function properly over

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the required frequency band with fixed and equal values for capacitors C_1 and C_2 having reactances X_2 and X_3 respectively. For a well designed inductor, β will be small compared to unity, and equations (19) and (20) can be written

$$2X_1 = X_2 + d \qquad (21)$$

and

$$X_3 = X_2 + e \qquad (22)$$

where d and e are small compared to X_2.

9. The second approximation terms (d and e) can be evaluated by the following method:

(a) Substitute equations (21) and (22) in equations (16) and (17).

(b) Neglect all terms containing d^2, e^2, β^2, de, $d\beta$, and $e\beta$.

(c) Solve the resulting equations for d and e.

The equations for d and e thus become

$$d = 2\beta(2X_2 - X_a) \qquad (23)$$

$$e = \frac{2\beta}{X_2}(2X_2 - X_a)^2 + R_a^2 \qquad (24)$$

10. The following equations, which are accurate to the second approximation, are obtained by substituting equations (23) and (24) in equations (21) and (22):

$$2X_1 = X_2 + 2\beta(2X_2 - X_a) \qquad (25)$$

$$X_3 = X_2 + 2\beta/X_2\left[(2X_2 - X_a)^2 + R_a^2\right] \qquad (26)$$

11. A study of either equations (25) and (26) or equations (16) and (17) reveals the following facts:

(a) The effect of the output impedance, $R_a + jX_a$, upon the adjustment of the balancing circuit is very small because terms involving R_a and X_a also contain β. This fact has been verified by experiment.

(b) The reactance X_1 and X_3 can be readily expressed in terms of the reactance X_2 and terms containing β.

(c) The capacitive reactances X_2 and X_3 are essentially equal at all operating frequencies.

(d) If points "a" and "b" in the circuit (see Plate 39) are connected together, then the proper value for inductance L_1 for balanced output operation to a good approximation would occur at the series-resonance frequency. This fact was observed experimentally even without the short between points "a" and "b".

12. The necessary condition for a unity standing wave ratio on the transmission line feeding and balancing circuit is that the input impedance (Z_t) presented by the balancing circuit must be equal to the characteristic impedance of the transmission line. Thus, equation (3) becomes

$$R_o = E_{ag}/i_1$$

or, after substituting equation (5) in the above,

$$R_o = R_1 + jX_1 - jX_2\, i_2/i_1 \qquad (27)$$

13. The requirements for matched input to the balancing circuit (equation (27)) and the equation for the current ratio i_2/i_1 (equation (15)) will be used to obtain two equations which give relationships between the quantities R_o, R_a, X_a, R_1, X_1, X_2, and X_3. After substituting equation (15) in equation (27) and equating the real and imaginary parts one has

$$R_o - \beta R_a = \frac{X_2^2\, R_a}{(X_2 + X_3 - X_a)^2 + R_a^2} \qquad (28)$$

and,

$$X_1 = \frac{X_2\left[(X_3 - X_a)^2 + X_2\,(X_3 - X_a) + R_a^2\right]}{(X_2 + X_3 - X_a)^2 + R_a^2} \qquad (29)$$

14. Equations (16), (17), (21), and (22) are given again for convenient reference.

$$2X_1 = X_2 + 2\beta\,(X_2 + X_3 - X_a) \qquad (16)$$

$$2X_1\,(X_2 + X_3 - X_a) = X_2\,(2X_3 - X_a) - 2\beta R_a^2 \qquad (17)$$

$$2X_1 = X_2 + d \qquad (21)$$

$$X_3 = X_2 + e \qquad (22)$$

15. In equations (16), (17), (28), and (29) the unknown quantities X_1, X_2 and X_3 are independent variables while the unknown quantities R_a and X_a are dependent variables. The results must be expressed in terms of one of the independent variables because the number of variables (five) is greater than the number of equations to be solved (four). From an analytical viewpoint the logical independent variable to express the results in terms of is X_2.

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16. Equations (16), (17), (28), and (29) cannot be readily solved for X_1, X_3, R_a, and X_a. However, an approximate solution can be obtained if β is set equal to zero in these equations. The approximate solutions for R_a and X_a are

$$R_a' = \frac{4 R_o X_2^2}{4 R_o^2 + X_2^2} \tag{30}$$

$$X_a' = \frac{8 R_o^2 X_2}{4 R_o^2 + X_2^2} \tag{31}$$

17. More accurate formulas can be obtained for R_a and X_a by adding second order correction terms as follows:

$$R_a = \frac{4 R_o X_2^2}{4 R_o^2 + X_2^2} + m \tag{32}$$

$$X_a = \frac{8 R_o^2 X_2}{4 R_o^2 + X_2^2} + n \tag{33}$$

18. If equations (21), (22), (32), and (33) are substituted in equations (28) and (29) and terms are neglected which contain d^2, e^2, m^2, n^2, de, dm, dn, em, en, mn, β^2, $d\beta$, $e\beta$, $m\beta$, and $n\beta$, then equations are obtained which can be readily solved for the correction terms m and n. When the results of these computations are substituted in equations (32) and (33), equations for computing R_a and X_a are obtained which are sufficiently accurate for practical applications.

$$R_a = \frac{4 R_o X_2^2}{4 R_o^2 + X_2^2} \left[1 + \frac{R_1}{R_o} \left[\frac{(12 R_o^2 + X_2^2)(4 R_o^2 + X_2^2)}{X_2^4 + 16 R_o^2 X_2^2 - 16 R_o^4} \right] \right] \tag{34}$$

$$X_a = \frac{8 R_o^2 X_2}{4 R_o^2 + X_2^2} \left[1 - \frac{R_1}{R_o} \left[\frac{(4 R_o^2 + X_2^2)^2}{X_2^4 + 16 R_o^2 X_2^2 - 16 R_o^4} \right] \right] \tag{35}$$

19. Substitution of equations (34) and (35) in equations (25) and (26) results in the following desired design equations for X_1 and X_3.

$$2 X_1 = X_2 (1 + R_1/R_o) \tag{36}$$

$$X_3 = X_2 (1 + 2 R_1/R_o) \tag{37}$$

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where, $X_1 = \omega L_1$ (see Plate 39)

$X_2 = 1/\omega C_1$ (see Plate 39)

$X_3 = 1/\omega C_2$ (see Plate 39)

R_1 is the resistance of inductance L_1

R_o is the characteristic impedance of the transmission line feeding the balancing circuit.

20. Equations (34), (35), (36), and (37) are the fundamental design equations for the balancing circuit. The importance of equations (34) and (35) is restricted primarily to determining the output impedance of the balancing circuit. In most applications it may not be necessary to know this impedance accurately but only the range of values expected. It will be shown that by proper choice of the minimum value of the reactance X_2, it will not be necessary to compute R_a and X_a and the design constants for the balancing circuit can be determined from equations (36) and (37). A study of equations (34) and (35) will reveal the following facts:

(a) If X_2 is large compared to R_o, then $R_a = 4\,R_o$ or for greater accuracy $R_a = 4\,R_o\,(1 + \frac{R_1}{R_o})$ and X_a is small compared to R_a. This means that the balancing circuit will act as a nearly perfect transformer with a turns ratio of two. Obviously this is the best operating condition for the balancing circuit. The second order correction term in equations (34) and (35) will be about R_1/R_o and thus would be small compared to unity.

(b) If it is assumed that $R_a = X_a$, then $X_2 = 2R_o(1 - \frac{3R_1}{R_o})$ and $R_a = 2R_o(1 - R_1/R_o)$. Again the second order correction term is small and is in the order of R_1/R_o in equations (34) and (35). It should be noted that R_a is only one half of the value as for the condition when X_2 is large compared to R_o. This is considered the minimum value of X_2 for which the design of the balancing circuit can be computed from equations (36) and (37) without considering equations (34) and (35).

(c) If a value of the fixed capacitor C_1 is selected such that its reactance X_2 at the highest operating frequency for the balancing circuit satisfies the condition $X_2 = 2\,R_o$, then $X_a <$ $2\,R_o$ and $2\,R_o < R_a < 4\,R_o$ at any other operating frequency for the balancing circuit. The second order correction terms have been neglected in determining the above range of values for R_a.

21. A consideration of the design equations (36) and (37) will also yield some pertinent facts. It is evident from equation (37) that if R_1 is constant over the operating frequency band of the balancing circuit, then a balanced output voltage would be obtained when using fixed values for capacitors C_1 and C_2.

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Thus the inductor L_1 should be designed with a low and as nearly a constant resistance as possible in order that the output voltage will be essentially balanced at any operating frequency in the band. Equations (36) and (37) are sufficiently accurate for all practical purposes if the second order terms R_1/R_o and $2\ R_1/R_o$ do not exceed 0.20. The reactance X_2 of capacitor C_1 must be at least $2\ R_o$ and preferably $4\ R_o$ at the highest operating frequency for the circuit. If X_2 is less than $2\ R_o$, then it will be necessary to compute R_a and X_a. With the aid of these facts a balancing circuit can be easily designed by use of equations (36) and (37). The design data for the balancing circuit that was used with the subject directive antenna are given in Table 4.

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DESCRIPTION OF BALANCE INDICATOR UNIT

1. The schematic diagram of this unit is shown on Plate 2, Figure 3 and illustrations are shown on Plates 32 to 36 inclusive. The input to this unit is coupled capacitively, by means of capacitors C7 and C8, to the output of the impedance-matching network (or antenna-feeder terminals) in the coupling unit. Since the r-f voltages at this point in the coupling unit are 180 degrees out of phase, any difference in the two voltages appears at the common connection between capacitors C7 and C8. This resultant voltage is attenuated by resistor R3 which serves also to protect the remainder of the circuit in the event of an over-voltage condition. The tuned circuit, composed of inductance L4 and capacitor C9 serves to improve the sensitivity and selectivity of the unit and, since C9 is adjustable from the front panel, the circuit can be used to control the deflection on microammeter M4. Resistor R2 and capacitor C10 in combination with the tuned circuit, act to reduce the variation in sensitivity of the unit over the frequency range. Inductance L4 is tapped at 3/4 turn up from the ground end and thus provides the input voltage for the detector circuit. Resistors R4 and R5 form a voltage divider, in the R5 branch of which is inserted crystal detector Y1 and d-c microammeter M4. Capacitor C11 bypasses stray r-f currents around meter M4.

2. This unit is of "plug-in" construction, being provided with a track arrangement for mounting in the coupling so that it can be easily withdrawn or plugged into the coupling unit from the front panel without removal of any electrical connections.

3. During actual operation of the directive antenna system the coupling unit is adjusted for minimum indication on microammeter M4. This meter has a range of 0-100 microamperes with the first significant division indicating 2 microamperes; readings with good accuracy down to 1 microampere are possible. A reading of 1 microampere corresponds to a voltage unbalance on the antenna-feeder lines of from 6.0 volts at 15 mc to 7.0 volts at 6 Mc. Thus the variation in sensitivity over the frequency range is about 1.17 to 1. The normal r-f voltage on the antenna-feeder lines for full power operation is in the order of 300 to 400 volts over most of the frequency range. At about 12.5 Mc the impedance at the input to the feeder lines is at a minimum $(Z = 35 + J0)$ and here the line voltage is about 100 volts. Therefore, by observing the deflection on this balance indicator unit, it is possible to adjust the voltage (or current) balance on the feeder lines to within 2 to 6 per cent.

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DESCRIPTION OF TYPE RA-23538 ANTENNA SELECTOR UNIT

1. Referring to Plate 2, Figure 2, the transmitter output current is indicated by r-f ammeter M5 (0-5 ampere range) when either directive antenna or the 50-ohm dummy-antenna load are in use. When the non-directive (whip or tower) type antenna is used, this ammeter must be short-circuited for protection since the transmitter output current may rise to 10 or 12 amperes at some frequencies. A shorting switch, which is operated from the front panel and which bears a suitable warning nameplate, is provided. A mechanical interlock prevents switching to the non-directive antenna until this shorting switch is closed. The antenna selector switch is a Navy Type CNB-24314 Antenna Switching Unit with some minor modifications to adapt it to this application. These modifications are as follows:

(a) Two minor machining operations to facilitate mounting the switch in the cabinet.

(b) Machining finger grips on the dial knob.

(c) Changing the dial designations to correspond to the antennas used in this system.

(d) Changing the cable connector for the electrical interlock to a type which will facilitate disconnecting the cable so the unit can be removed from the transmitter.

2. The dummy load consists of six 300-ohm, 100-watt resistors connected in parallel to provide approximately a 50-ohm resistive load with ample wattage capacity to dissipate 500 watts. The impedance presented at the selector-switch output terminal by this dummy load varies from 49 to 54 ohms over the frequency range of 6 to 15 Mc. The actual A-N impedance rating of type RG-18/U coaxial cable is 52 ohms. Thus the dummy-antenna load presents approximately the same impedance as the 52-ohm cable terminated in a 52-ohm resistive load. It is therefore possible to pretune the transmitter using the dummy-antenna load, then switch to the directive antenna system and adjust the coupling unit at the antenna as a separate operation until it also presents approximately a 52-ohm resistive load. This requirement is pointed out in paragraph 14 as necessary for proper operation of the antenna system. Even the highest quality commercially available resistors which would be suitable for this application are somewhat reactive and thus the dummy-antenna load does not present a pure resistance. However, this reactive component is not sufficiently large to have an appreciable effect upon the adjustment of the antenna system. A slight retrimming of the transmitter output circuits may be necessary at certain frequencies after switching from the dummy load to the antenna system in order to improve the ratio of transmission-line input and output currents when adjusting the coupling unit.

[redacted]

APPENDIX 4

TUNING PROCEDURE FOR THE DIRECTIVE ANTENNA SYSTEM

1. The following procedure is necessary when tuning the directive antenna system to an uncalibrated frequency: The operator at the transmitter first rotates the Antenna Selector Switch to the "Dummy" position and then tunes the transmitter in a normal manner to the desired frequency. The operator at the coupling unit determines an approximate calibration from the tuning data and curves supplied with the unit. This done, the operator at the transmitter switches the transmitter power-output control to Step 2 (Tune) and switches the Antenna Selector to the proper directive-antenna position (Port Directive or Starboard Directive). At the coupling unit there should then be input current showing on the Input Current meter M_1 (see Plate 2, Figure 2) when the transmitter test key is closed. The operator at the coupling unit then tunes inductance L_1 for maximum current indication on Meter M_1. It is possible that before adjustment of inductance L_1 the Balance Indicator (M_4) may show a considerable reading, indicating unbalanced voltage on the antenna-feeder lines. The tuning control on the Balance Indicator unit should then be adjusted for maximum reading on the microammeter. Then, as inductance L_1 brings the balancing circuit into resonance, the reading on the microammeter drops to a low value (10 microamperes or lower). The impedance-matching network is then adjusted until the output meters M_2 and M_3 show current in the feeder lines. The transmitter can then be switched to "Operate". From this point on, the procedure is a matter of trimming the coupling-unit controls until the following conditions are obtained:

(a) The Balance Indicator meter reads no more than one division (one division = 2 microamperes, and corresponds to 8 to 9 volts unbalance on the feeder lines). Readings to one-half of one division with good accuracy are possible, and this corresponds to a voltage unbalance of 6 to 7 volts.

(b) The feeder-line currents are approximately equal.

(c) The input current is about 2.9 amperes or about 93 per cent of the current at the input end of the coaxial transmission line (assuming that 300 feet of type RG-18/U coaxial line is used).

(d) The input current to the transmission line (indicated by the meter in the Antenna Selector Unit) is about 3.1 amperes or approximately equal to the current input to the dummy-antenna load.

The antenna system is then properly balanced and matched and should operate at maximum efficiency.

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TABLE 1

ANTENNA IMPEDANCE

Frequency (Mc)	λ (ft)	Feeder Length (ℓ/λ)	Z_A Antenna Impedance	Z_f Feeder-Line Impedance
5.0	197.0	0.089	40-J200	35 + J75
6.0	164.0	0.107	68+J0	107 + J360
7.5	131.0	0.134	145+J425	2800 - J485
9.0	109.4	0.160	400+J950	212 - J640
10.0	98.5	0.178	850+J1600	89 - J366
11.1	88.7	0.197	2500+J2500	54 - J212
11.7	84.2	0.208	5000+J0	49 - J126
12.3	80.0	0.219	2500-J2500	42 - J46
13.35	73.0	0.240	500-J1600	35 + J93
15.0	65.6	0.267	120-J700	65 + J382

TABLE 2

FRONT-TO-BACK RATIOS AND BEAM WIDTHS OF RADIATION PATTERNS MEASURED ON BLIMP

Frequency (kc)	Vertical Angle (degrees)	Front-to-Back Ratio *		Beam Width at Half Power (degrees)
		Voltage	db	
6275	4.6	5.3	15	45
6275	15.0	4.2	13	34
6275	33.7	4.8	14	115
6275	45.0	3.6	11	95
9000	3.0	10.0	20	44
9000	16.0	20.3	26	46
9000	33.0	7.2	17	56
9000	45.0	5.7	15	78
14280	18.5	15.0	23	127
14280	33.7	17.3	25	127
14280	45.0	68.0	36	65

* Ratio of maximum front to maximum back field strengths.

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TABLE 3

FRONT-TO-BACK RATIOS AND BEAM WIDTHS OF RADIATION PATTERNS MEASURED AT DISTANT POINTS

Frequency (kc)	Front-to-Back Ratio *		Beam Width at Half Power (degrees)	Distant Receiving Station
	Voltage	db		
6275	10	20	65	Washington, D. C.
6275	15	23	80	Riverhead, N. Y.
6275	55	35	50	Great Lakes, Ill.
9000	44	33	60	Riverhead, N. Y.
9000	10	20	40	San Juan, P. R.
9000	26	28	44	Point Gourde, B.W.I.
14280	25	28	41	San Juan, P. R.
14280	100	40	36	Point Gourde, B.W.I.

* Ratio of maximum front to maximum back field strength.

TABLE 4

DESIGN DATA FOR BALANCING CIRCUIT

Freq. (Mc)	C_1 (μμf)	X_2 (ohms)	R_1 (ohms)	L_1 (μh)	X_1 (ohms)	C_2 (μμf)	X_3 (ohms)	R_a (ohms)	X_a (ohms)
6	53	500	3.77	7.0	268	46.5	571	207	36
8	53	375	3.44	4.0	200	46.9	424	200	47
10	53	300	3.11	2.5	159	47.4	336	192	57
12	53	250	2.78	1.75	132	47.9	277	183	66
15	53	200	2.26	1.11	104	48.7	218	168	77

NOTE: The fixed value of C_1 was so chosen that $1/\omega c_1 = X_2 = 4R_o$ at the highest operating frequency. R_1 was obtained by measurement.

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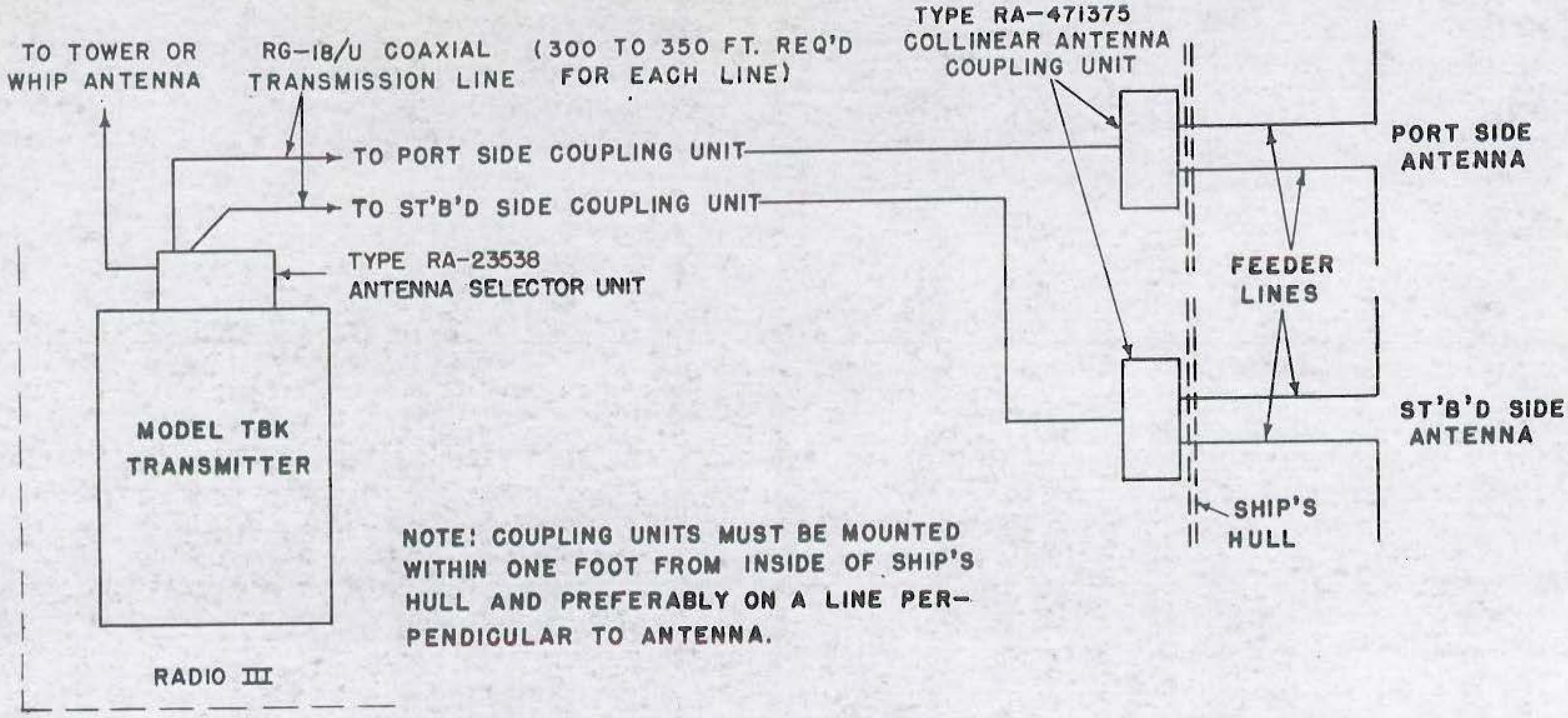

BLOCK DIAGRAM OF DIRECTIVE ANTENNA SYSTEM FOR ESSEX CLASS CARRIERS

PLATE I

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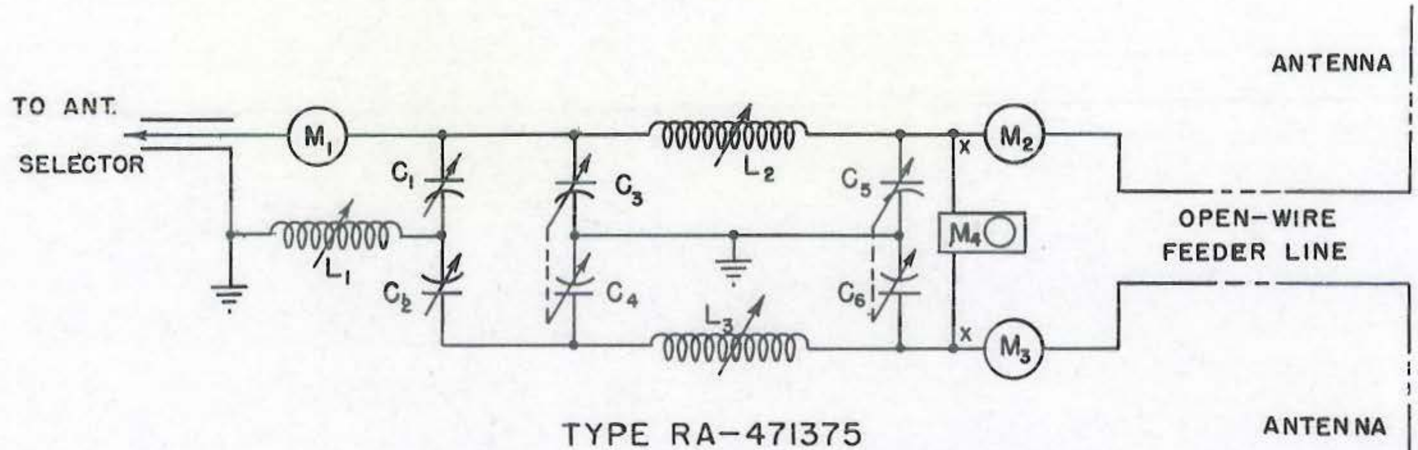
SCHEMATIC DIAGRAMS OF MAJOR UNITS

R-2738

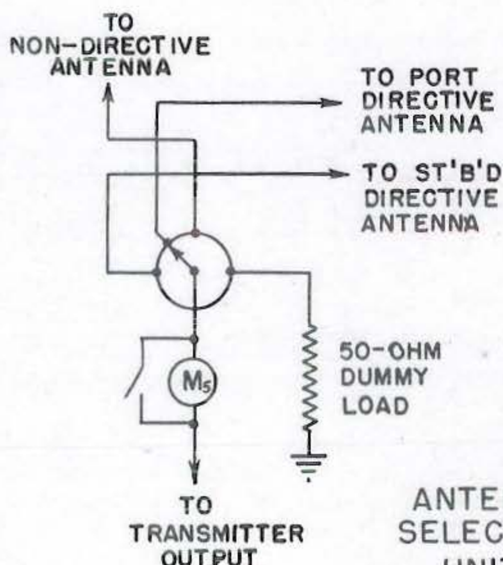
PLATE 2



TYPE RA-471375

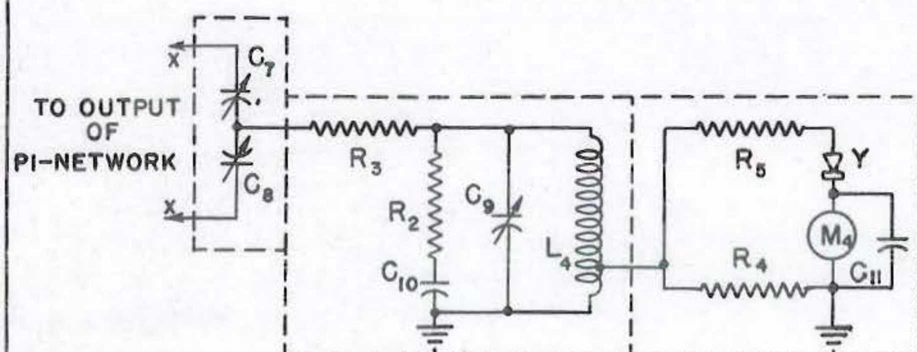
COLLINEAR ANTENNA COUPLING UNIT

FIG. 1



ANTENNA SELECTOR UNIT

FIG. 2



BALANCE INDICATOR UNIT

FIG. 3

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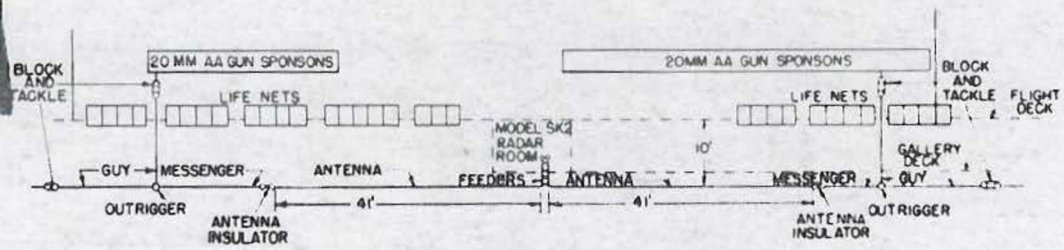
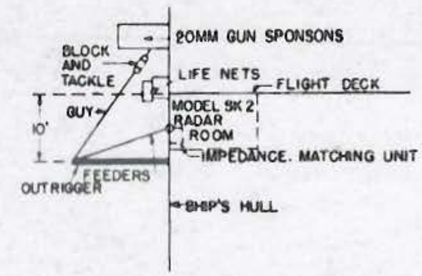
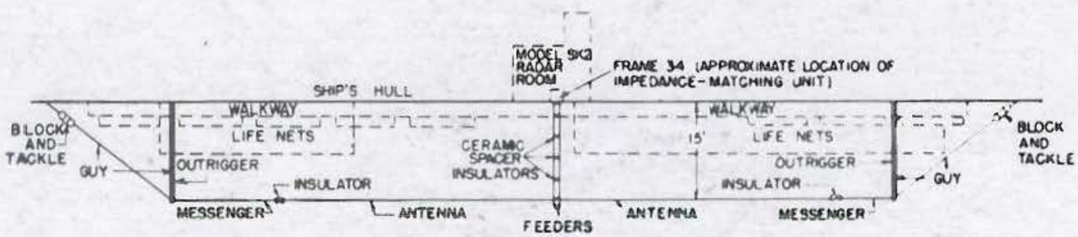


FRONT VIEW OF ANTENNA

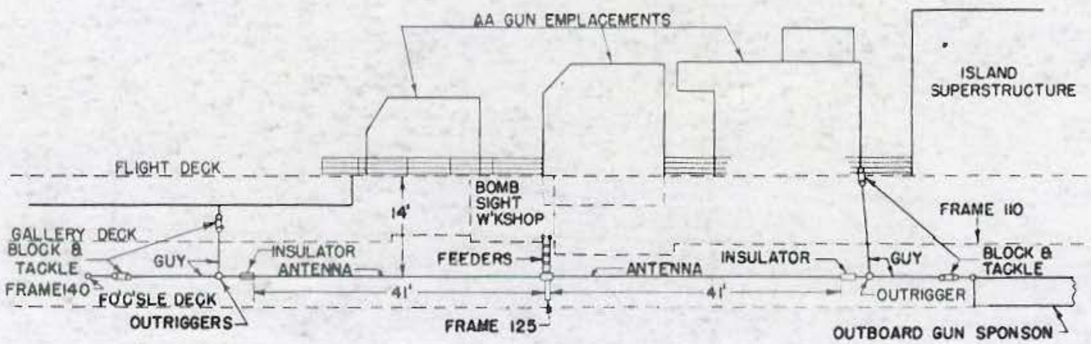


END VIEW OF ANTENNA

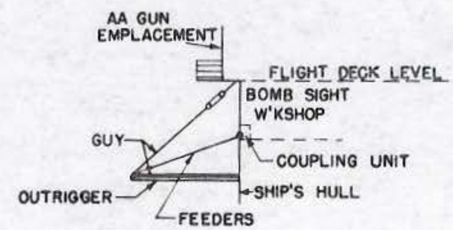


PLAN VIEW OF ANTENNA

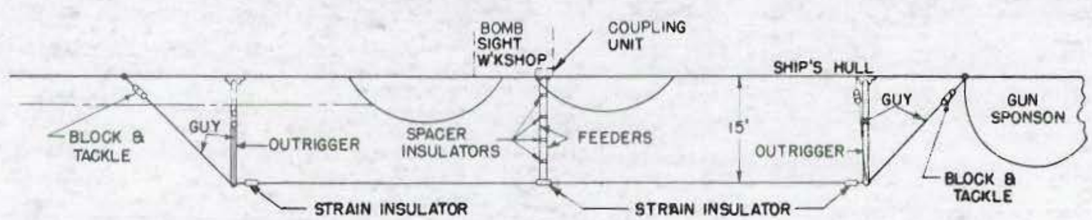
TEST INSTALLATION OF DIRECTIVE ANTENNA
ON CARRIER C. V. 39



FRONT VIEW OF ANTENNA



END VIEW OF ANTENNA



PLAN VIEW OF ANTENNA

PROPOSED STARBOARD INSTALLATION

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PLATE 4

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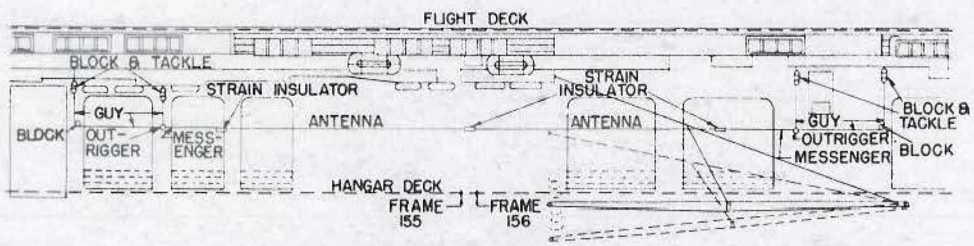
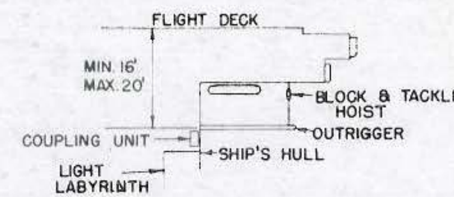
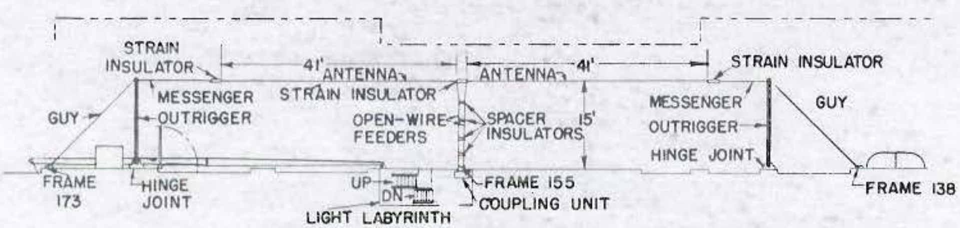


FRONT VIEW OF ANTENNA



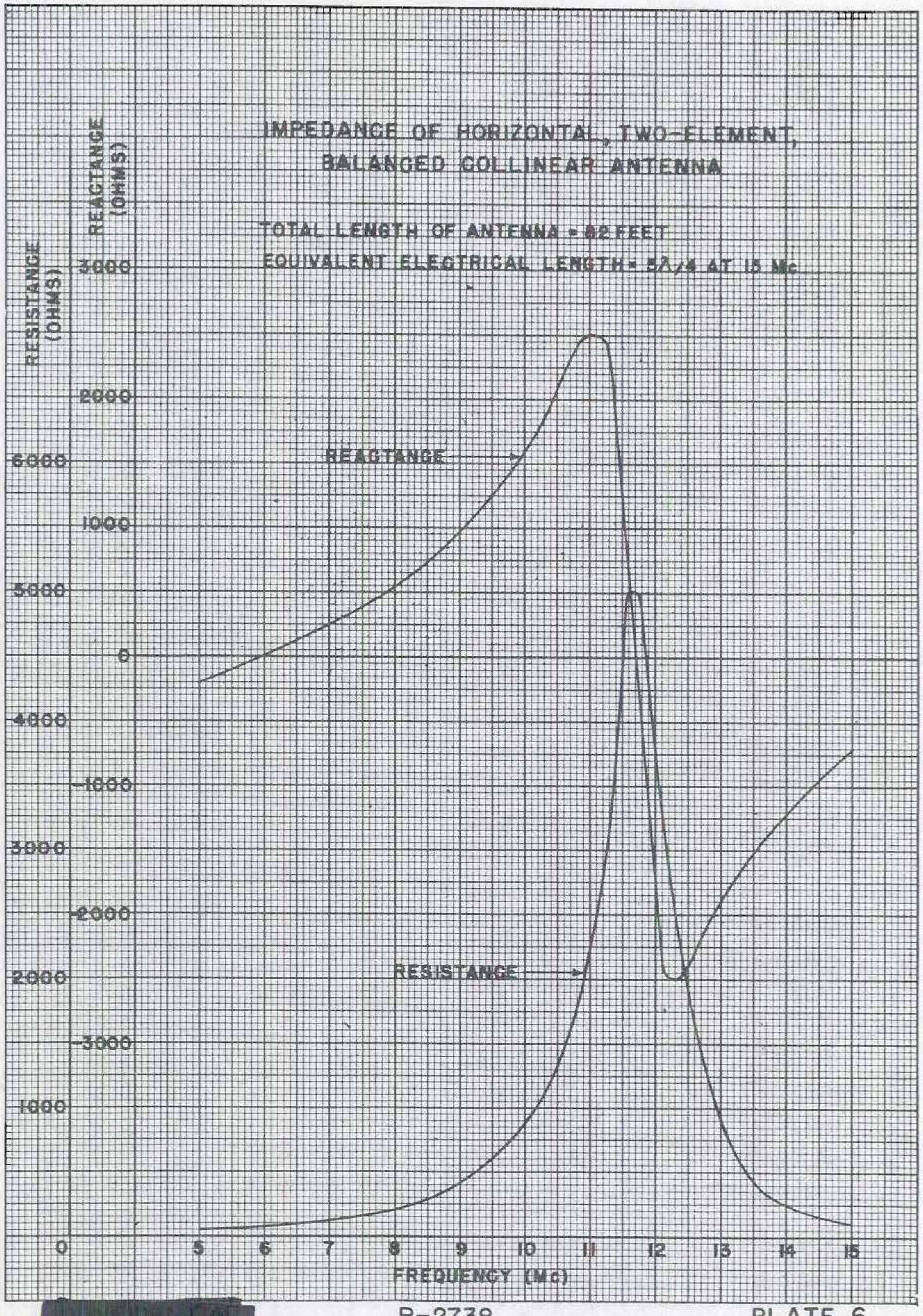
END VIEW OF ANTENNA



PLAN VIEW OF ANTENNA
(FORECASTLE DECK LEVEL)

PROPOSED PORT SIDE INSTALLATION

PLATE 5



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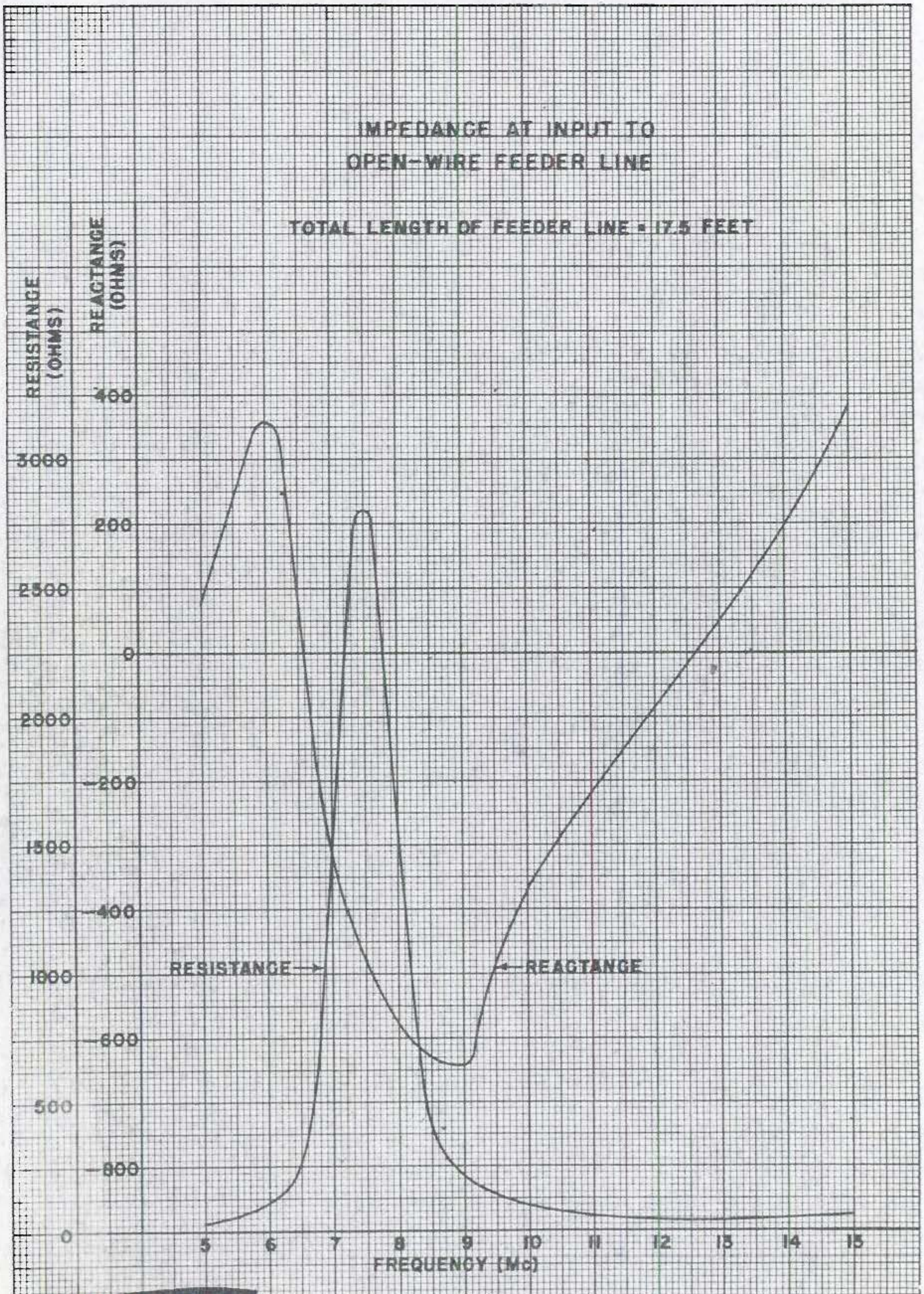

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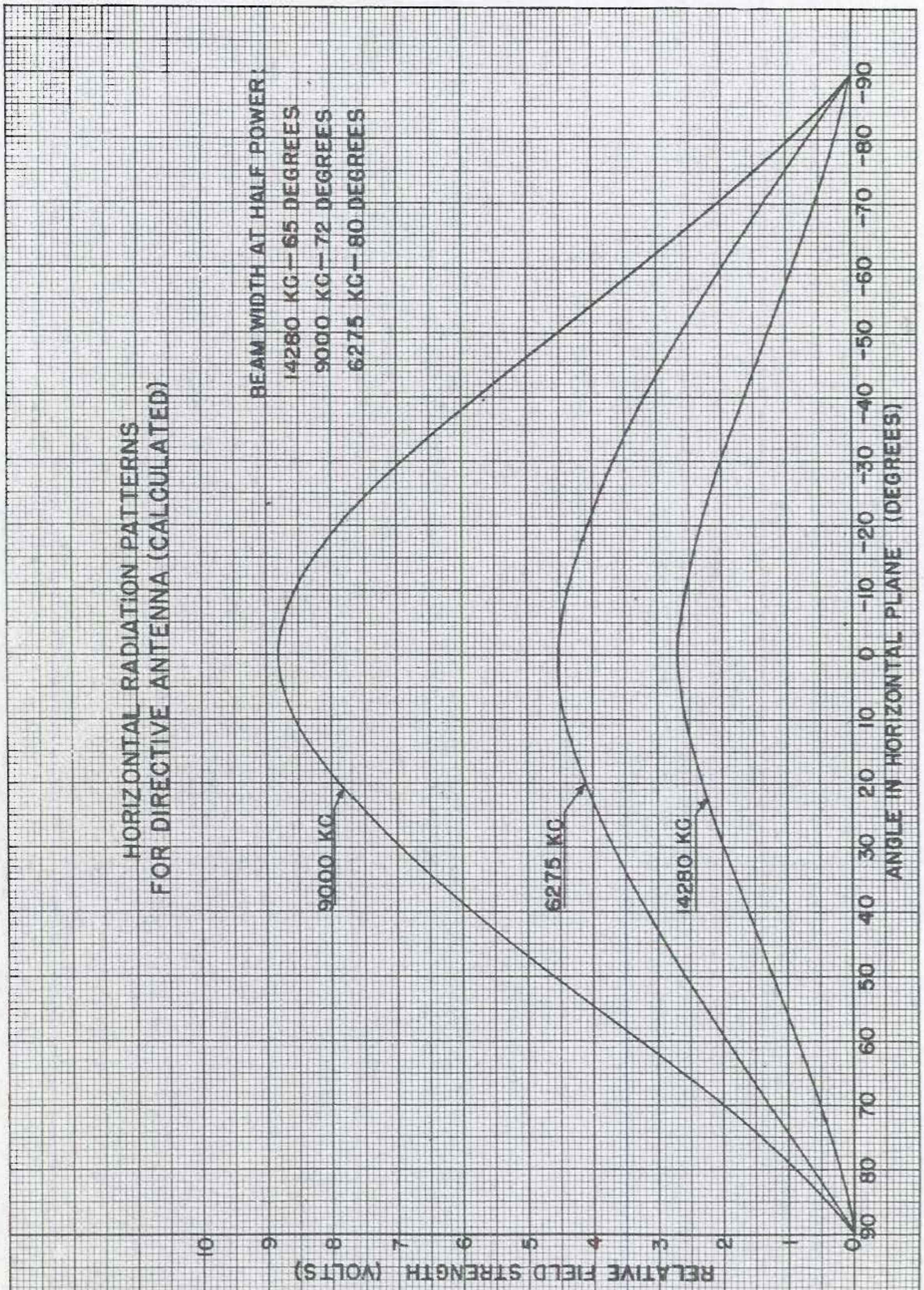

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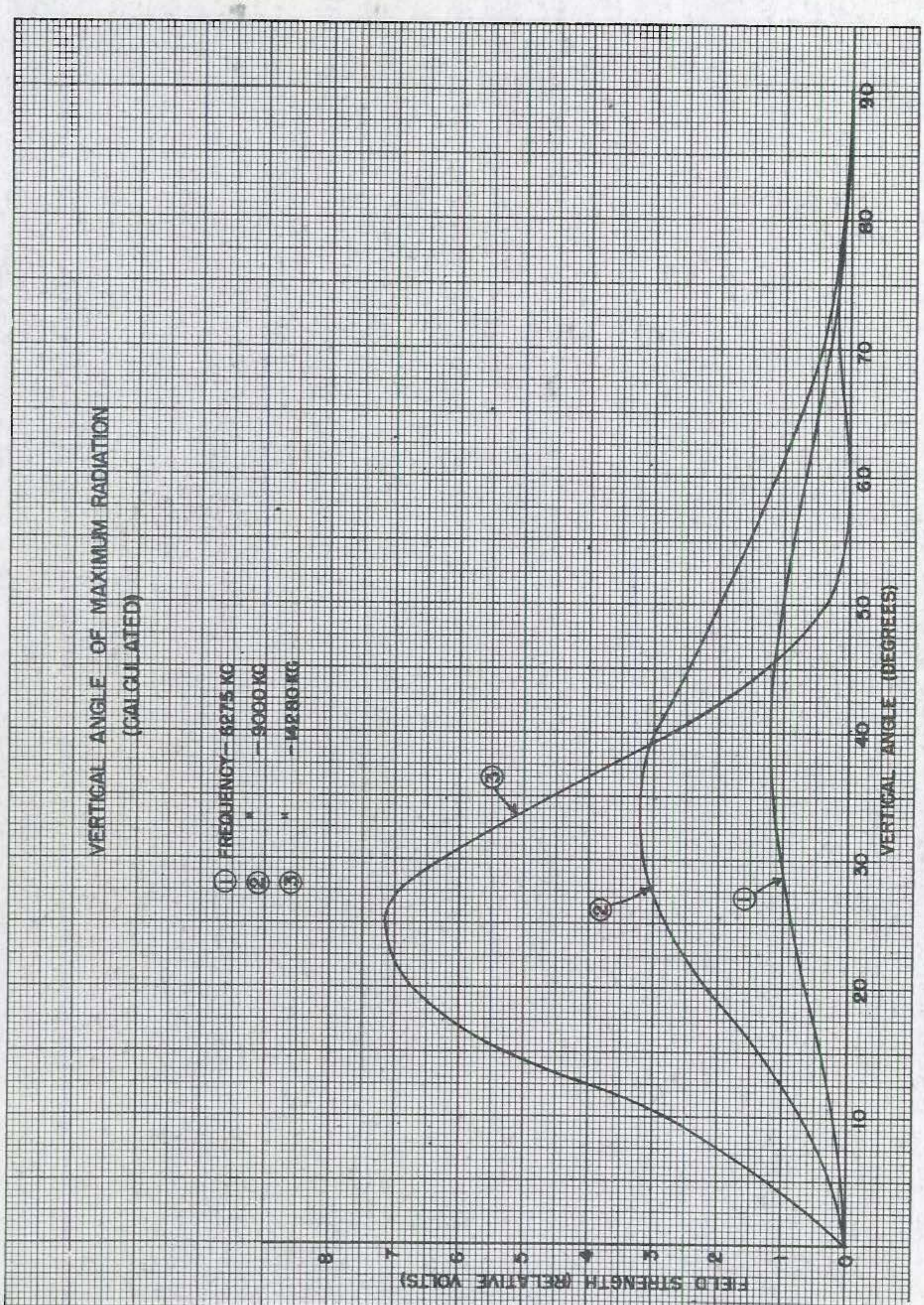

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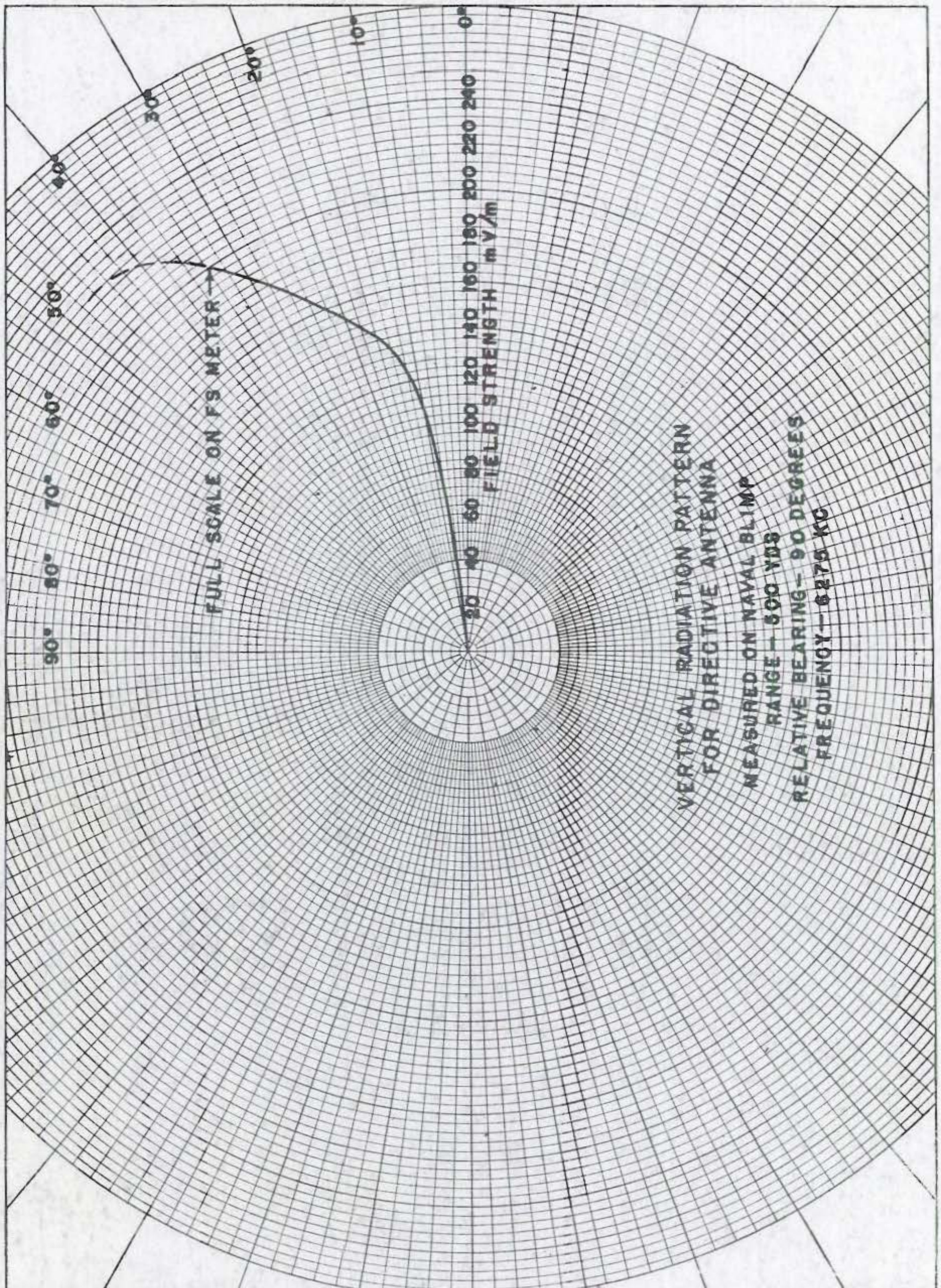

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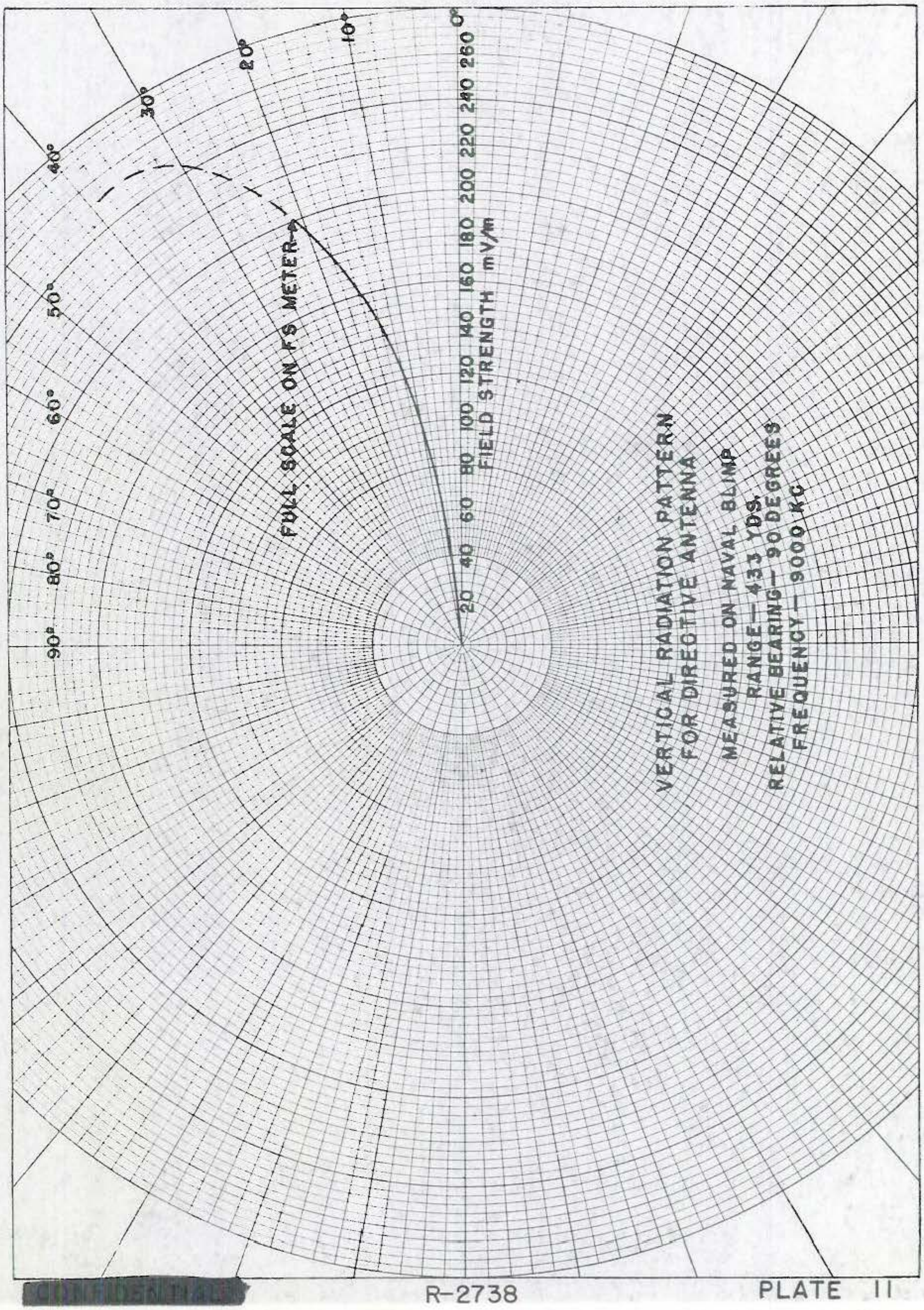

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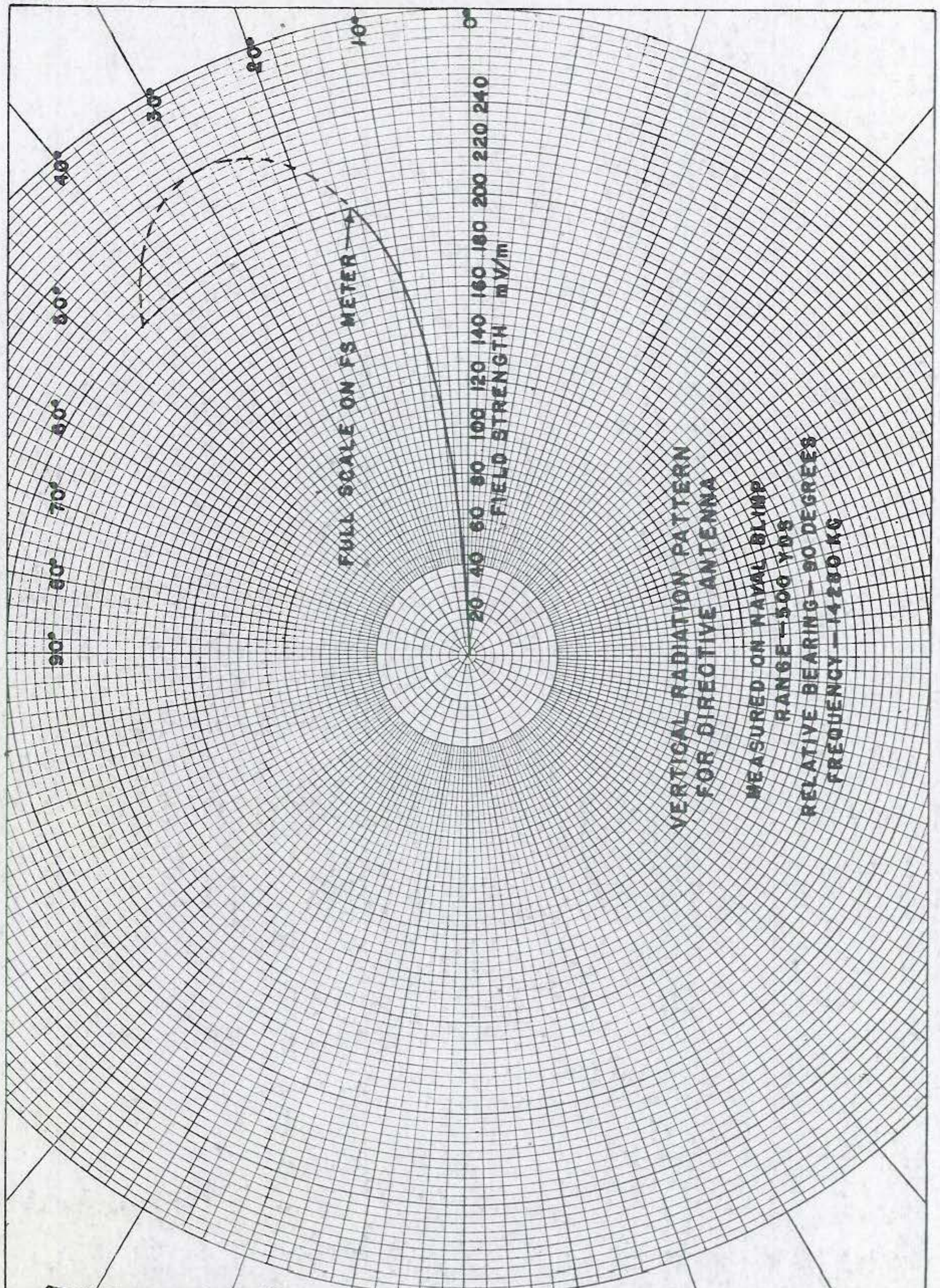

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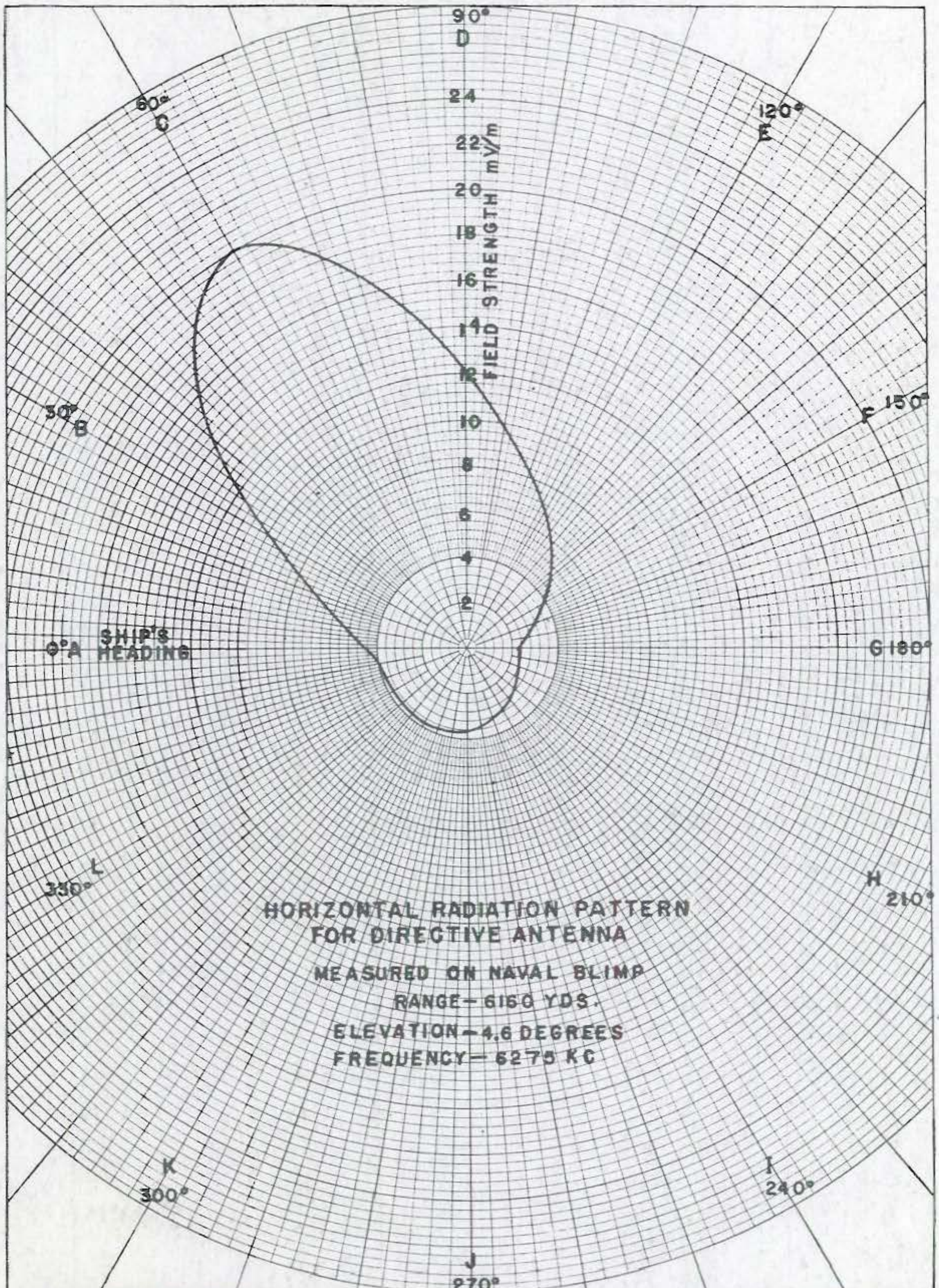

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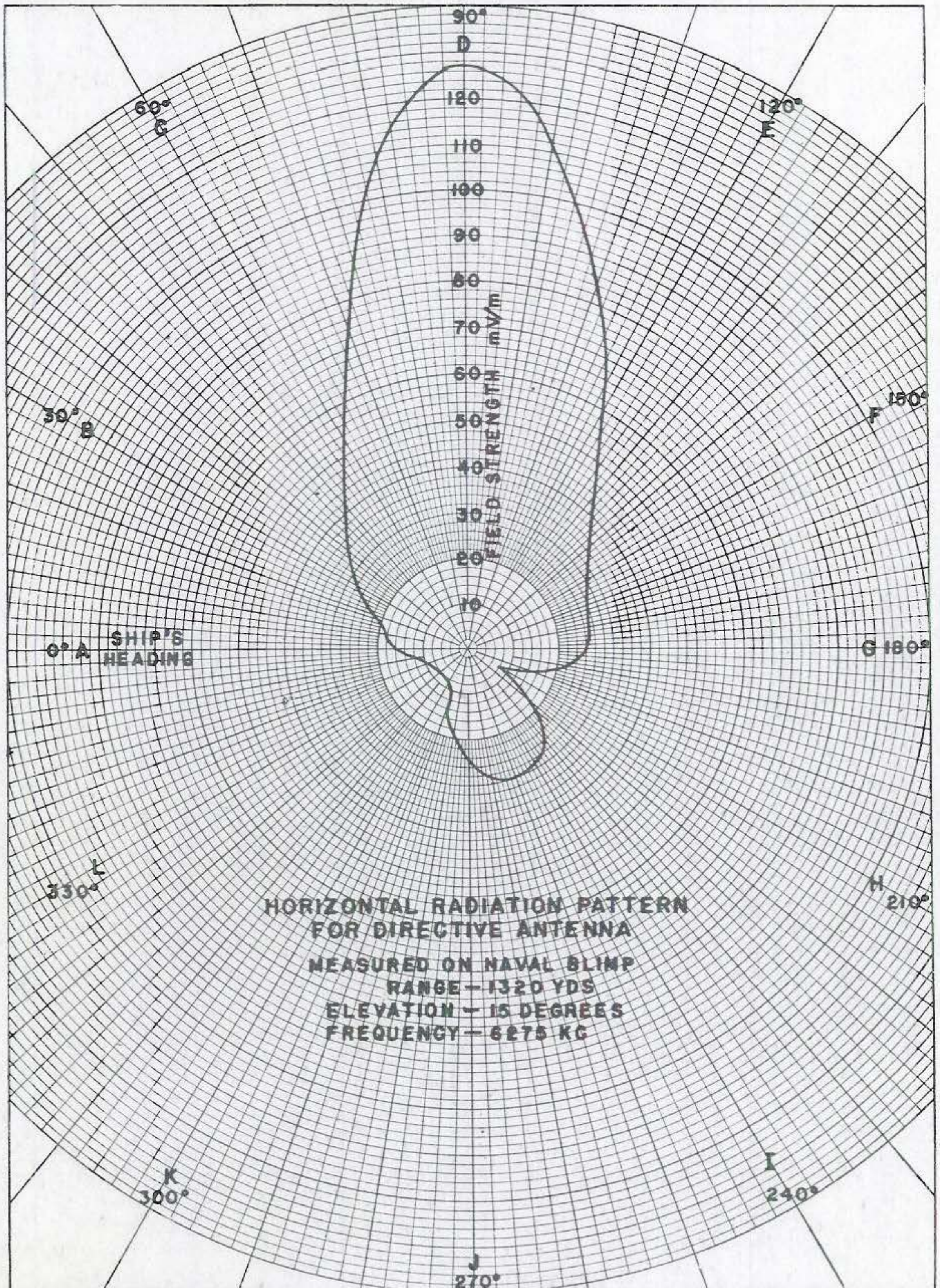

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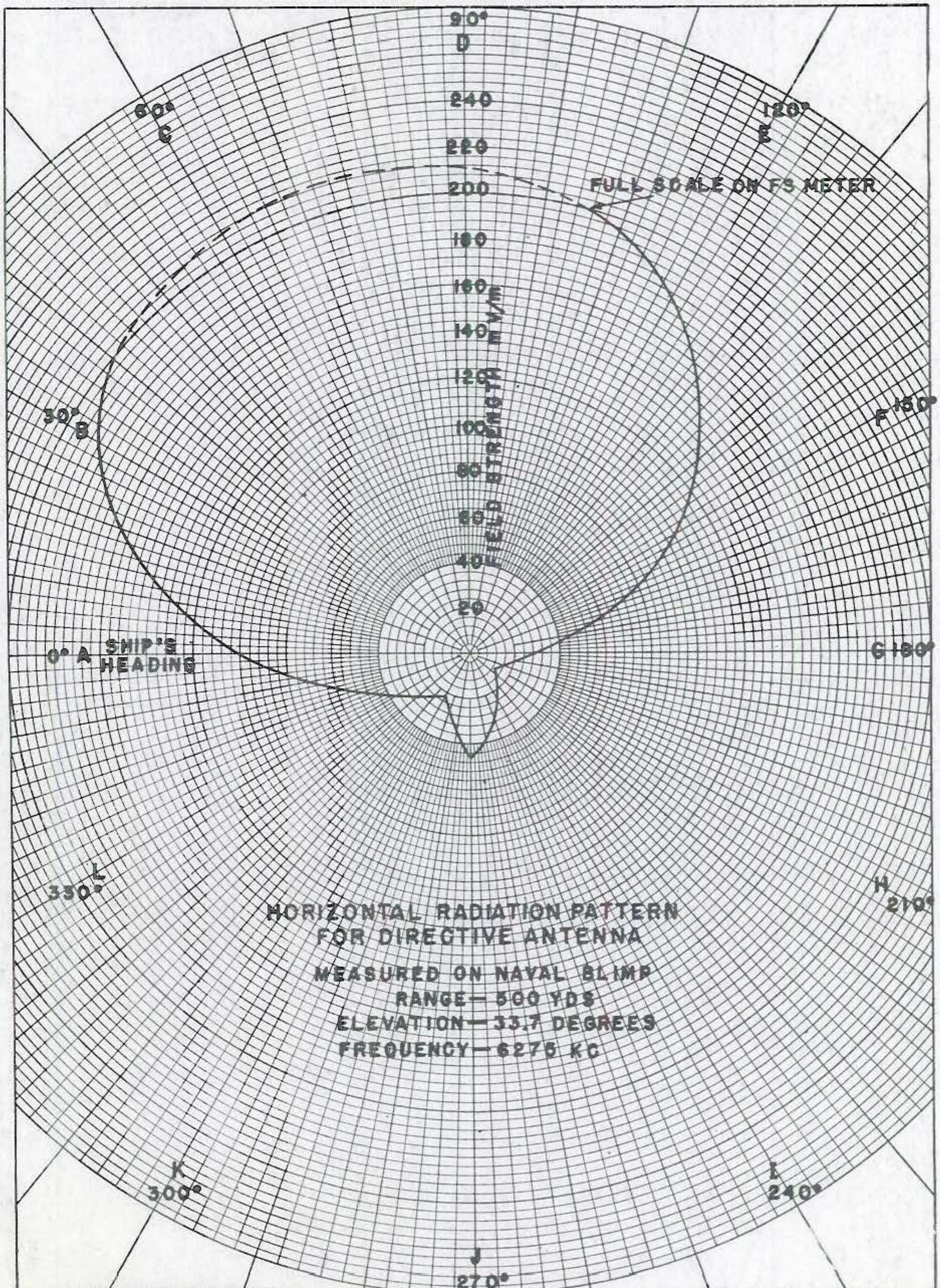

[redacted] R-2738 PLATE 15

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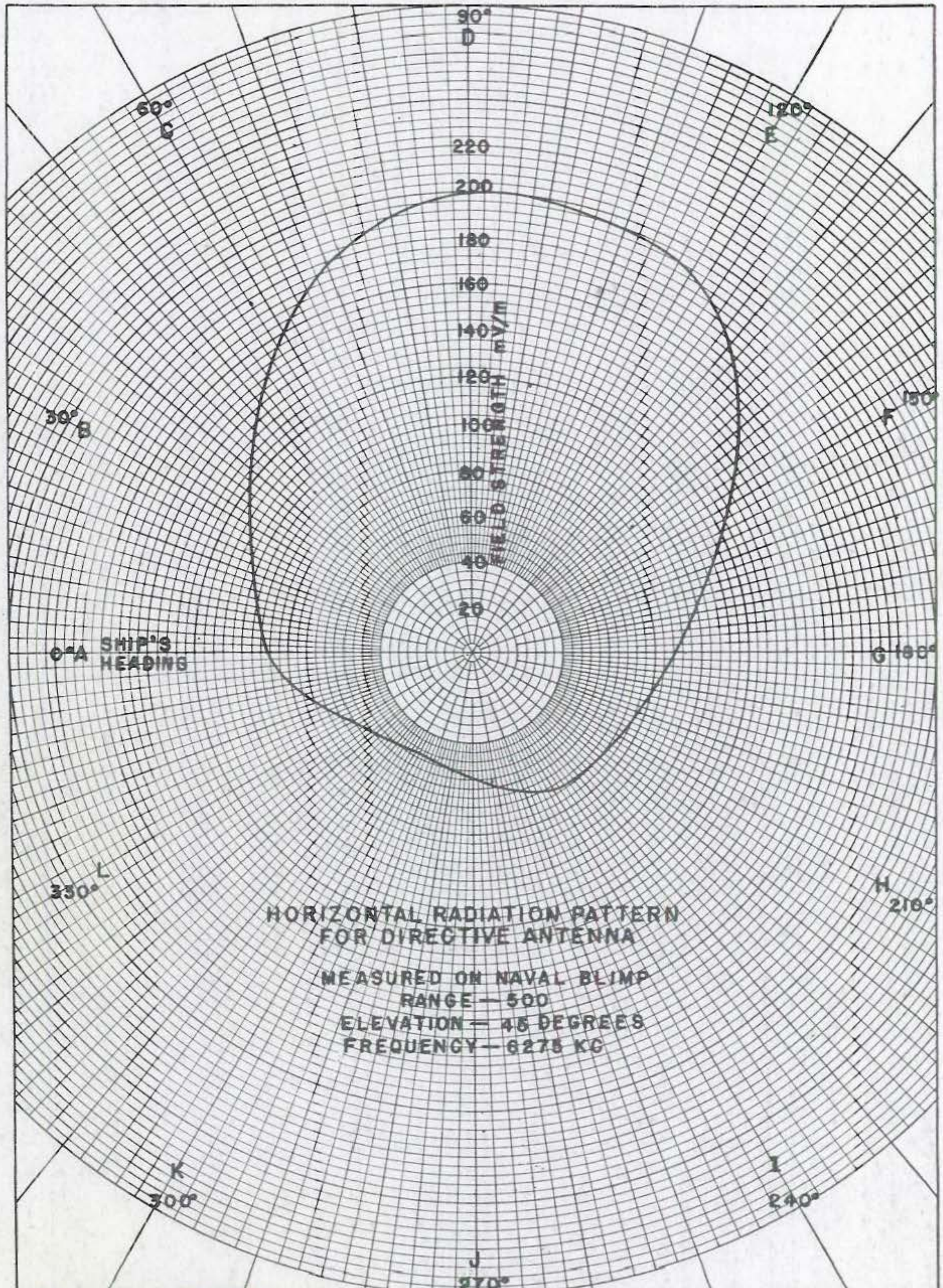

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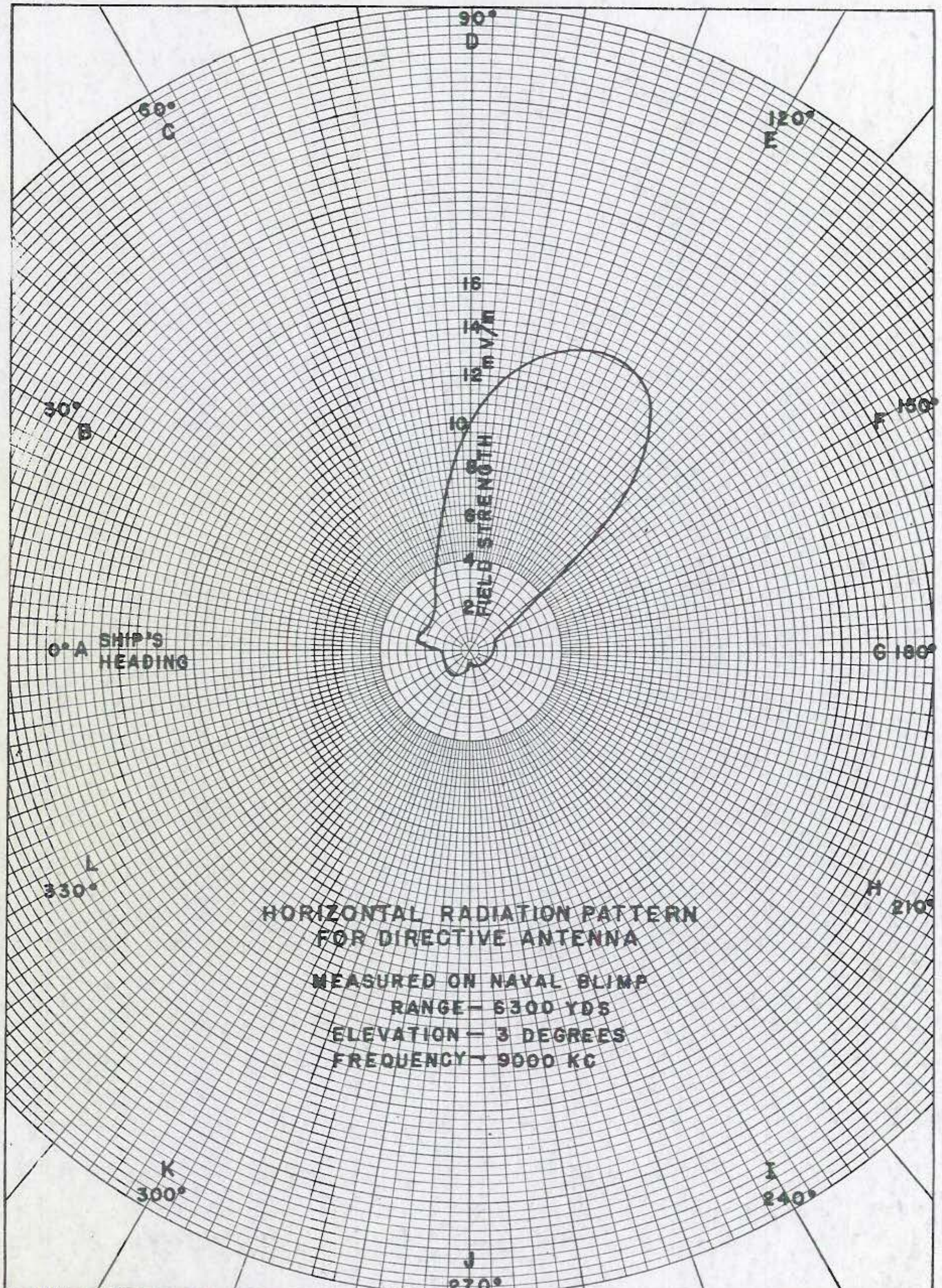

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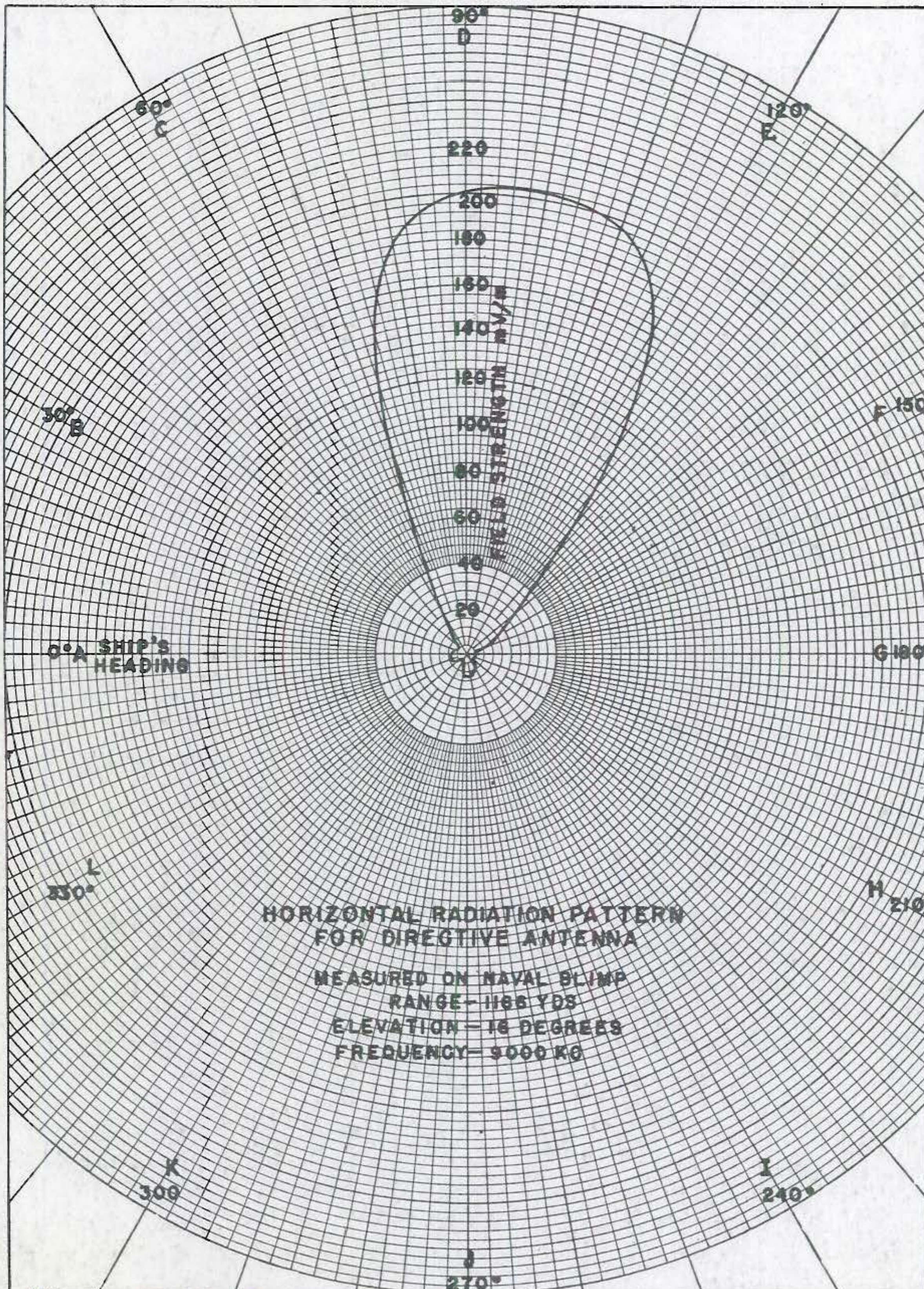

HORIZONTAL RADIATION PATTERN
FOR DIRECTIVE ANTENNA

MEASURED ON NAVAL BLIMP
RANGE- 1166 YDS
ELEVATION = 16 DEGREES
FREQUENCY- 9000 KC

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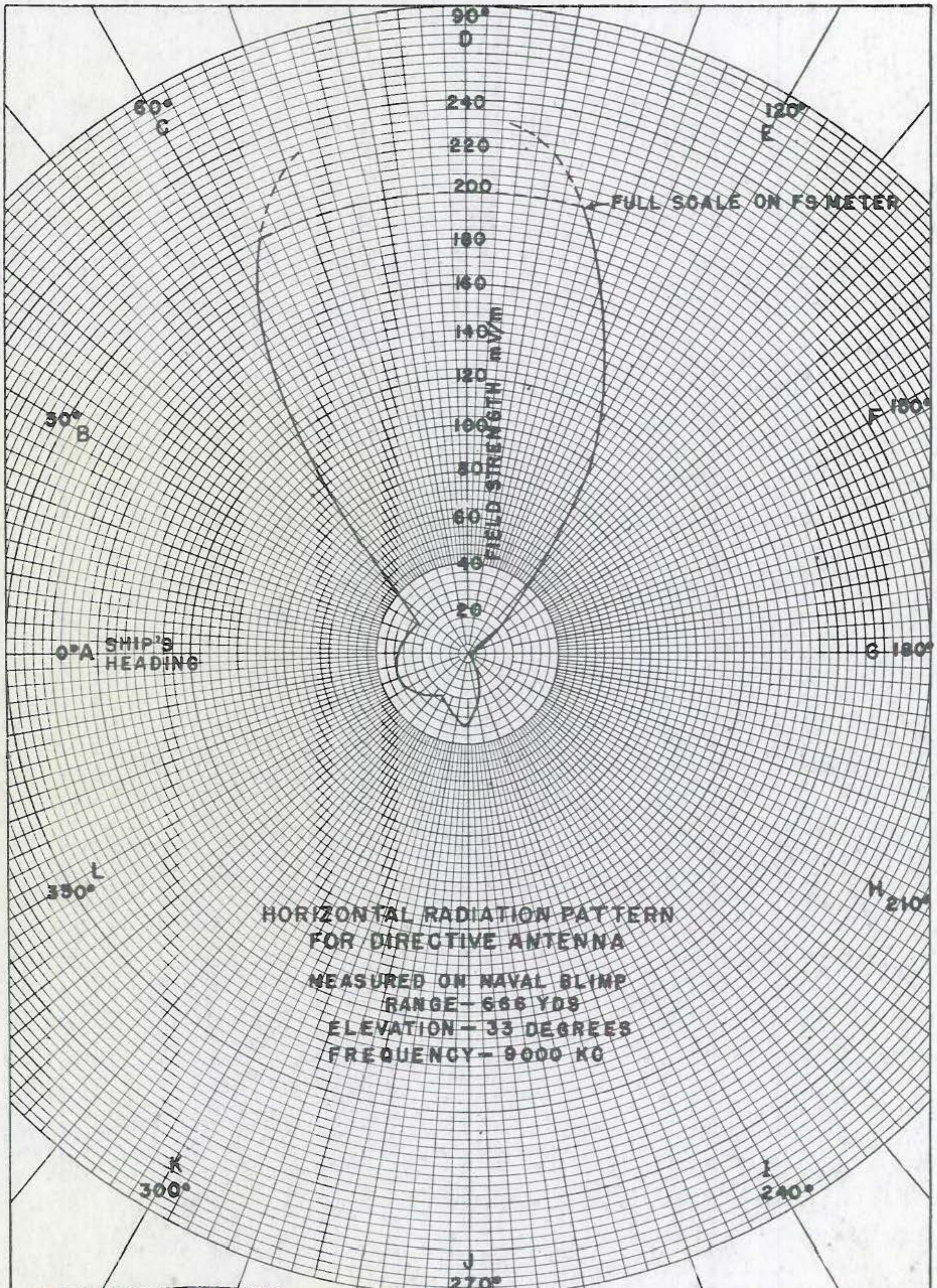

HORIZONTAL RADIATION PATTERN
FOR DIRECTIVE ANTENNA

MEASURED ON NAVAL BLIMP
RANGE — 666 YDS
ELEVATION — 33 DEGREES
FREQUENCY — 9000 KC

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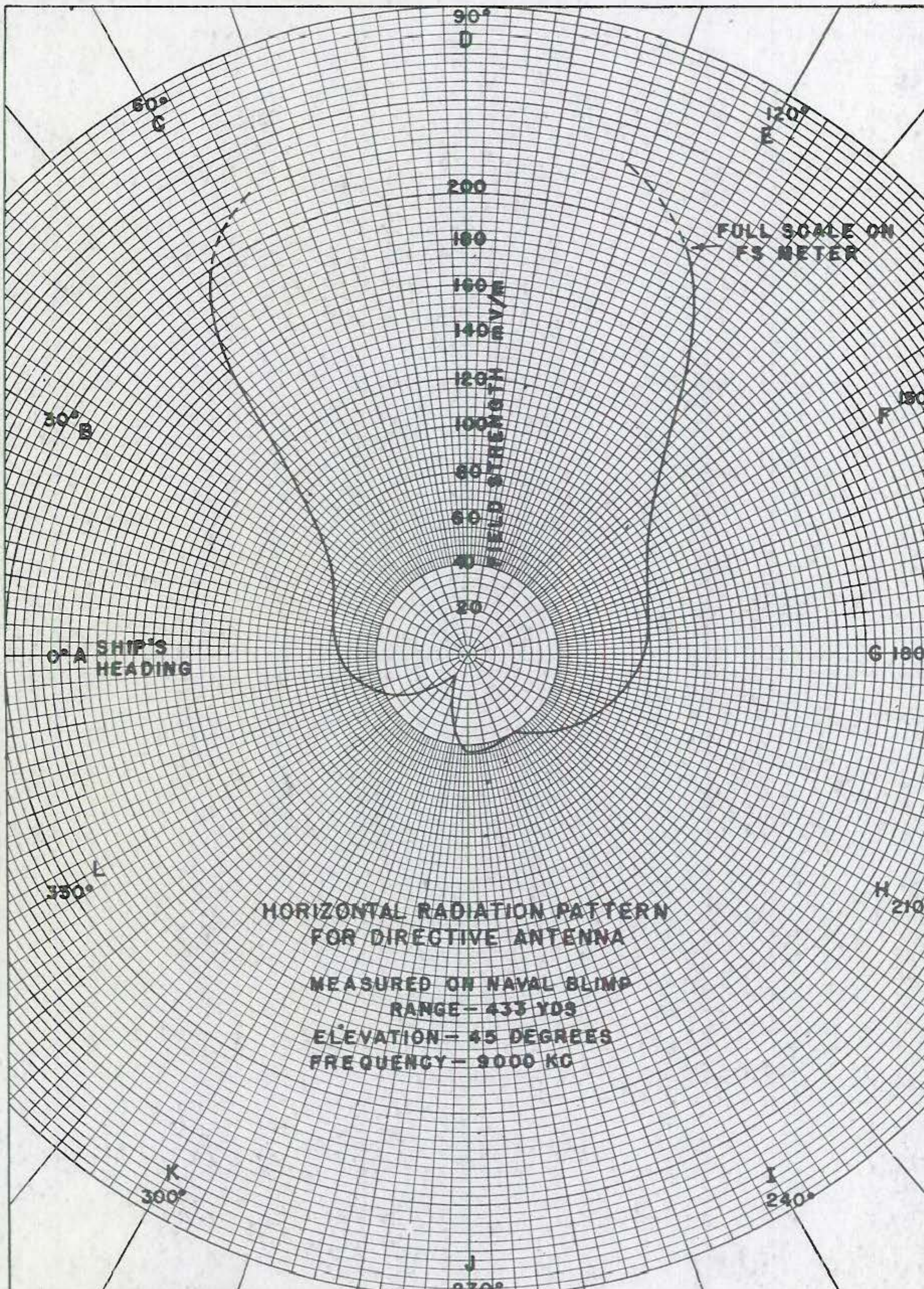

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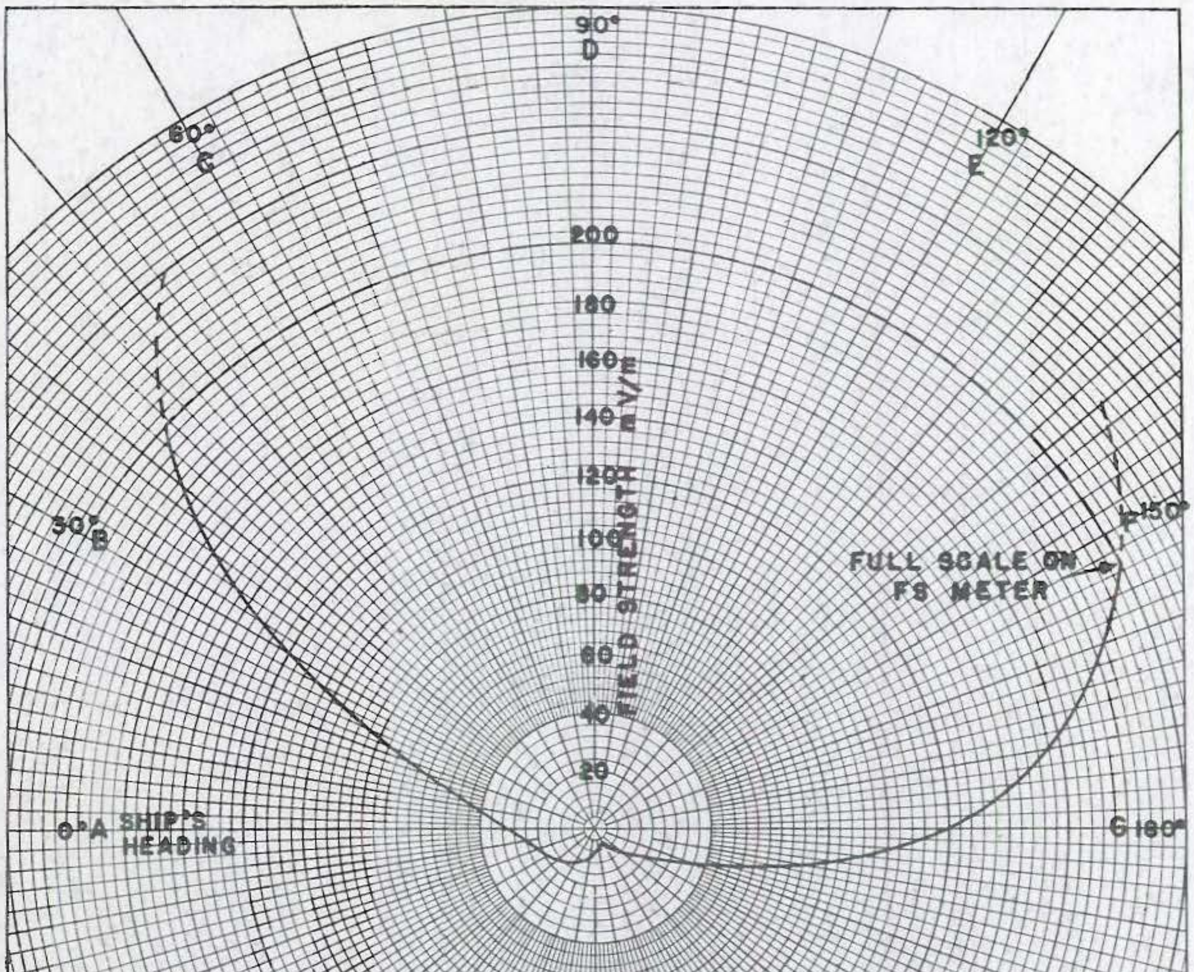

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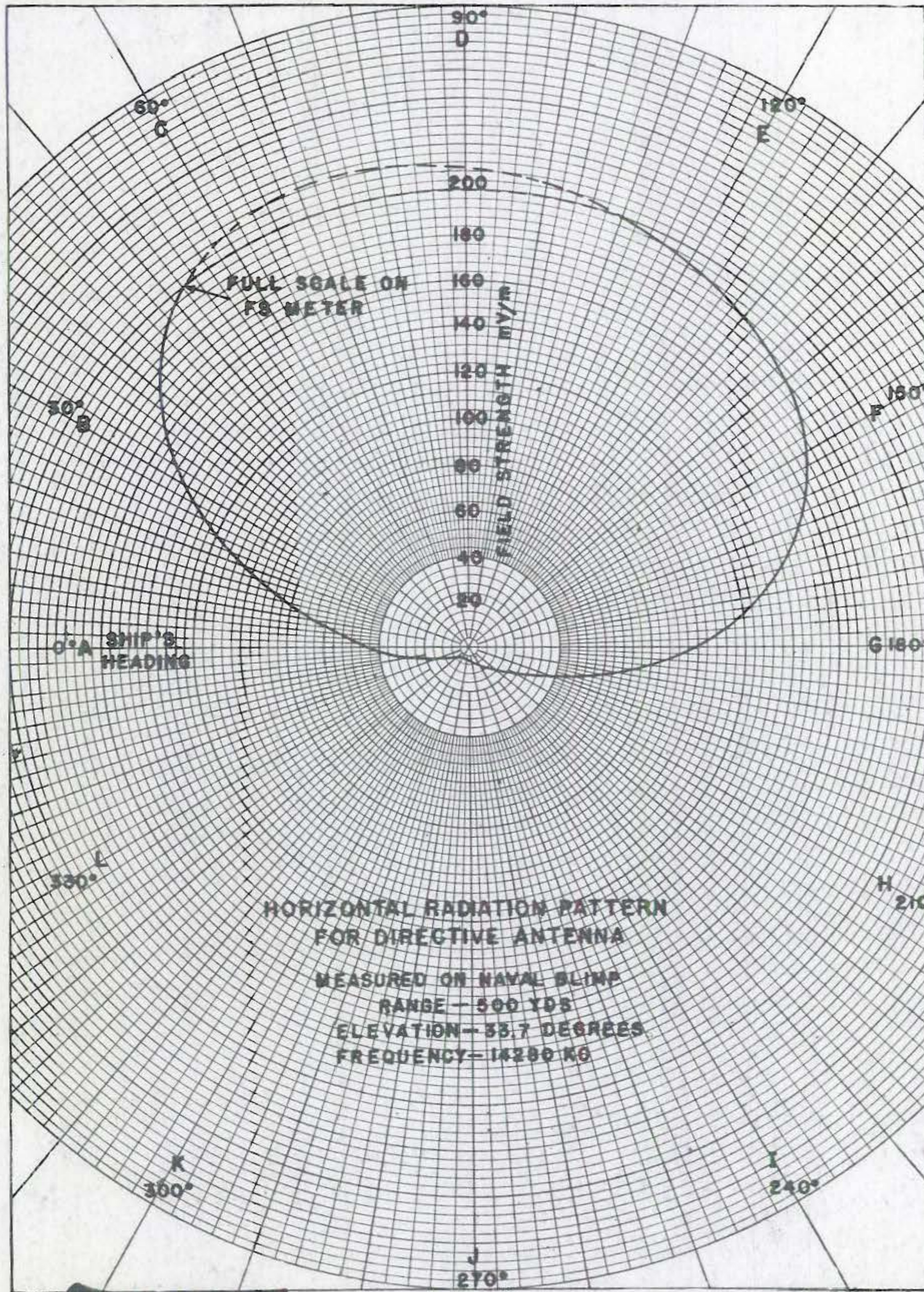

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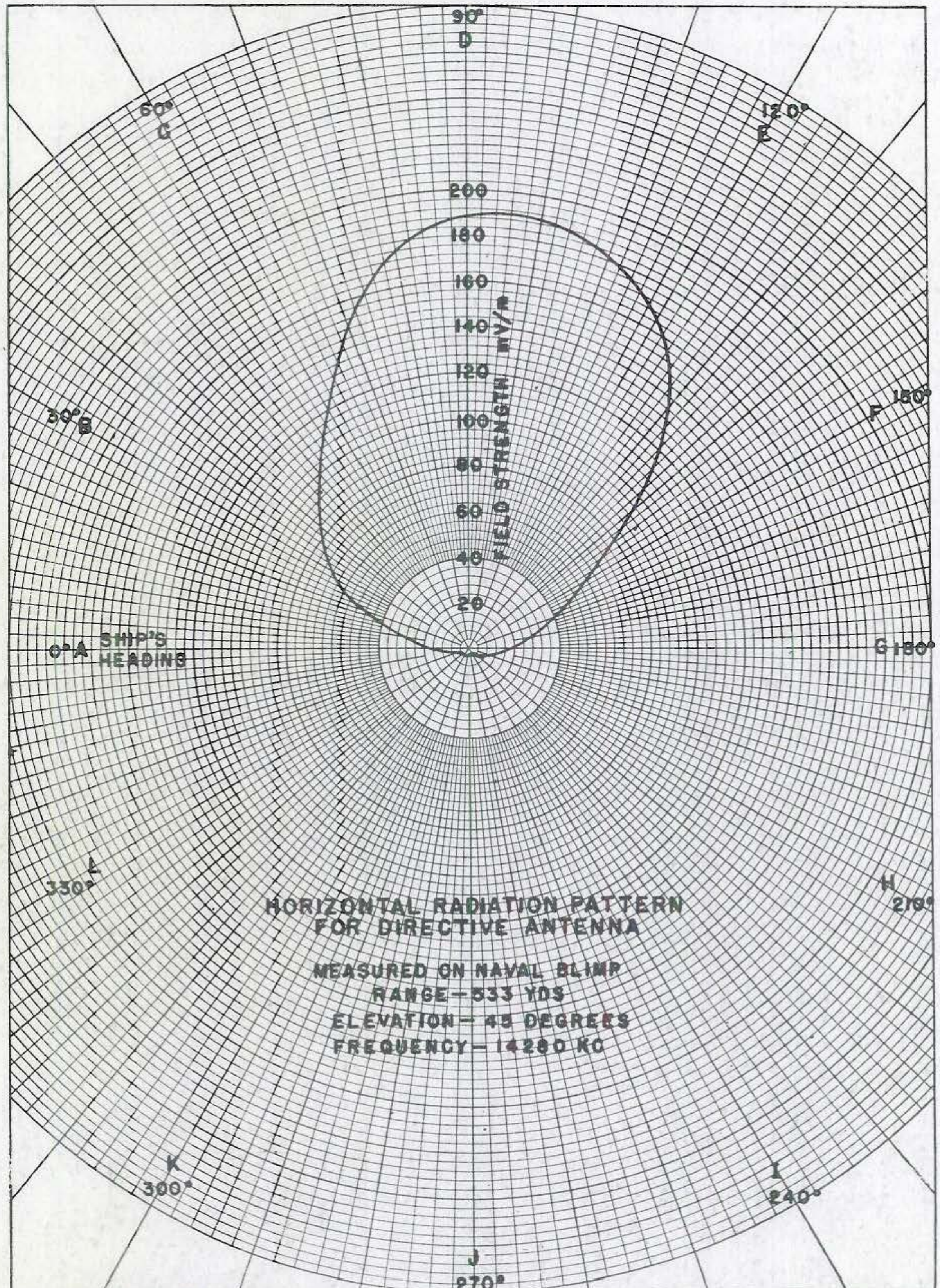

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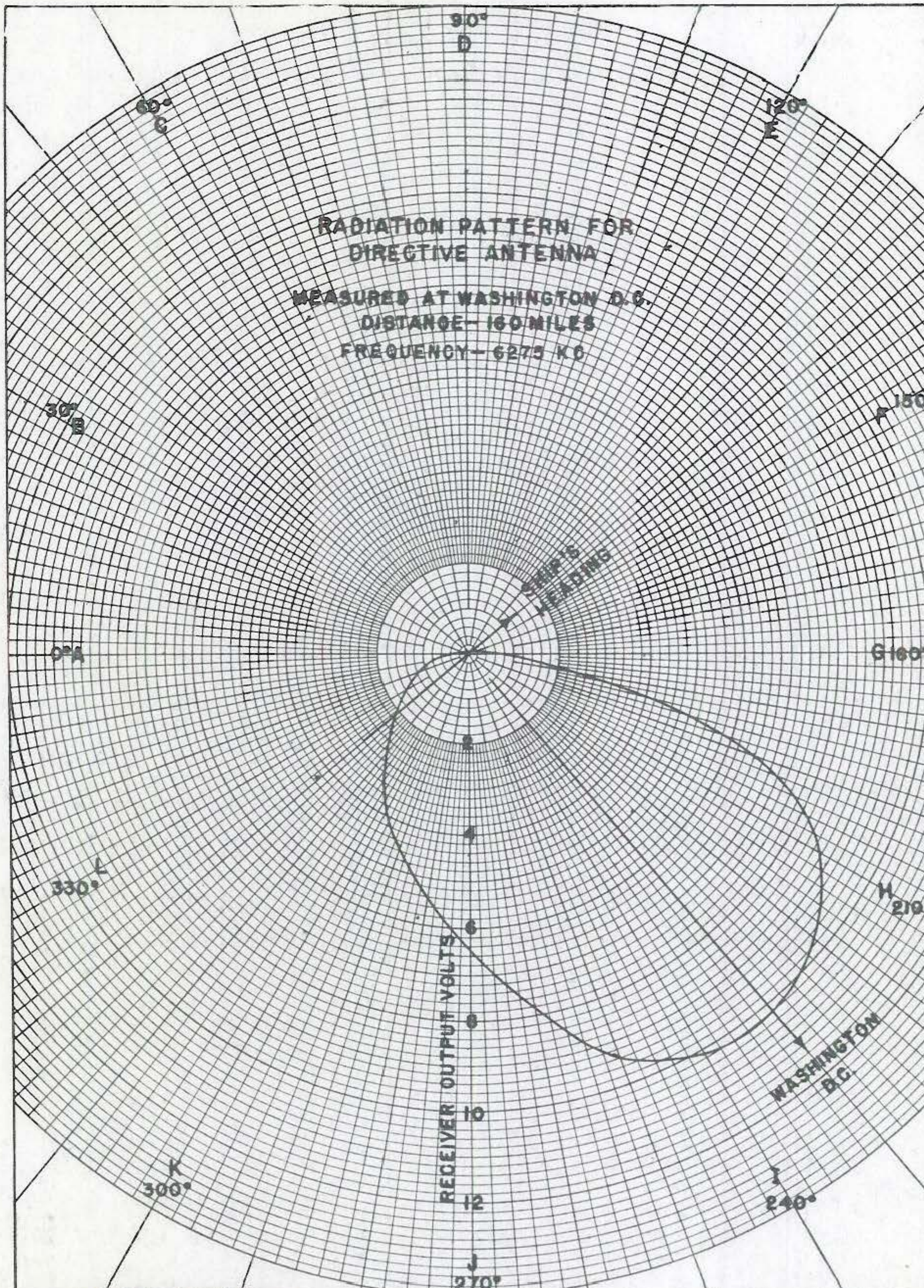

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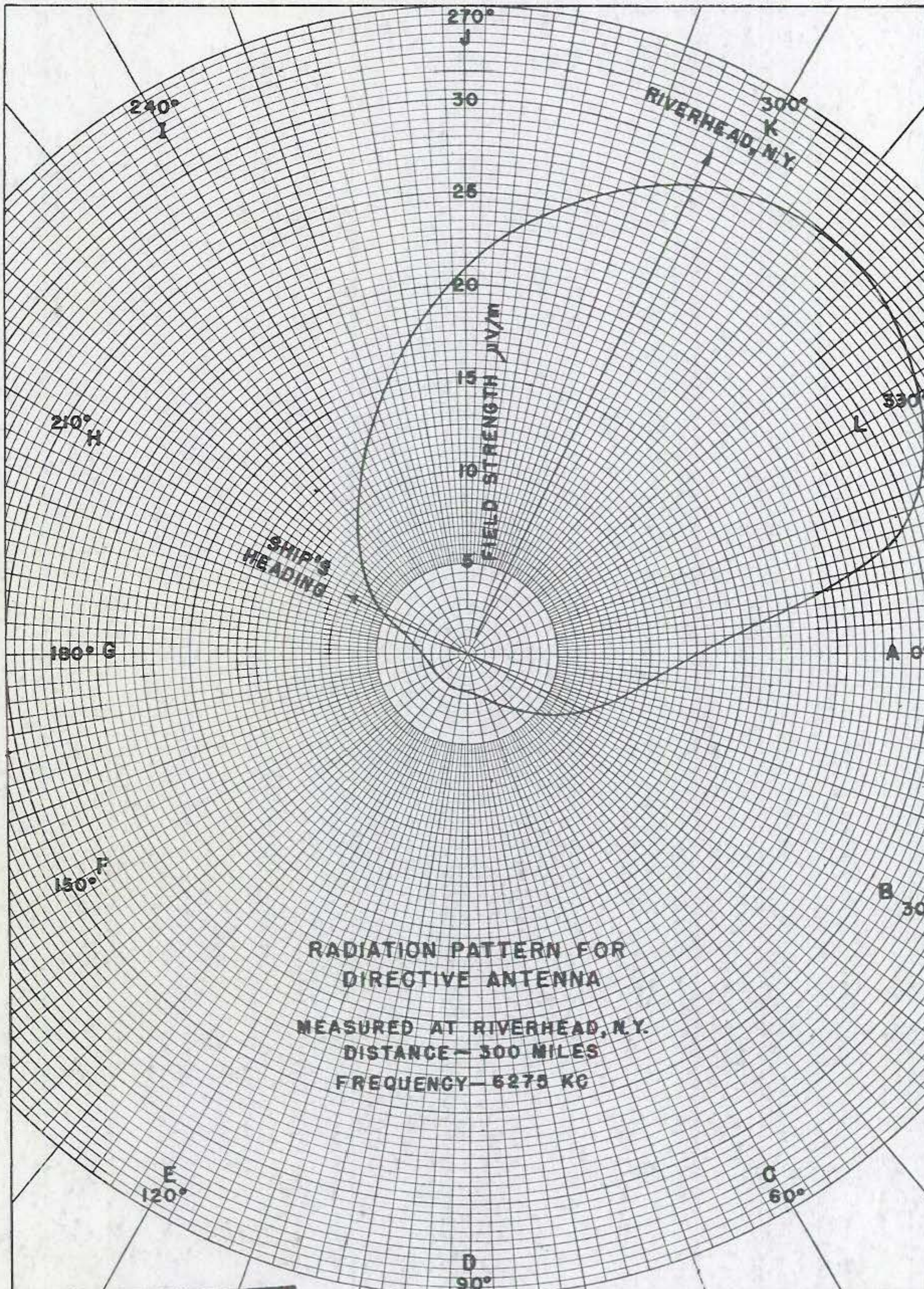

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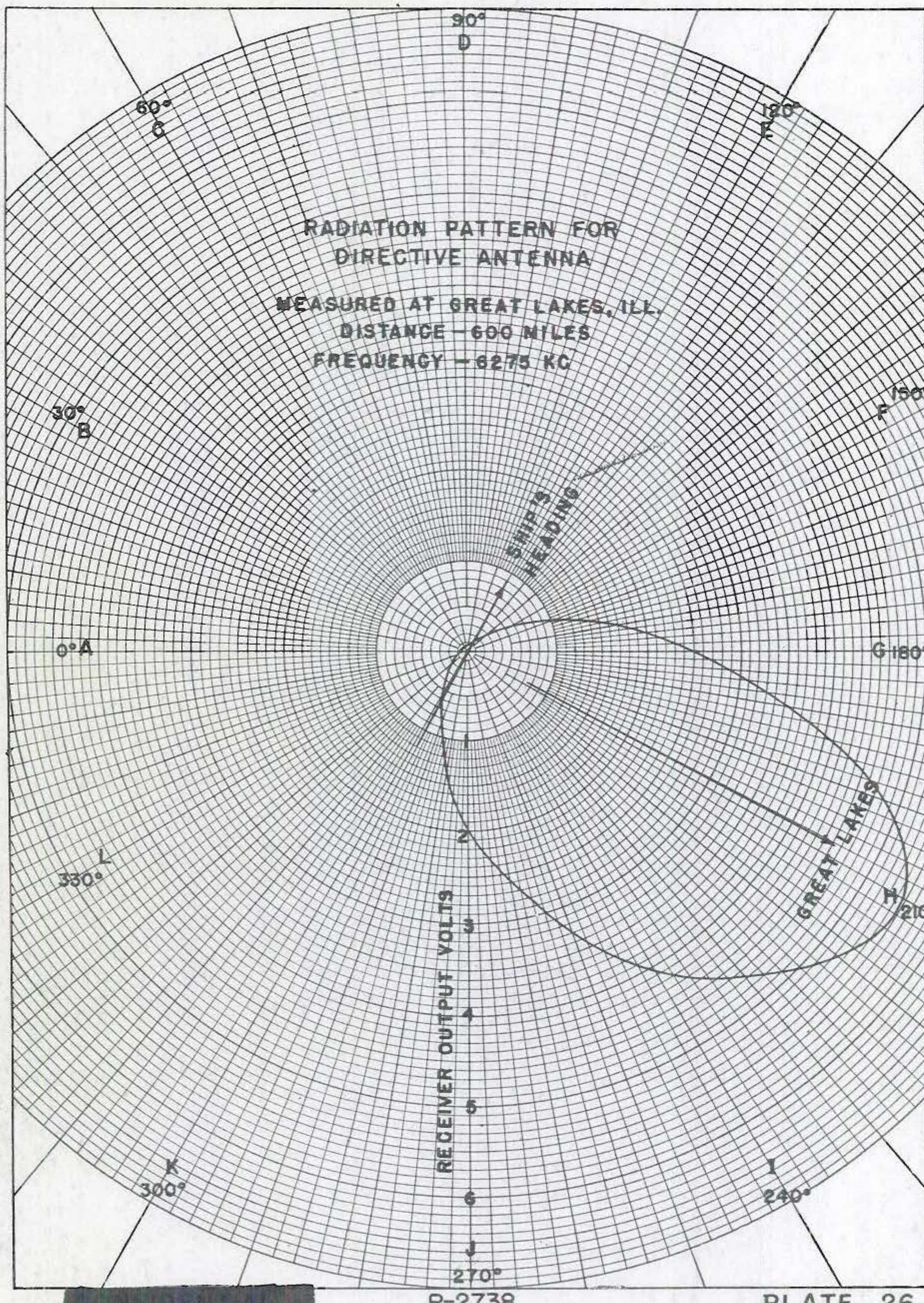

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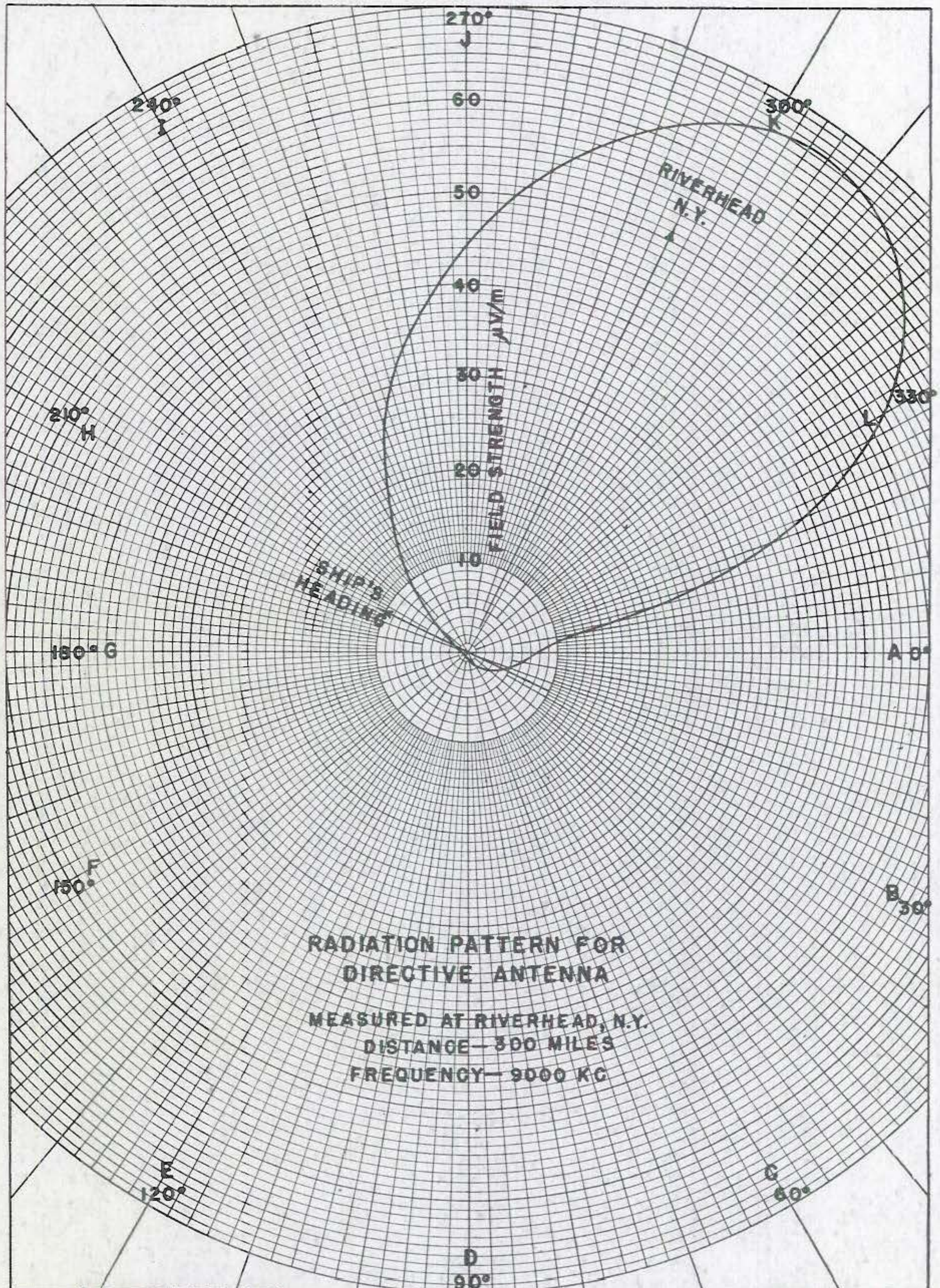

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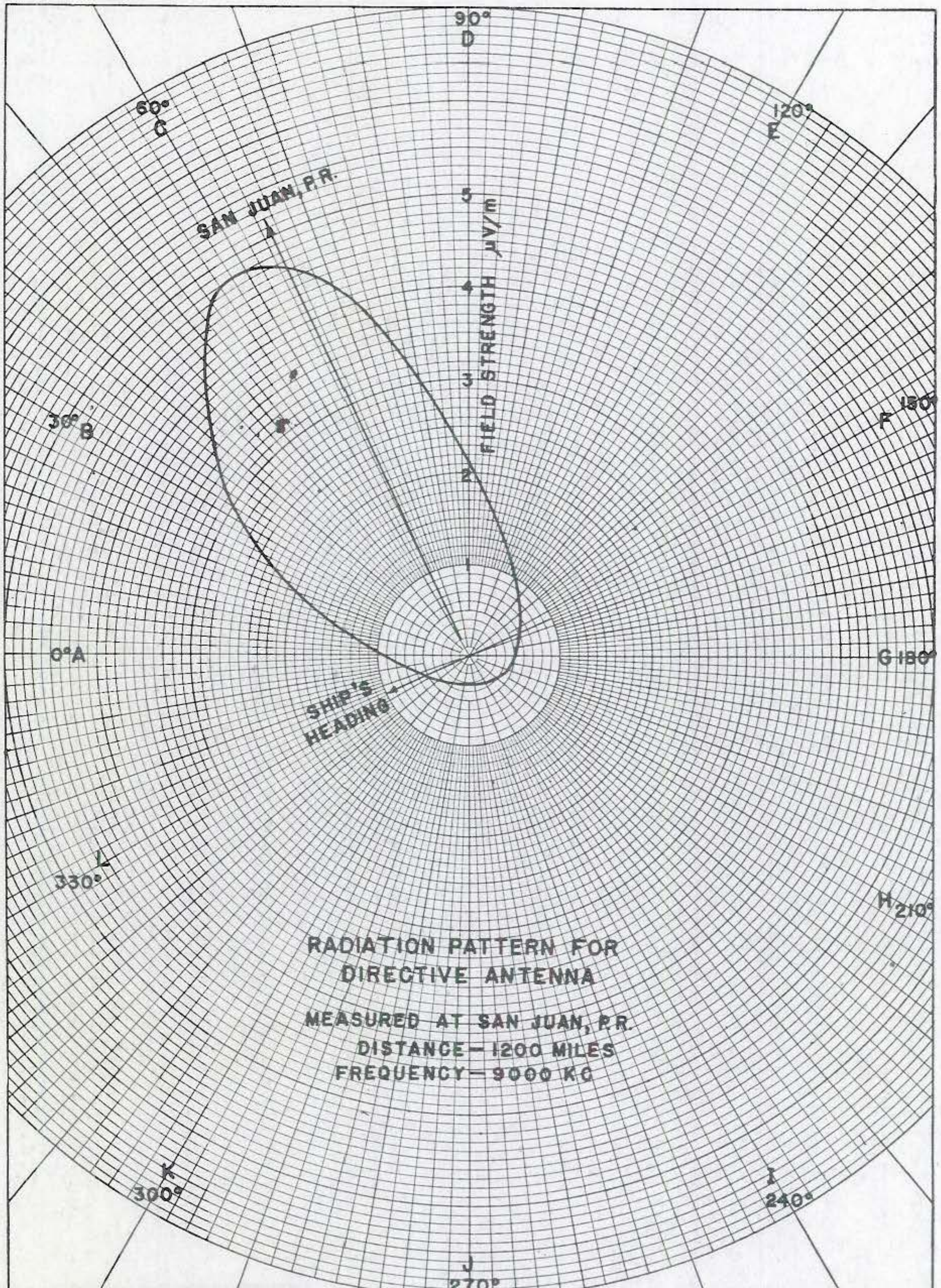

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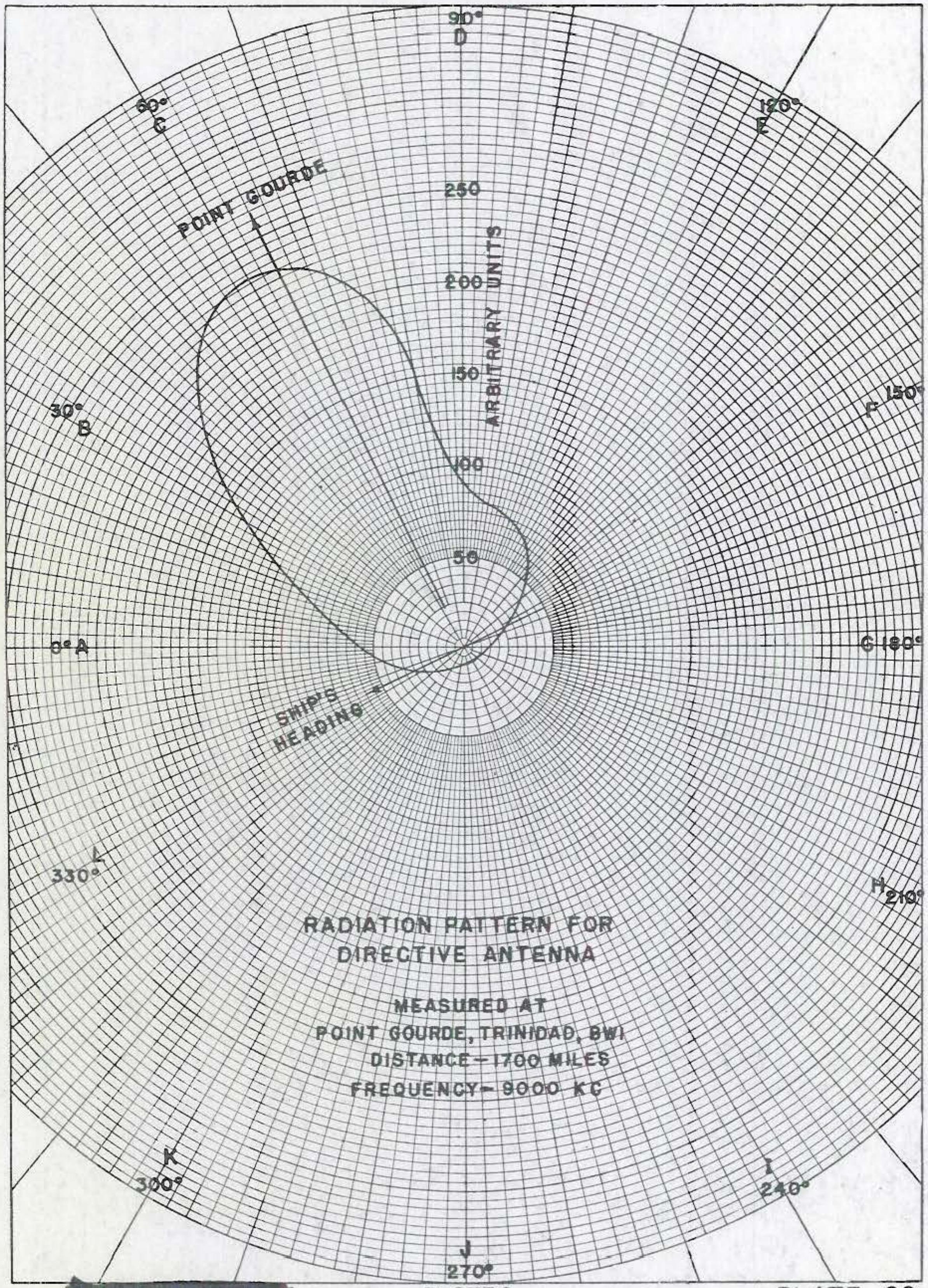

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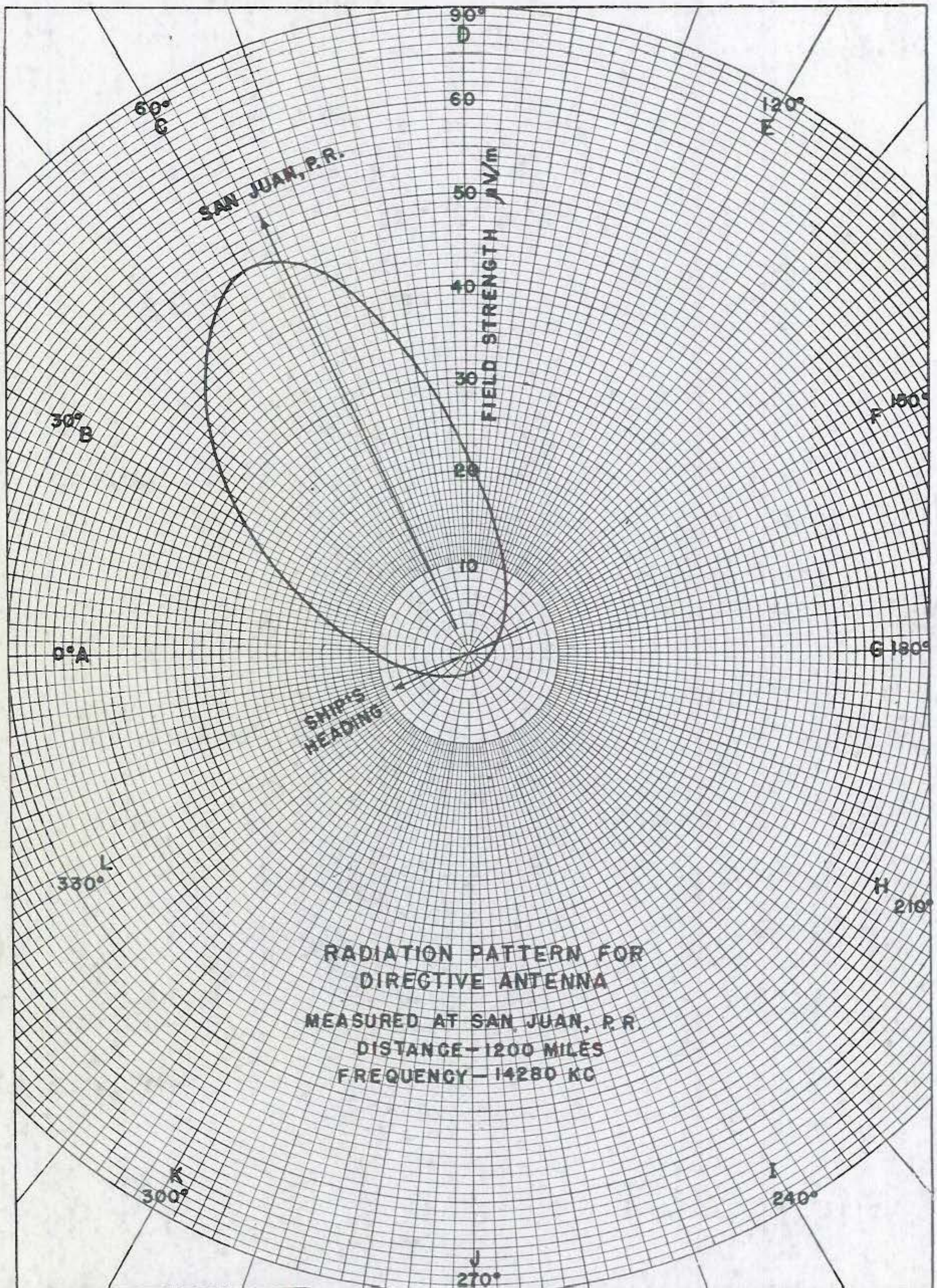
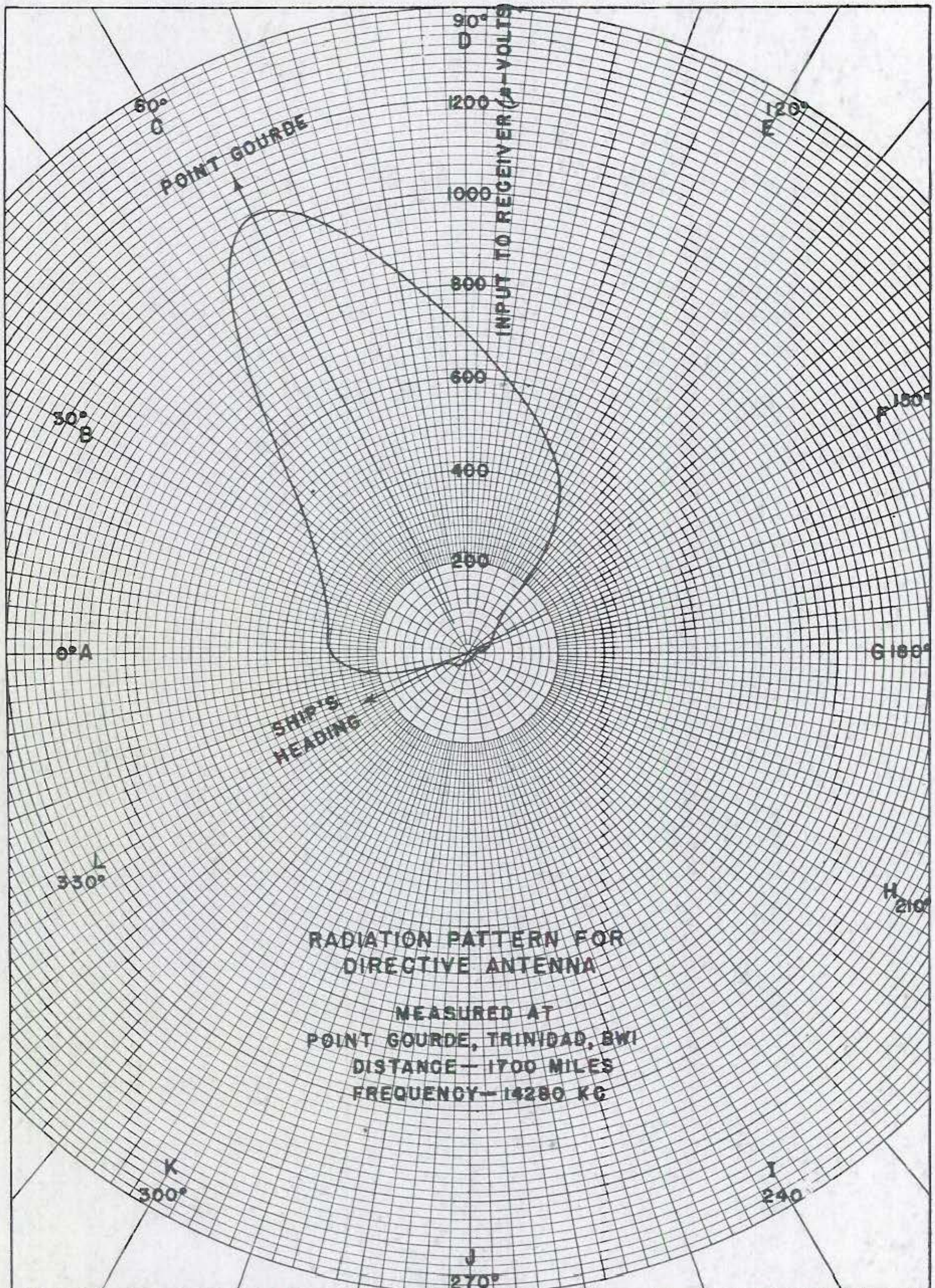


RADIATION PATTERN FOR DIRECTIVE ANTENNA

MEASURED AT SAN JUAN, P.R.
DISTANCE—1200 MILES
FREQUENCY—14280 KC

DECLASSIFIED



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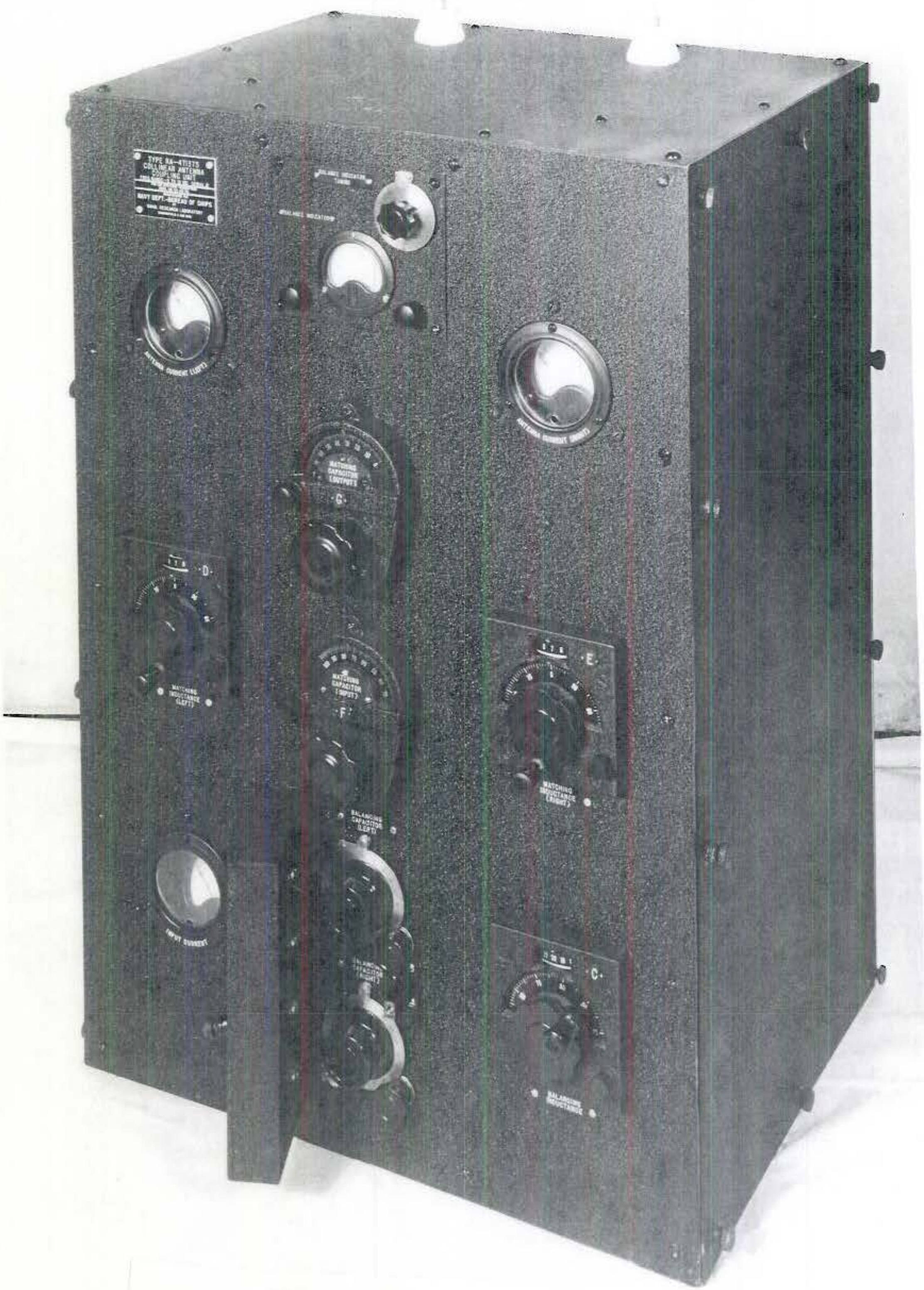
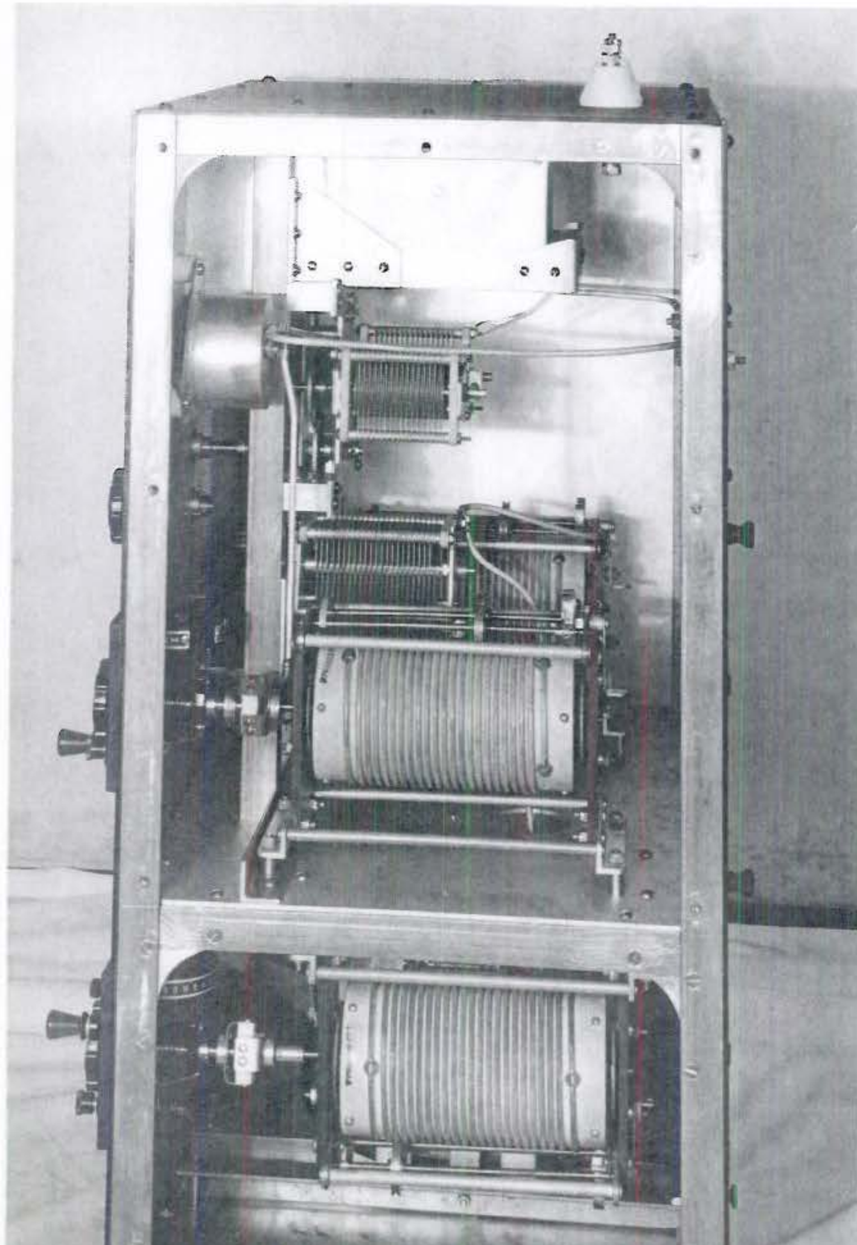


DECLASSIFIED

[redacted]

TYPE RA-471375 COLLINEAR ANTENNA
COUPLING UNIT - FRONT OBLIQUE VIEW

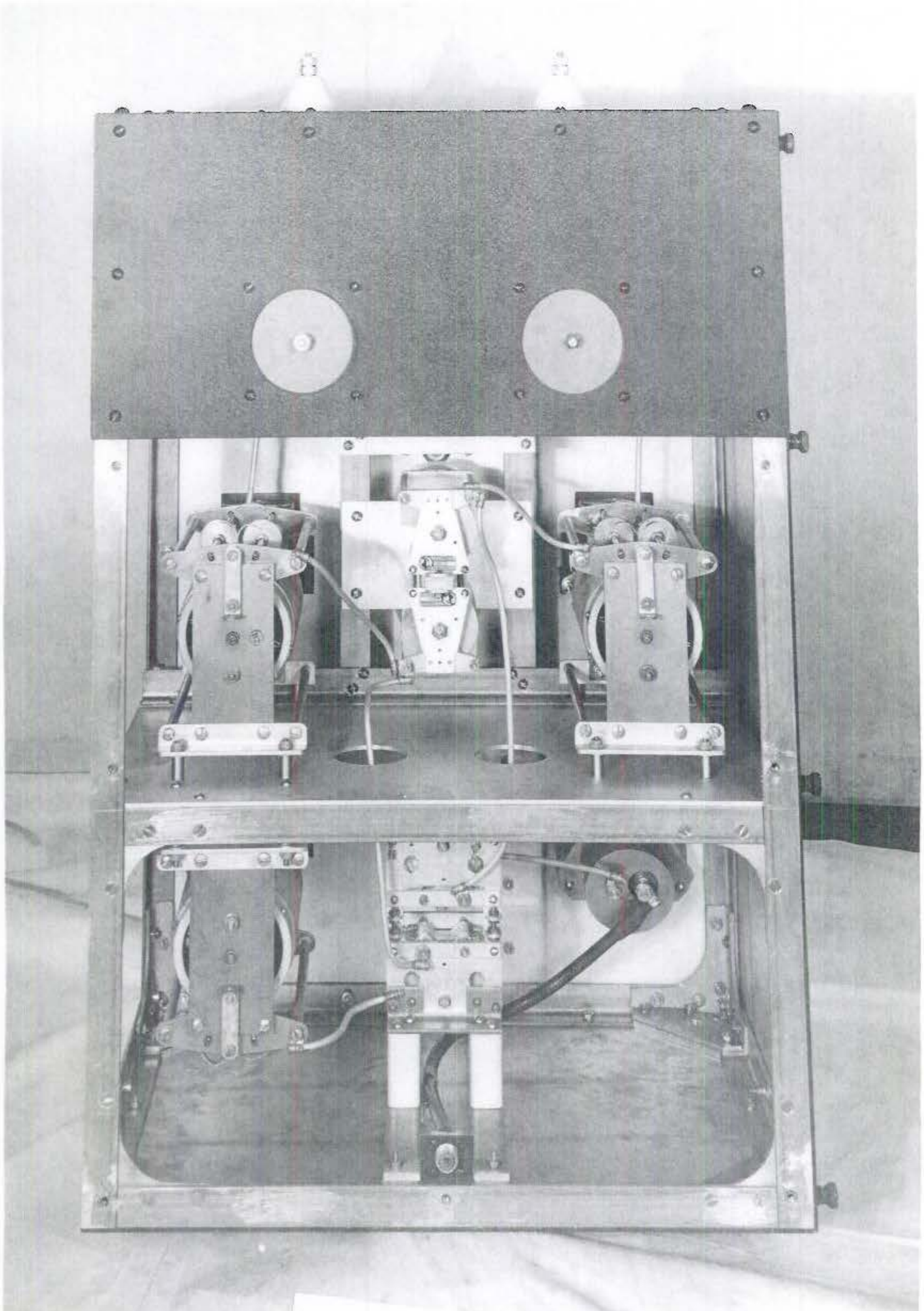
PLATE 32



TYPE RA-471375 COLLINEAR ANTENNA
COUPLING UNIT - SIDE VIEW, SHIELD REMOVED

[redacted]

DECLASSIFIED

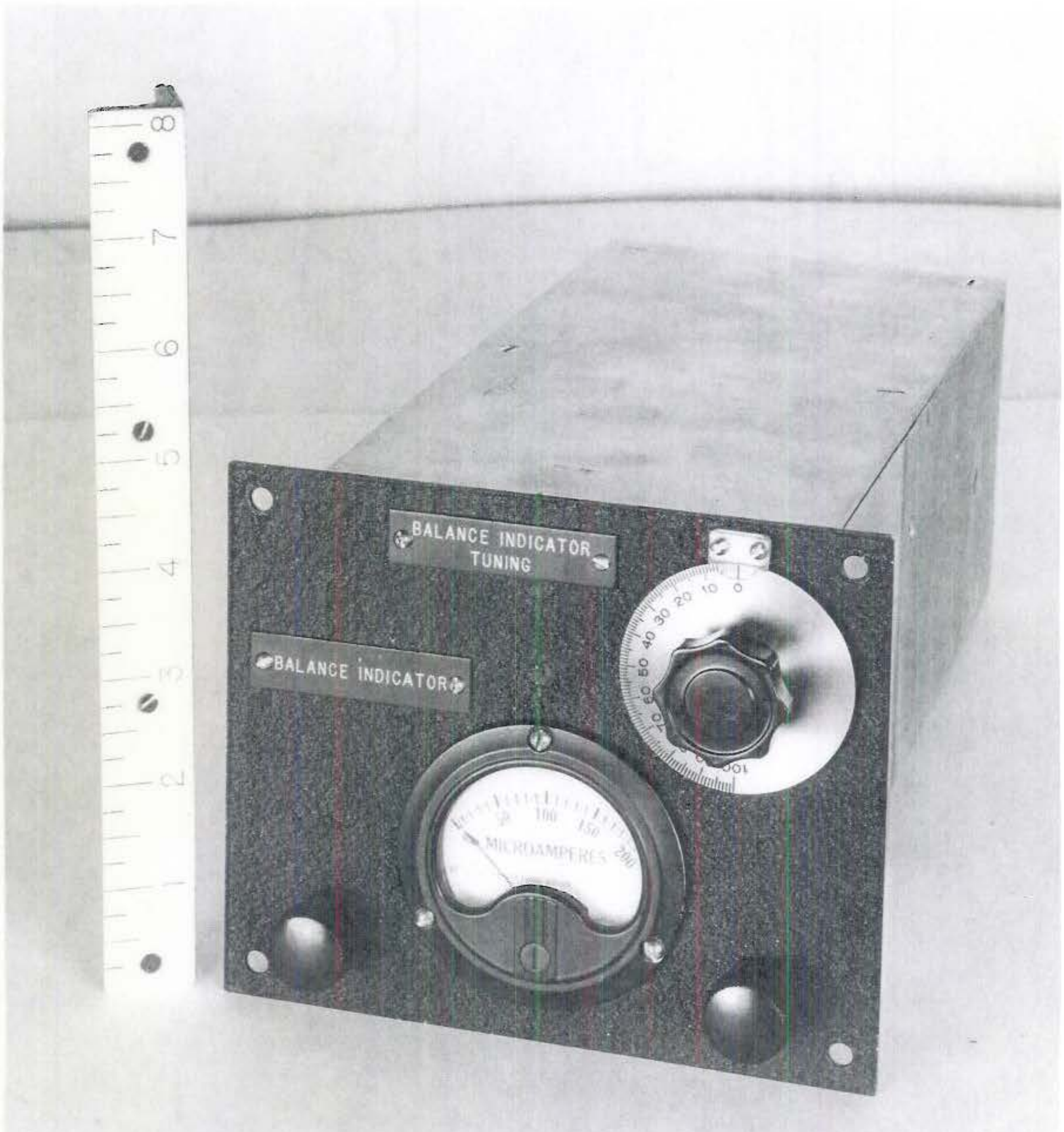


DECLASSIFIED

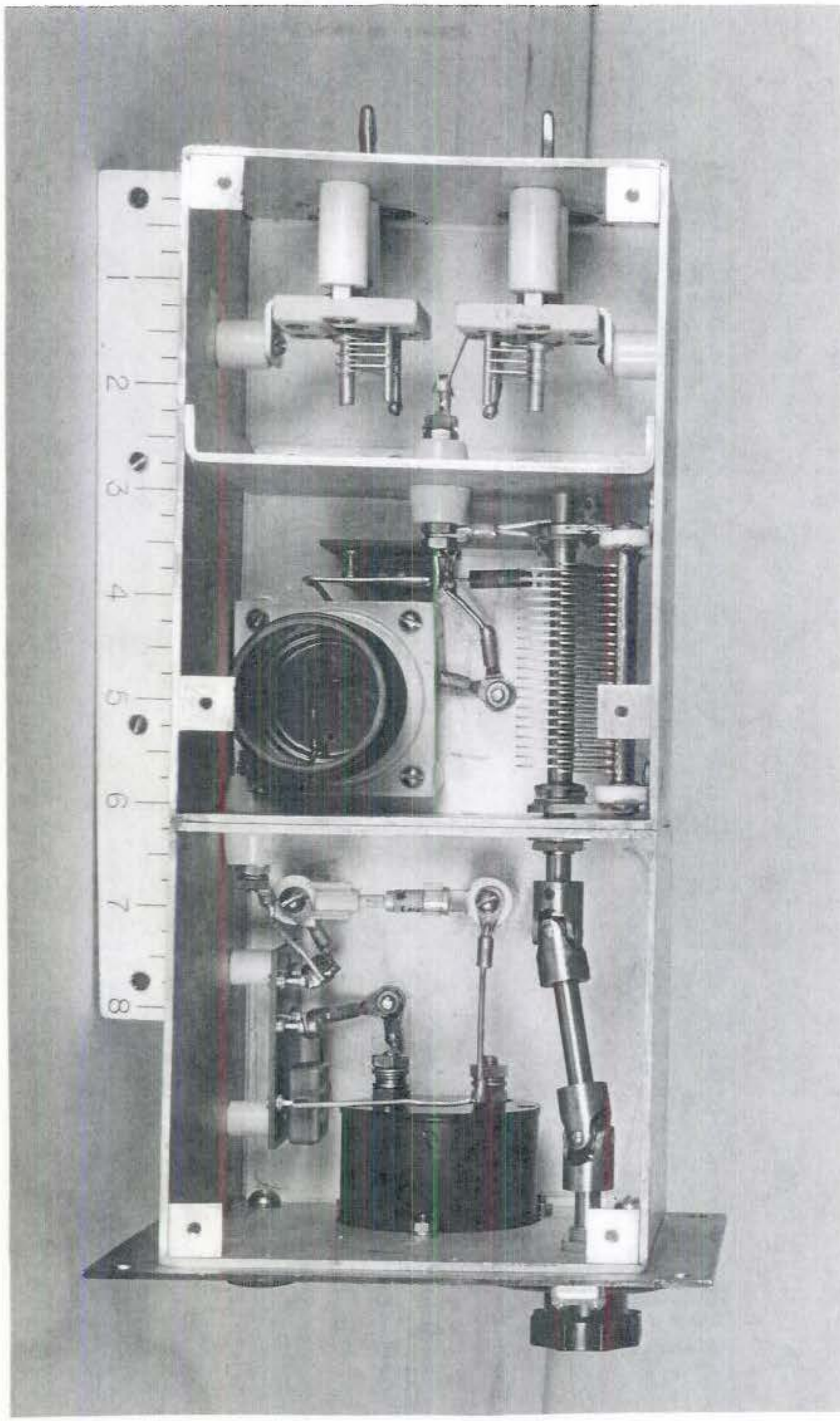
[redacted]

TYPE RA-471375 COLLINEAR ANTENNA
COUPLING UNIT - REAR VIEW, SHIELD REMOVED

PLATE 34



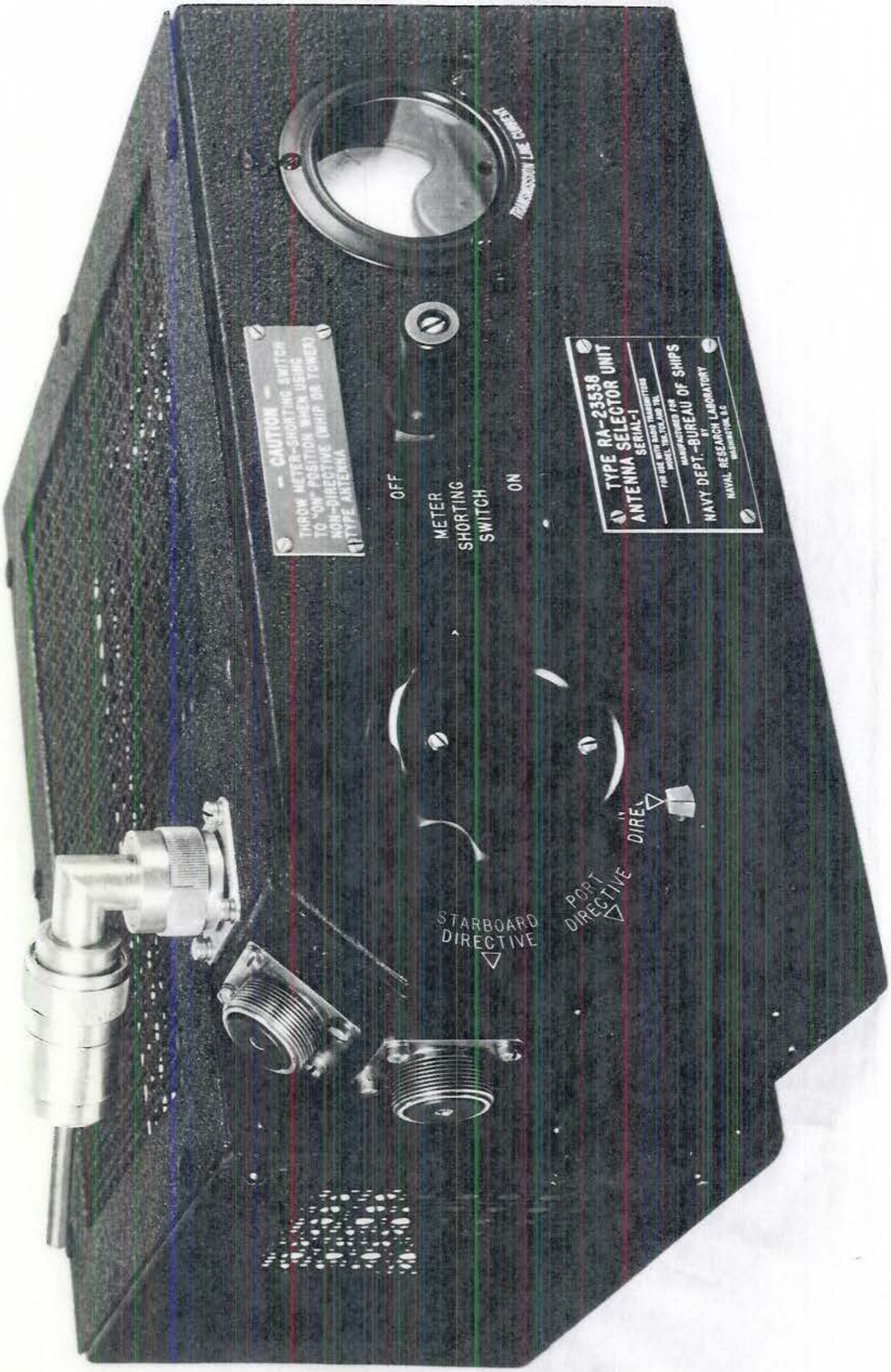
BALANCE INDICATOR UNIT
FRONT OBLIQUE VIEW



BALANCE INDICATOR UNIT
PLAN VIEW, COVER REMOVED

DECLASSIFIED

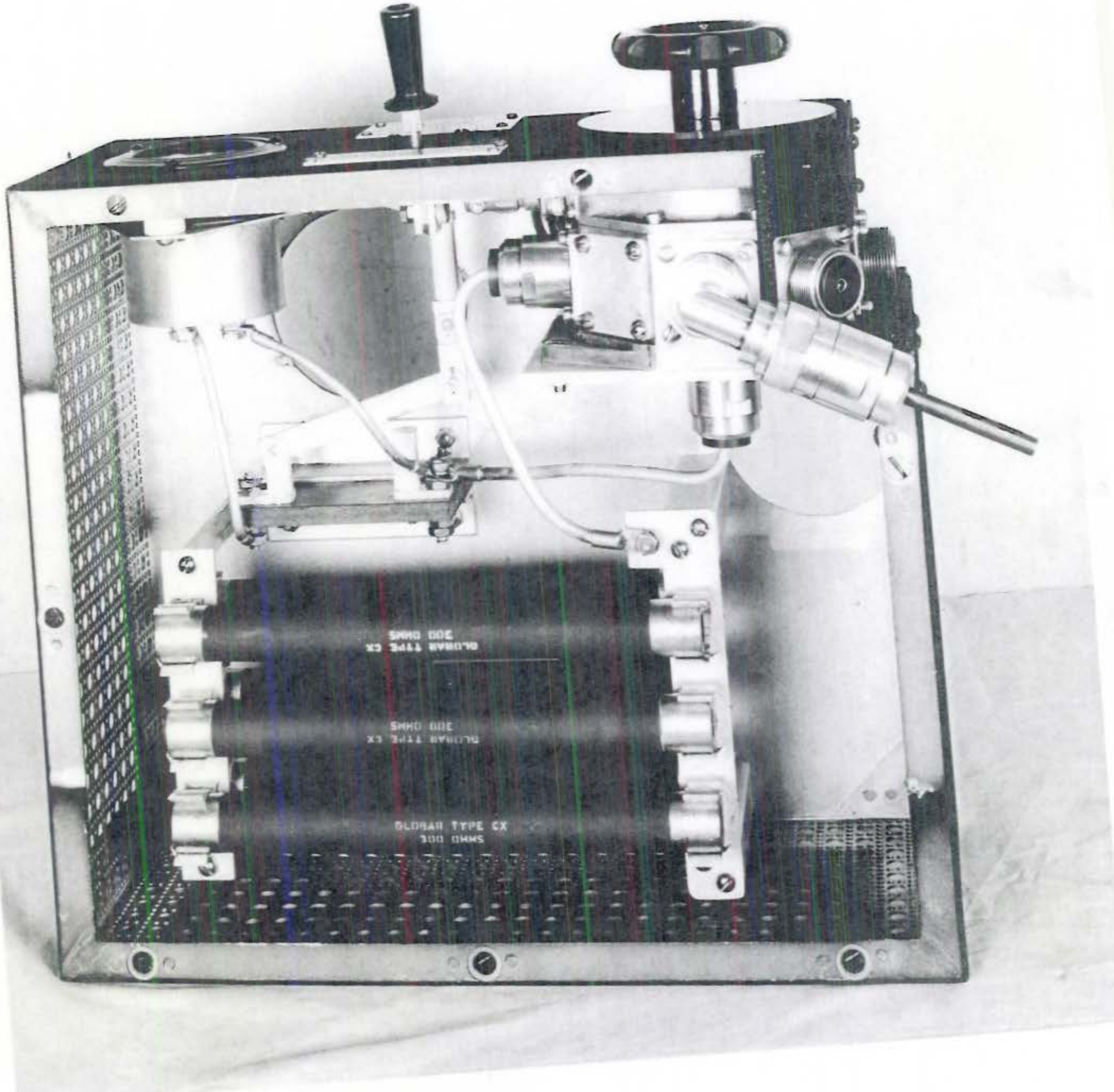
[redacted]



TYPE RA-23538 ANTENNA SELECTOR UNIT
FRONT OBLIQUE VIEW

DECLASSIFIED

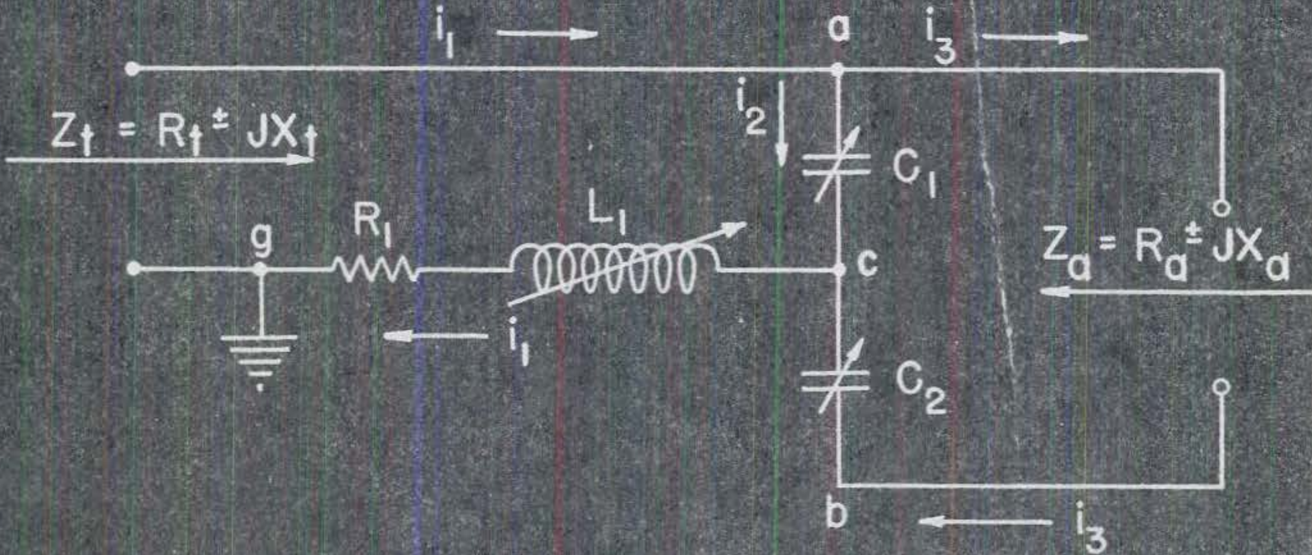
[redacted]



TYPE RA-23538 ANTENNA SELECTOR UNIT
PLAN VIEW, COVER REMOVED

DECLASSIFIED

[redacted]



i_1, i_2, i_3 — CURRENTS IN BALANCING CIRCUIT.

Z_t — TRANSMISSION LINE TERMINATING IMPEDANCE.

Z_o — OUTPUT TERMINAL IMPEDANCE.

$C_1, C_2,$ — BALANCING CAPACITORS.

L_1 — BALANCING INDUCTANCE.

R_1 — R-F RESISTANCE OF INDUCTANCE L_1

SCHEMATIC DIAGRAM OF BALANCING CIRCUIT
(UNBALANCED TO BALANCED FEED NETWORK)

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