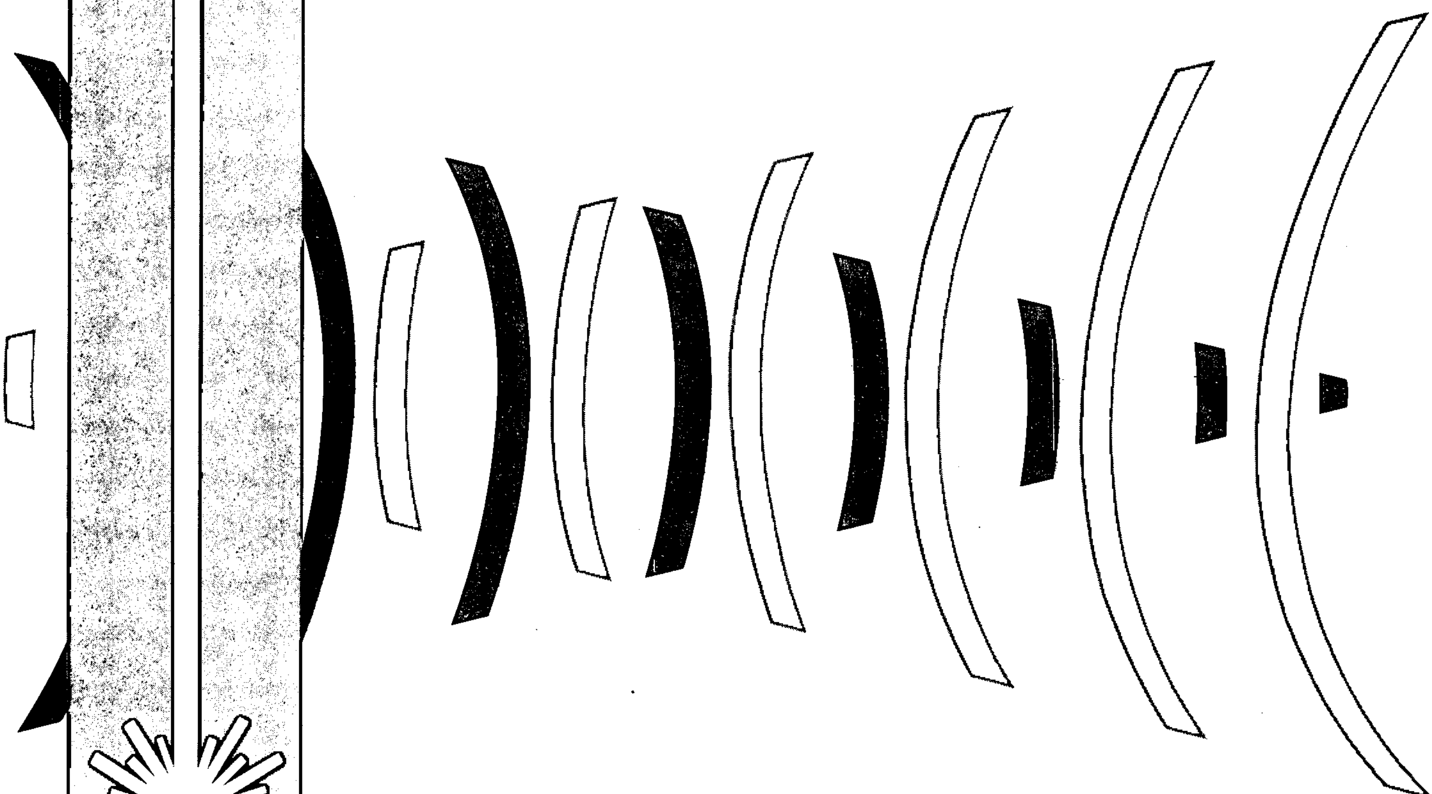
Measurement of Power Density from Marine Radar



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Measurement of Power Density from Marine Radar

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FOREWORD

The Bureau of Radiological Health conducts a national program to limit man's exposure to ionizing and nonionizing radiations. To this end, the Bureau (1) develops criteria and recommends standards for safe limits of radiation exposure, (2) develops methods and techniques for controlling radiation exposure, (3) plans and conducts research to determine health effects of radiation exposure, (4) provides technical assistance to agencies responsible for radiological health control programs, and (5) conducts an electronic product radiation control program to protect the public health and safety.

The Bureau publishes its findings in appropriate scientific journals and technical report and note series prepared by Bureau divisions and offices. Under a memorandum of agreement between the World Health Organization and the Bureau of Radiological Health, the Bureau became a WHO Collaborating Center for Standardization of Protection Against Nonionizing Radiation. As a WHO Collaborating Center, the Bureau makes available its technical reports and notes to participating WHO members.

Bureau publications provide an effective mechanism for disseminating results of intramural and contractor projects. The publications are distributed to State and local radiological health personnel, Bureau technical staff, Bureau advisory committee members, information services, industry, hospitals, laboratories, schools, the press, and other concerned individuals. These publications are for sale by the Government Printing Office and/or the National Technical Information Service.

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John C. Villforth
Director
Bureau of Radiological Health

PREFACE

The Food and Drug Administration's Bureau of Radiological Health is responsible for implementing the Radiation Control for Health and Safety Act of 1968. Among other requirements, the Act directs the Bureau to study and evaluate emissions of and conditions of exposure to electronic product radiation. In fulfillment of this responsibility, the Bureau's Division of Electronic Products has conducted a study to determine the microwave power density levels emanating from small craft marine radar units.

This report details the results of the marine radar study. It describes the instrumentation and measurement techniques used and presents a comparison of theoretically calculated and experimentally measured power densities from marine radar.

Roger H. Schneider
Director
Division of Electronic Products

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ABSTRACT

This paper describes both theoretical predictions of and empirical measurements of the magnitude of microwave power density radiating from small-craft marine radar units. A brief compendium of relevant manufacturers' specifications is also presented.

MEASUREMENT OF POWER DENSITY FROM MARINE RADAR

SECTION 1. INTRODUCTION

The Radiation Control for Health and Safety Act of 1968 (P.L. 90-602) declares that the public health and safety must be protected from the dangers of electronic product radiation. This Act requires the study and evaluation of emissions of, and conditions of exposure to, electronic product radiation.

The expanding use of marine radar is increasing the exposure of the public to nonionizing radiation. Therefore, it is necessary that methods be developed to assess microwave power density levels from marine radar to evaluate potential health hazards.

The purposes of the study described in this report are (1) to estimate the range and magnitude of microwave exposure from marine radar and (2) to determine if theoretically calculated power densities, using manufacturer's nominal parameters, are comparable to experimentally measured power densities. This report also points out problems encountered in marine radar power density measurements.

It was impossible to perform measurements on every manufactured type, therefore, measurements were made on only a small sample of marine radar, and the data obtained were compared to the theoretically calculated power density.

SECTION 2. MARINE RADAR COMPONENTS

The term "marine radar," as used in this report, refers to the type of navigational radar used on small pleasure craft. This imposes a limitation on the peak power output of the units of approximately 20 kW, although the peak power on these small boats is usually 10 kW or less. For these units, the range of detection is limited by the earth curvature and the limited antenna height on small craft.

The basic application of a marine radar unit is to detect and display in some convenient form the location of all objects of interest on or close to the surface of the water. Specific objects such as ships, breakwaters, buoys, channel markers, docks, beaches and other landmarks are detected and displayed so that their range and bearing can be determined simultaneously with adequate resolution for safe navigation. Typically, the unit yields a 360° pictorial representation of the area surrounding the transmitting boat extending out to the effective range of the radar. This information is available regardless of visibility, and a radar unit can often determine position more precisely than a visual or radio bearing. These radar units are used for coastal and harbor navigation, coastal charting, harbor surveillance, and related applications.

Most of the units currently on the market operate within the frequency band from 9,330 to 9,500 MHz. The polarization of the transmitted wave is usually horizontal but some units have vertical polarization. The vertical beamwidth of most of the antennas is much wider (18° to 40°) than the horizontal beamwidth (0.8° to 3°) at the -3 dB points of the radiation patterns. The wider vertical beamwidth is used to insure that objects on the surface of the water will be illuminated during the rolling movements of the ship. All civil marine radar units are pulsed. The Pulse Repetition Frequency (P.R.F.), also called Pulse Repetition Rate (P.R.R.), of these transmitters varies from 625 to 6720 pulses per second, and the Pulse Width (P.W.) varies from 0.05 to 1.0 microsecond. These pulses are transmitted by means of slotted waveguide or folded parabolic antennas whose power gains vary from approximately 24 to 33 dB. Depending on the gain of the antenna, the peak power of the transmitters, and other relevant parameters, the maximum range of these units varies from 16 to 48 nautical miles.

The basic components of a radar consist of an antenna, transmitter, receiver, and convenient display. The most commonly used type of antenna is the slotted waveguide (linear-array). The slots in the waveguide are inclined to the vertical and spaced about 0.5 (waveguide) wavelength apart and coupled in alternate phases to create an equiphase surface at the antenna aperture. An equiphase surface is one in which all electric field vectors are either in phase or 180° out of phase with each other. This slotted waveguide is positioned in the throat of a flare antenna. This linear array design results in relatively low sidelobes. The horizontal sidelobes within ± 10° of the main beam can be less than -30 dB. The bandwidth of the waves that the antennas will propagate is inherently narrow and is usually limited to 5 percent of the transmitted frequency.

The power source feeding the antennas in marine radar units is usually a cavity magnetron. The cavity magnetron transmitting tubes used in these units range up to 75 kW in peak power output, but commonly the types found on small pleasure craft do not exceed 20 kW. Improved receiver noise figures now allow lower output powers to be used with results comparable to higher output units.

All civil marine radars are pulse-modulated in order that the range may be measured by timing reflected signals. The modulator turns the tube off and on so as to generate the desired waveform. The three basic types of modulators presently in common usage are the line-type, the hard-tube or valve type, and the pulsactor type. The hard-tube type is frequently used because the pulse length, pulse shape, and pulse repetition frequency can be changed with ease. In addition, the time jitter from pulse to pulse is quite small.

After a portion of the transmitted wave has been reflected by the object of interest to the antenna, the reflected signal or echo is analyzed by the receiver and fed to a suitable display unit.

In all the present display systems, the data are presented on a cathode-ray tube (CRT) face. The range scales consist of concentric circles centered in the middle of the CRT face. The bearing-marker typically consists of a radial line rotating 360° about the center of the CRT face. The rotation of the radial line is synchronized with the antenna rotation. The heading-marker, which can be a radial trace or a marker point, indicates the direction of the ship. All bearings are read relative to the ship's heading. The displays can be relative-motion or true-motion configurations. The relative-motion display presents all objects relative to the sending ship which is stationary at the center of the display. For example, a stationary target ahead appears to be moving toward the ship. The true-motion display shows the true-motion of the sending ship and all targets on a nautical chart.

SECTION 3. THEORETICAL PREDICTIONS

Initially, predictions of the far-field power densities resulting from the operation of marine radar were computed by employing (a) conventional far-field antenna relationships and (b) nominal manufacturers' specifications. In section 5 and tables 2, 3, 4, and 5, these computed values are compared with the actual measured values of power density. Among the several factors which might tend to cast doubt on the applicability of such "ideal" computations are the particular siting considerations present in each actual nonideal case (including, for example, reflections from nearby structures), and the variation in unit-to-unit performance resulting from manufacturing tolerance. Table 1 presents the nominal values of key parameters of many (but not all) of the small craft radar units which are currently in use.

Several relations are important in determining the theoretical predictions against which actual measurements were subsequently compared. One of the most fundamental is

$$|\vec{S}| = \frac{P_t G}{4\pi |\vec{r}|^2} \qquad (1)$$

where

$|\vec{S}|$ = power density at a distance $|\vec{r}|$ from a transmitting antenna (mW/cm^2) 211

P_t = power transmitted (mW)

G = power gain in the direction of $\vec{r}$ of an antenna with respect to an isotropic source (dimensionless quantity)

$\vec{r}$ = spatial location of the point of measurement with respect to the radiating antenna

$|\vec{r}|$ = distance from the radiating antenna to the point of measurement 223

If the peak (instantaneous) power density is desired, P_t is assigned the value of the peak transmitted power, as listed in table 1. If the time-averaged value of the power density is desired for a nonrotating antenna, P_t is assigned the value of the average transmitted power. This average transmitted power is obtained by multiplying the peak power by the product of the pulse width, τ, and the pulse repetition rate, P.R.R. (see Fig. 1). The latter dimensionless product is known as the duty factor and may be envisioned as the fraction of a pulse cycle actually occupied by the pulse.

A different type of time-averaging is obtained if the rotation of the antenna is taken into account. In this case, the average power density is lower than it would be in the main beam of a fixed antenna since this beam sweeps past the measurement point. Thus, the measurement point occupies the antenna's main beam only during the time that the rotating beam is directed toward the measurement point. An approximate value of this rotating-beam average power density may be obtained by multiplying the fixed-beam power density in the previous paragraph by the factor

$$\frac{-3 \text{ dB horizontal beam width } (^{\circ})}{360^{\circ} \text{ rotation}} \qquad (2)$$

Table 1. Technical Specifications*

Manufacturer or U.S. Distributor	Model	-3dB Horiz. Beam Width(°)	-3dB Vertical Beam Width(°)	Antenna Turn Radius (r_{tc}) (feet)	PRF (PPS)	Pulse Width (μsec)	Frequency (MHz)	Antenna Type	P pk (kW)	Antenna Gain Relative to Isotropic Radiator (db)	Maximum Range (nm)
Astaron	Nova 69	2.4	23	1.83	4000	0.10	9410±30	Slotted	5.0	25	24
					2000	0.25		Waveguide			
					1000	0.70					
	200	1.8	23	2.42	2000	0.50	9410±30	"	5.0	27	24
	250	1.2	23	3.16	2000	0.25	9410±30	"	5.0	29	24
	300	1.2	23	3.16	1000	0.80	9410±30	"	20.0	31	48
	400	0.9	23	4.08			9410±30	"	20.0	31	48
Bendix	MR4	2.6	30	1.71	1600	0.1	9375±30	"	5.0	28	32
(Benmar)	MR5	2.6	30	1.71	625	0.4	9375±30	"	7.5	28	32
	MR6	2.6	30	1.71			9375±30	"	7.5	28	32
Decca	101	2.5	30	1.75	3000	0.25	9445±35	Slotted	3.0	24	15
Marine (ITT)					3000	0.08		Centerfeed			
	Super 101	2.5	30	1.75	1500	0.5	9445±35	"	3.0	24	18
					3000	0.08					
	202	2.5	27	2.12	1000	0.1	9445±35	"	3.0	26	24
					1000	0.5					
	Rm. 914	1.9	20	2.38	3400	0.05	9445±30	Endfed	3.0	28	48
					1700	0.25		Slotted			

*All units listed are in current use, though not all are currently being manufactured.

Table 1. Technical Specifications—Continued

Manufacturer or U.S. Distributor	Model	-3dB Horiz. Beam Width(°)	-3dB Vertical Beam Width(°)	Antenna Turn Radius (r_{tc}) (feet)	PRF (PPS)	Pulse Width (μsec)	Frequency (MHz)	Antenna Type	P_{pk} (kW)	Antenna Gain Relative to Isotropic Radiator (db)	Maximum Range (nm)
Decca Marine	Rm. 916	1.2	20	3.42	850	0.75	9445±30	Endfed Slotted	3.0	30	48
	314	1.9	27	2.25	2000 1000 1000	0.05 0.15 0.5	9410±30	"	10.0	27	48
	316 (416)	1.2	18	3.44	1000	0.5	9410±30	"	10.0	30	48
	319 (419)	0.8	15	4.80	1000	0.5	9410±30	"	10.0	33	48
EMI Electroscan		3.5	25	1.33	2530 2530	0.1 0.3	9445±30	Slotted Waveguide	3.0	24	16
KAAR	LN 55 (3)	2.5	22	1.75	1500	0.18	9375±30	Slotted Waveguide (Endfed)	7.5	26	16
	LN 55 (4)	1.8	25	2.37	1500	0.18	9375±30	"	7.5	28	16
	LN 66 (4)	1.8	25	2.37	1250 2500	0.05 0.5	9370±25	"	10.0	28	24
	LN 66 (8)	0.85	25	4.04	1250	0.05	9370±25	"	10.0	31.5	24
Kelvin Hughes	Type 305	2.2	25	1.5[a]	800 800	0.08 0.6	9375±45	Center-fed	5.0	24	20
	Type 17 (4)	1.8	25	2.0[a]	2200 2200 1100	0.06 0.2 0.5	9445±30	End-fed	3.0	25	24
	Type 17 (6)	1.2	25	3.0[a]	2200 2200 1100	0.06 0.2 0.5	9445±30	"	3.0	27	24

Table 1. Technical Specifications-Continued

Manufacturer or U.S. Distributor	Model	-3dB Horiz. Beam Width(°)	-3dB Vertical Beam Width(°)	Antenna Turn Radius (r_{tc}) (feet)	PRF (PPS)	Pulse Width (μsec)	Frequency (MHz)	Antenna Type	P_{pk} (kW)	Antenna Gain Relative to Isotropic Radiator (db)	Maximum Range (nm)
Kelvin Hughes	Type 18/9 (6)	1.2	25	3.0[a]	3200	0.05	9445±35	Slotted Waveguide	25.0	28	64
	Type 18/12(7.5)	1.0	18	3.75	1600	0.25	9445±35		25.0	31	64
	(10.0)	.75	18	5.0	800	0.75	9445±35		25.0	33	64
Konel	KRA 121	2.5	25	1.5[a]	1000	0.08	9375±30	"	5.0	26	20
					1000	0.6					
	KRA 221	1.8	25	2.0[a]	800	0.08	9375±30	"	10.0	27	32
					800	0.6					
Plessy	MR-12	3.0	40	1.50	6720	0.1	9445±30	"	3.0	24	16
					3360	0.2					
					1680	0.4					
					840	0.8					
Radiomarine	CRM-N6A-10	1.8	25	2.0	800	0.1	9445±30	"	10.0	27	32
					800	0.6					
	N11A	1.7	24	2.42	1600	0.08	9445±30	"	5.0	27	30
					1600	0.25					
Raytheon	1900A	3.0	27	1.38	2000	0.16	9375±30	Folded Parabolic	5.0	25	18

Table 1. Technical Specifications-Continued

Manufacturer or U.S. Distributor	Model	-3dB Horiz. Beam Width(°)	-3dB Vertical Beam Width(°)	Antenna Turn Radius (r_{tc}) (feet)	PRF (PPS)	Pulse Width (μsec)	Frequency (MHz)	Antenna Type	P pk (kW)	Antenna Gain Relative to Isotropic Radiator (db)	Maximum Range (nm)
Raytheon	2840(A)	1.6	21	3.00	4000 2000 1000	0.05 0.5 1.0	9375±30	Slotted Waveguide	20.0	29.5	48
	2900	3.0	22	1.38	3000 1500	0.1 0.67	9375±50	"	7.0	26	32
Ridge	AN/SPS/57	1.8	27	2.0[a]	2000 1000	0.1 0.5	9375±50	"	3.0	27	16
Sperry	Mark VII	1.9	20	2.0[a]			9410±45	"	5.0	24	16
	Mark VII (4)	1.9	20	2.62	1000 1000	0.08 0.6	9410±45	"	5.0	27	16
	Mark VII (6)	1.3	20	3.92			9410±45	"	5.0	29	16
	Mark VIII (4)	1.9	20	2.62	1000 1000	0.08 1.0	9410±45	"	10.0	27	32
	Mark VIII (6)	1.6	20	3.92			9410±45	"	10.0	29	32
	Mark X (4)	1.9	20	2.62	1000 1000	0.1 1.0	9410±45	"	10.0	27	50
	Mark X (6)	1.3	20	3.93			9410±45	"	10.0	29	50

[a] true turn circle slightly larger than this.
No information as to the actual TCR was available.

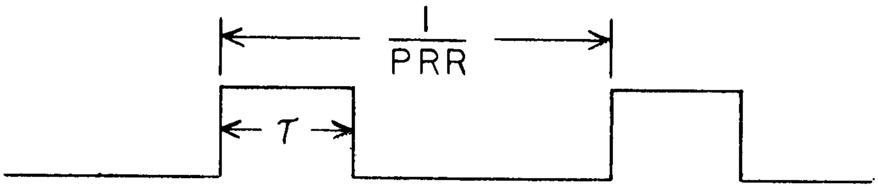

FIG 1. RELATIONSHIP OF τ AND PULSE REPETITION RATE

Although it is apparently not commonly employed on small craft, an option enabling repeated scanning of a small horizontal angular sector is available on some units. The effect of this scanning on average power density is handled in a manner analogous to that employed for the 360° rotation described above: the applicable sector scan is substituted for the 360° denominator.

The approximations employed for both rotating and scanning antennas may be improved for any particular radar unit by considering the horizontal radiation pattern characteristic of the particular antenna employed and determining the mean applicable horizontal gain. This value would then be assigned to G in equation (1) above.

Finally, it should be emphasized that equation (1), in which G is treated as if it were independent of $|\vec{r}|$, is inherently a far-field relationship and cannot be meaningfully employed at close proximity to the radiating antenna. Because of the deterioration of approximations implicit in equation (1) at these close proximities, and because array antennas of the type often employed on marine radar are usually designed to optimize gain in the far field, it is probable that equation (1) will yield values of $|\vec{S}|$ which exceed those which actually exist in regions close to the radiating antenna.

SECTION 4. MEASUREMENT TECHNIQUES

In order to determine if the far-field power density associated with marine radar units in operation can be reasonably approximated by calculations which employ nominal parameters, measurements were made on small craft radar in the Miami-Ft. Lauderdale, Florida, and Mobile, Alabama, areas. These two locations were chosen because of the density of small radar units and the variety in operating conditions and types of units. The units surveyed in Florida were predominantly mounted on pleasure craft as opposed to shrimp boats in Alabama.

Before measuring the power density of a particular marine radar, the environmental frequency spectrum was scanned with a Systron-Donner 751 spectrum analyzer and an Electro-Data AN112F log-periodic antenna. This measurement was made to determine whether or not other sources present contributed any ambiguity to the marine radar power density measurements.

Next, a Narda 640 standard gain x-band horn (8.2 to 12.4 GHz) was mounted atop several short lengths of conduit which were fixed to a tripod, permitting the height of the receiving horn to be continuously varied from 5 to 20 feet. The central axis of the main beam pattern of the receiving horn was visually aligned with the center of rotation of the transmitting antenna. This permitted the central axis of the radar antenna to coincide at some point in its rotation with the central axis of the receiving horn, allowing the maximum power density to be measured. A block diagram of the equipment utilized in the field measurements is shown in figure 2. The microwave power is detected by a Narda P603-4.5 bolometer element for reading on a Narda 66A3A peak power meter. The Narda 66A3A accuracy is specified by the manufacturer as ±5 percent of full scale.

Peak power measurements could not be obtained with the radar antenna rotating, using the peak power meter as obtained from the manufacturer. The Narda 66A3A power meter requires approximately 35 random triggers per second to maintain a stable reading. However, during a sweep of the radar antenna, only 10 pulses would be observed during a 3-second sweep. This rate was not sufficient to charge the capacitor in the peak detector circuit for feedback to close the input gate. Under this condition, the meter will not range properly. For this reason, the peak detector circuit was modified as shown in figure 3.

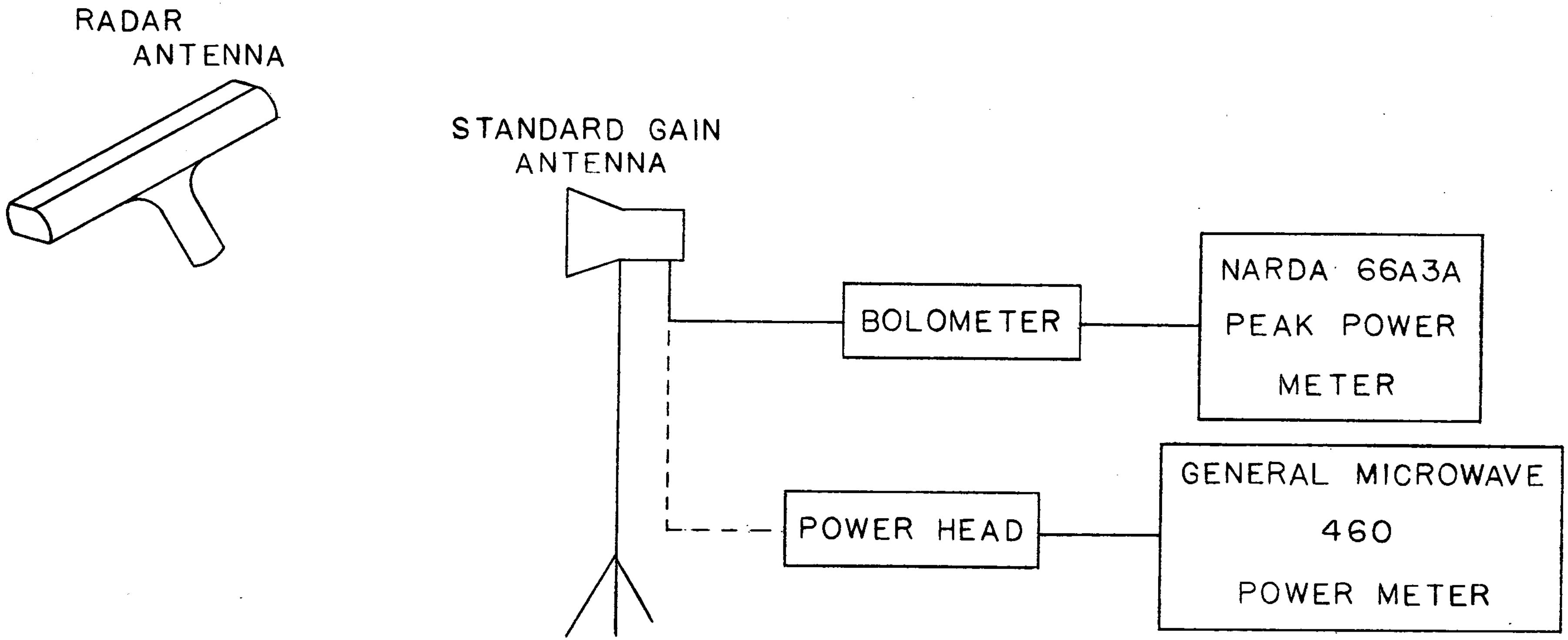

FIG. 2. ARRANGEMENT FOR POWER DENSITY MEASUREMENTS

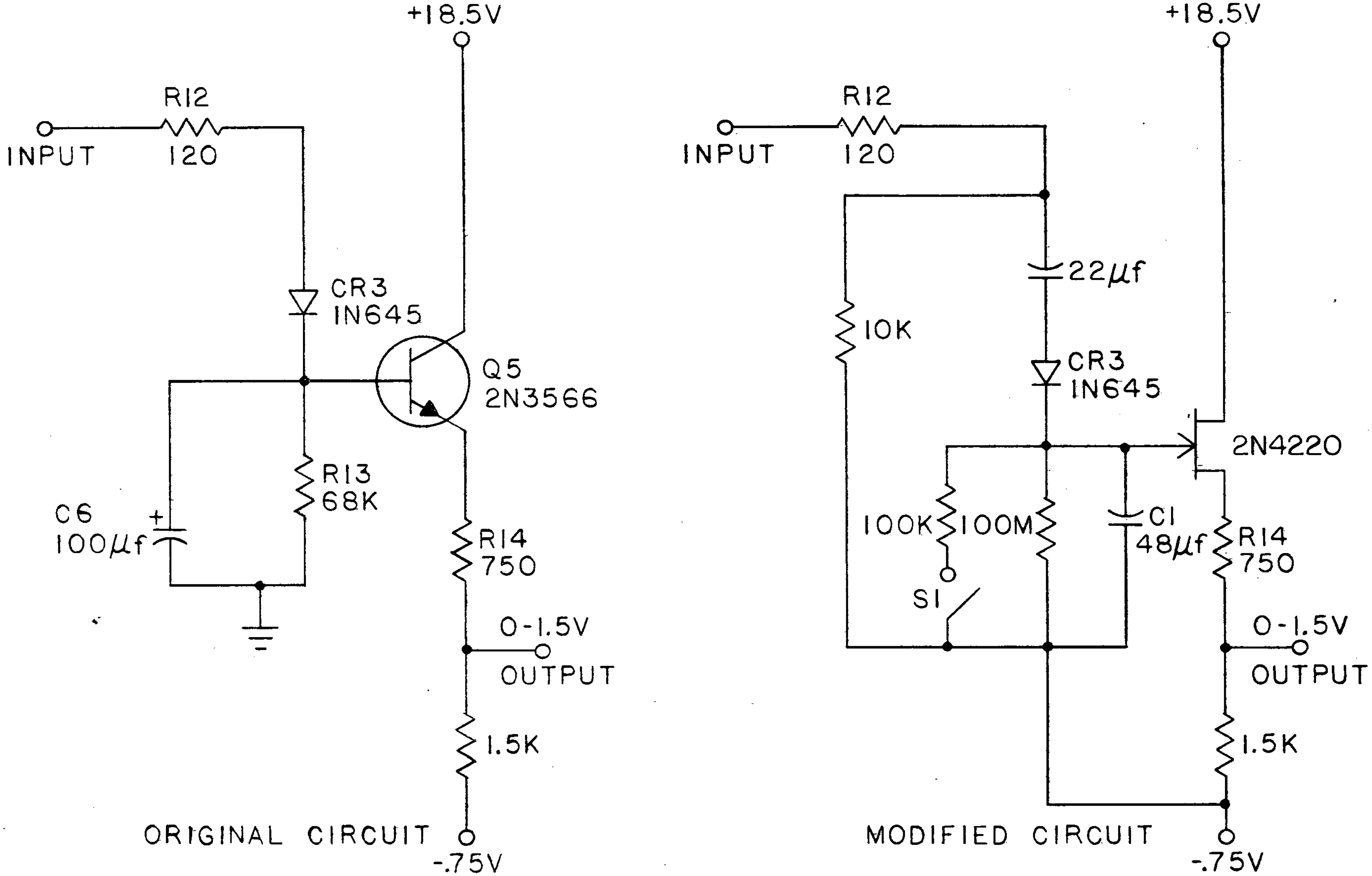
+18.5V
R12
INPUT
120
CR3
IN645
Q5
2N3566
R13
68K
C6
100μf
R14
750
0-1.5V
OUTPUT
1.5K
-.75V
ORIGINAL CIRCUIT
+18.5V
R12
INPUT
120
22μf
10K
CR3
IN645
2N4220
100K
100M
C1
48μf
R14
750
S1
0-1.5V
OUTPUT
1.5K
-.75V
MODIFIED CIRCUIT

FIGURE 3.

This modification permitted measurements from the rotating antenna with as few as 2 pulses during a 3-second interval. Each pulse was stored in the capacitor (C1), which increased the meter reading, until a stable meter reading was obtained. After the measurement was recorded, the capacitor was discharged by closing the switch (S1) and the meter was ready for the next measurement. Results of the peak power measurements are given in tables 2 and 3.

Average power density measurements could be made only with the antenna in a fixed position due to the short decay time of the General Microwave 460 average power meter and N420C thermoelectric power head. In most cases, we found it impossible to obtain average fixed-orientation power density measurements because the operator would not permit the antenna rotation to be stopped or the antenna could not be accurately pointed at the receiving antenna at a stopped position. Therefore, average power density values reported in table 4 were obtained by multiplying the field measured peak power density values by the maximum duty factor calculated from manufacturers' specifications. This procedure of multiplying peak power density by duty factor to obtain an average value was checked by taking average and peak power measurements simultaneously on two different types of units supplied by radar dealers and comparing the measured average power to that calculated using manufacturers' specifications. These measurements were obtained at various distances with the antenna rotation stopped. The results showed that the calculated average power was correct within experimental error.

Because of these same difficulties in performing average power density measurements on rotating antennas, the approximations described in section 3 above were employed to obtain the "measured" rotating-average values in table 5 from the actual peak power-density measurements.

Power-density measurements of units operating on boats were made at distances within the range of D^2/λ to $2D^2/\lambda$, where D was the maximum physical dimension of the radar antenna and λ is the free-space wavelength of the microwave radiation being measured. This distance was measured with a steel tape. The D values of the radar antennas were used because they were much larger than that of the receiving horn in each case. At such distances, slight variations in the separation distance due to movements of either antenna will not cause a readable difference in the measured power observed on the meter. The separation distance was usually limited to a point where major obstacles, such as boats, riggings, buildings, etc., did not intervene between the radar and receiving antenna.

Although equation (1) may be used to predict the power densities to be encountered at considerable distances from a radar antenna (in the "far field"), difficulties arise when an attempt is made to apply it at relatively close distances (only a few meters for the marine radar antennas under consideration here). The construction of the slot-array antennas usually employed in small-craft marine radar is designed to optimize the narrow horizontal beam and maximize the gain in the far field (where the intended targets are presumed to lie) rather than in the near field. Although the gain, G, is simply a constant (for a particular antenna) in the far field, typically this gain is found to decrease in value at points close to the antenna. In general, for close distances the gain must be considered a function of distance, $G(\vec{r})$, rather than a constant. If G is taken to be the gain at very large distances, at small distances equation (1) should be modified to

$$|\vec{S}| = \frac{P_t \, G(\vec{r})}{4\pi|\vec{r}|^2} \qquad (3)$$

where

$$G(\vec{r}) = G\,C(\vec{r}) \qquad (4)$$

in which

$C(\vec{r})$ = a correction factor which is a function of $\vec{r}$

The particular $C(\vec{r})$ associated with one marine radar antenna was measured in an anechoic chamber in the laboratories of the Division of Electronic Products. A Narda 8300 radiation monitor was used to measure the power density as a function of distance from a slot-array antenna of the type employed on the Decca 101 marine radar. Measuring the power delivered to the antenna, P_t, and the distance, $|\vec{r}|$, and knowing the nominal far-field gain, G, the correction curve, C(r), was obtained from equations (3) and (4). The results shown in figure 4 clearly reveal the decrease in gain, $G(\vec{r})$, at small distances from the antenna in the horizontal plane of the antenna's rotation. The measured fields decreased in value above and below this plane.

SECTION 5. DISCUSSION OF RESULTS

Tables 2, 3, 4 and 5 present the results of our empirical measurements and compare them with the theoretically predicted values.

It is difficult to determine the overall error in these measurements. The polarization alignment of the receiving antenna was difficult to determine in some cases when the radar was not mounted on a plane parallel to the water surface. Boats were observed to roll and pitch, even when docked, and to change polarization and beam alignment.

The multipath interference (MPI) must be considered in evaluating the measurements. This includes: (1) image MPI radiation consisting of radiation reflected by some objects other than the receiving antenna, and (2) mutual MPI consisting of radiation reflected from the receiving antenna to the radar antenna and back to the receiving antenna. The image MPI radiation component will contribute the major portion of MPI when the separation distance of the antennas is of the order of D^2/λ. The problems of estimating image MPI in each measurement is that the reflecting surfaces change planes relative to the primary beam as in the case where other boats are the primary reflecting surfaces, or that there may be relative changes in the reflecting surfaces of ground and surrounding buildings due to boat motion resulting from waves. In some cases, measurements had to be taken at positions where steel cables, masts, or power lines were in or near the measured beam.

In the worst case, it is estimated that multipath interference and attenuation contributed no more than 20 percent error to the measurements. System errors of cable attenuation, meter reading, meter error, etc., are estimated to be no more than 7 percent.

Table 1 presents the relevant technical parameters of some marine radar units of the type which might be employed on small pleasure craft. All of the indicated models are in current use in the field, though not all are currently being manufactured. Specific information on the availability of any individual model should be obtained from the particular manufacturer. In the far field of the radar antenna, equations (1) and (2) can be used to predict the power density at specified distances. As previously noted, a correction factor will, in general, be required for closer distances. Figure 4 presents the correction

Table 2. Comparison of individual measurements and calculations

Manufacturer	Model No.	Measured peak Power density mW/cm² @ D^2/λ	Predicted peak Power density mW/cm² @ D^2/λ	D^2/λ separation distance (feet)
Decca	101	8.2	9.1	85.5
Decca	101	6.4	9.1	85.5
Decca	101	16.5	9.1	85.5
Decca	101	13.2	9.1	85.5
Decca	101	7.0	9.1	85.5
Decca	101	10.2	9.1	85.5
Decca	101	9.1	9.1	85.5
Decca	Super 101	8.0	9.1	85.5
Decca	Super 101	8.0	9.1	85.5
Decca	Super 101	8.0	9.1	85.5
Decca	Super 101	13.1	9.1	85.5
Decca	Super 101	8.0	9.1	85.5
Decca	Super 101	11.6	9.1	85.5
Decca	RM-316	10.2	7.4	340
Decca	RM-316	5.5	7.4	340
Decca	202	5.5	7.2	150
Decca	202	12.4	7.2	150
Decca	202	9.1	7.2	150
Decca	202	4.7	7.2	150
Decca	202	9.1	7.2	150
Decca	202	2.3	7.2	150
Decca	202	5.1	7.2	150
Decca	202	5.1	7.2	150
Decca	202	4.4	7.2	150
Decca	202	3.8	7.2	150
Decca	202	10.9	7.2	150
Decca	202	9.8	7.2	150
Decca	202	6.2	7.2	150
Kelvin-Hughes	Type 17	1.9	1.1	340
Kelvin-Hughes	Type 17	1.9	1.1	340
Konel	KRA-221	7.4	19.1	150
Konel	KRA-221	14.6	19.1	150
Konel	KRA-221	16.4	19.1	150

Table 3. Summary of measurements and calculations: peak power densities

Manufacturer	Model No.	Mean measured peak power density (mW/cm^2 @ D^2/λ) ±2 σ limits (%)[a]	Predicted peak power density (mW/cm^2 @ D^2/λ)	Number of surveyed units
Decca	101	10.1 ±7.4 (73.3%)	9.1	7
Decca	Super 101	9.4 ±4.6 (49%)	9.1	6
Decca	202	6.8 ±6.2 (91.2%)	7.2	13
Decca	RM-316	7.8 ±6.6 (84.6%)	7.4	2
Kelvin-Hughes	Type 17	1.9 ±0.0 (0%)[b]	1.1	2
Konel	KRA-221	12.8 ±9.4 (73.5%)	19.1	3

[a] (%) denotes 2 σ uncertainity limits divided by the average measured peak power density @ D^2/λ multiplied by 100%.

[b] sample of two identical measurements.

Table 4. Summary of measurements and calculations: average power densities, nonrotating antenna

Manufacturer	Model	Mean of measured[a] average power densities @ D^2/λ ($mW/cm^2 \times 10^{-3}$) ±2 σ limits (%)[b]	Predicted average power density @ D^2/λ ($mW/cm^2 \times 10^{-3}$)	Maximum duty cycle ($\times 10^{-3}$)
Decca	101	7.5 ±5.4 (73.3%)	6.8	0.75
Decca	Super 101	7.0 ±3.4 (49%)	6.8	0.75
Decca	202	5.1 ±4.6 (91.2%)	3.6	0.5
Decca	RM-316	5.9 ±5.0 (84.6%)	3.7	0.5
Kelvin-Hughes	Type 17	1.4 ±0.0 (0%)[c]	0.6	0.55
Konel	KRA-221	6.1 ±4.5 (73.5%)	9.2	0.48

[a] product of measured peak power and maximum duty cycle.

[b] (%) denotes 2 σ uncertainty limits divided by the mean of the measured average power densities @ D^2/λ multiplied by 100%.

[c] sample of two identical measurements.

Table 5. Summary of measurements and calculations: average power densities, rotating antenna

Manufacturer	Model No.	Mean of rotation corrected average power densities @ D^2/λ ($mW/cm^2 \times 10^{-6}$) ±2 σ limits (%)[a]		Predicted rotation-corrected average @ D^2/λ ($mW/cm^2 \times 10^{-6}$)
Decca	101	52.4 ±38.4	(73.3%)	47.2
Decca	Super 101	48.6 ±23.8	(49%)	47.2
Decca	202	36.4 ±33.2	(91.2%)	25.0
Decca	RM-316	19.7 ±16.7	(84.6%)	12.3
Kelvin-Hughes	Type 17	4.7 ±0.0	(0%)[b]	2.0
Konel	KRA-221	3.0 ±2.2	(73.5%)	4.6

[a] (%) denotes 2 σ uncertainty limits divided by the mean of rotation-corrected average power densities @ D^2/λ multiplied by 100%.

[b] sample of two identical measurements.

curve for one particular unit which is, at least, generically similar to most antennas employed in small-craft marine radar.

If, together with equations (2) and (3), the curve in figure 4 is taken as an approximation applicable to the various units listed in table 1, several interesting results would follow for these units:

(a) Peak power densities of 100 mW/cm^2 may exist out to distances of about 25 to 200 feet, depending on the units;

(b) because of the low duty factor and approximate gain corrections, all but three of the units would probably produce average power densities of less than 10 mW/cm^2 at distances corresponding to the respective antenna turning-circle radii, even when the antenna rotation was stopped; the three units which might exceed this level were all large, high-powered units (20 kW peak power or more), unlikely to be employed on small pleasure craft, and the highest computed turning-circle average power density even for these three is only about 13 mW/cm^2 for a nonrotating antenna;

(c) when the effect of the normal antenna rotation is considered, as in equation (2), the computed average power density for any of the units listed in table 2 is less than 0.05 mW/cm^2 at the turning-circle radius; using an analogous correction for the sector scan option on the Decca 101 units, the computed average power density is about 0.25 mW/cm^2.

The calculated values cited here would apply to a location on the horizontal plane of the antenna, but because of the broad vertical beam widths involved, roughly similar results might be encountered somewhat above and below the radiating antenna.

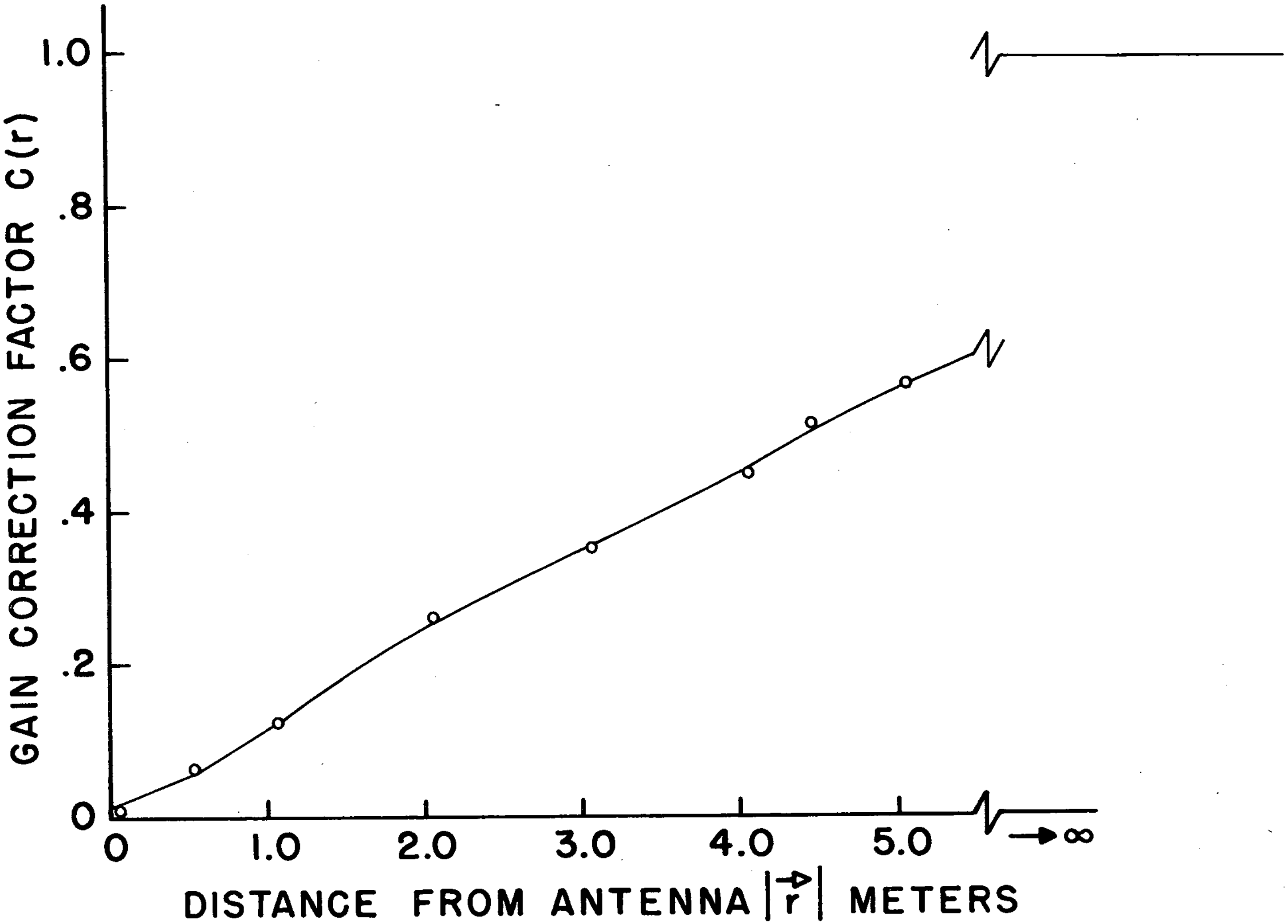

FIG. 4. DECCA-101 ANTENNA PERFORMANCE

SECTION 6. CONCLUSIONS

Tables 3 through 6 indicate that, in general, the approximate power densities in the far fields of marine radar units may be computed using conventional antenna relationships and nominal manufacturers' specifications for the radar parameters. It is also clear, however, that significant variations from the computed values may occur.

On the basis of our measurements and computations, it seems unlikely that personnel would normally be exposed to average power densities approaching 1 mW/cm^2 due to the radiation from a small-craft radar having a rotating antenna. The American National Standards Institute has recommended that occupational exposure not exceed a power density of 10 mW/cm^2 for 1 hour or more, nor an energy density of 1.0 $mW\text{-}hr/cm^2$ during any 0.1-hour period under normal environmental conditions. (American National Standards Institute (ANSI). Safety level of electromagnetic radiation with respect to personnel. C95.1 (1966)). It seems unlikely that these levels of average exposure would be encountered under the cited conditions.

Two caveats seem appropriate, however. Should a small-craft radar be operated with the antenna rotation stopped, significantly increased levels of exposure might be encountered. Exposure under such conditions probably should be avoided. Furthermore, peak power density in the regions surrounding the antenna may be quite high. Any possible biological hazards associated with these peak power densities are uncertain at present. Moreover, the possibility of interference phenomena in critical devices (such as cardiac pacemakers) due to high peak power densities seems to warrant caution and further research. Care should, therefore, be exercised to limit the unnecessary use of marine radar in areas of high population density (e.g., when docked in harbors).

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