

FIG. 1 CURVES FOR OBTAINING W_{MAX} (HIGH POWER/LARGE AREA CONDITIONS)

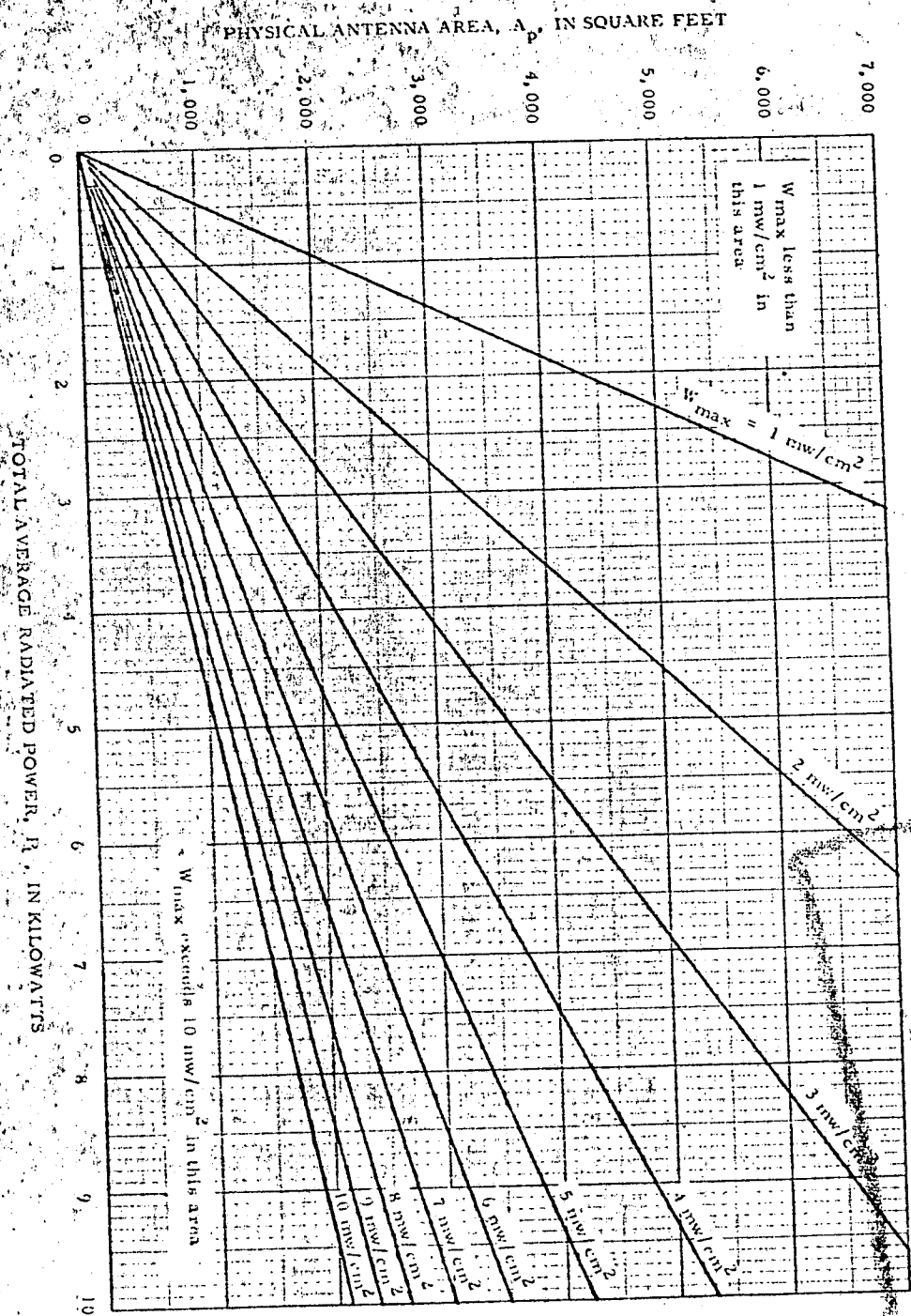


FIG. 2 CURVES FOR OBTAINING W_{MAX} (LOW POWER/SMALL AREA CONDITIONS)

When $W = W_1 = 1 \text{ mw/cm}^2$

and $W = W_{10} = 10 \text{ mw/cm}^2$

$$R = R_1 = \left(\frac{G_t P_t}{8 \pi W_1} \right)^{1/2} \quad (4)$$

and

$$R = R_{10} = \left(\frac{G_t P_t}{8 \pi W_{10}} \right)^{1/2} \quad (5)$$

respectively. R_1 and R_{10} are the distances in the far field where the power densities are 1 mw/cm^2 and 10 mw/cm^2 respectively. Figure (3) is a nomograph designed from equations (3), (4), and (5).

1. Using the Figures (1), (2), and (3). The steps in using Figures (1), (2), and (3) are as follows:

a. Determine W_{max} from Figures (1) or (2) using given data or data calculated from given data. If W_{max} falls below hazardous limits no further analysis is required.

b. Determine R_1 and/or R_{10} from Figure (3) as follows:

(1) Using the operating frequency and physical area, determine G_t .

(2) Using G_t (from part (a)) and P_t (radiated or transmitter power) find R_1 and/or R_{10} .

Examples:

a. Jet Propulsion Laboratory, Deep Space Instrumentation Facility (Reference 15).

$P_t = 10 \text{ Kilowatts}$

$f = 2295 \text{ Megacycles}$

$$d = 85 \text{ Feet (Parabolic Dish Antenna)}$$

$$A_p = \pi d^2 / 4$$

$$A_p = \pi (85)^2 / 4$$

$$A_p = 5,680 \text{ ft.}^2$$

Use Figure (2) to determine:

$$3 \text{ mw/cm}^2 < W_{\max} < 4 \text{ mw/cm}^2$$

If it is necessary to find the distance at which the power density is 1 mw/cm^2 use Figure (3) to determine:

$$G_t = 3.9 \times 10^5$$

$$R_1 = 12,500 \text{ feet}$$

The distance at which the power density is 1 mw/cm^2 is 12,500 feet. It is worth noting that the above parameters, if used to determine R_{10} without using step 1 of the procedure, give:

$$R_{10} = 3,900 \text{ feet.}$$

It must be pointed out that such a determination is incorrect in that the far field function from which the nomograph was constructed is valid only to the distance where $W = W_{\max}$ which was previously determined to be between 3 mw/cm^2 and 4 mw/cm^2 . Therefore, it is possible to find R_1 and R_{10} only if step (1) of the procedure indicates $W_{\max} > 1 \text{ mw/cm}^2$ or $W_{\max} > 10 \text{ mw/cm}^2$ respectively.

b. Jet Propulsion Laboratory, Deep Space Instrumentation Facility.

$$P_t = 10 \text{ Kilowatts}$$

$$f = 960 \text{ Megacycles}$$

$$d = 85 \text{ Feet (Parabolic Dish Antenna)}$$

As before: $A_p = 5,680 \text{ ft.}^2$

From Figure (2):

$$3 \text{ mw/cm}^2 < W_{\text{max}} < 4 \text{ mw/cm}^2$$

From Figure (3):

$$G_t = 5.37 \times 10^4$$

$$R_1 = 5,450 \text{ feet}$$

c. Given:

$$P_t = 5 \text{ Kilowatts}$$

$$f = 1,000 \text{ Megacycles}$$

$$d = 20 \text{ Feet (Parabolic Dish Antenna)}$$

$$A_p = \pi \frac{d^2}{4}$$

$$A_p = \pi \times 400/4$$

$$A_p = 314 \text{ Ft.}^2$$

From Figure (1):

$$W_{\text{max}} > 10 \text{ mw/cm}^2$$

From Figure (3):

$$G_t = 4.2 \times 10^3$$

$$R_1 = 940 \text{ Feet}$$

$$R_{10} = 298 \text{ Feet}$$

d. Given:

$$P_t = 2 \text{ Kilowatts}$$

$$f = 2,300 \text{ Megacycles}$$

$$d = 80 \text{ Feet (Parabolic Dish)}$$

$$A_p = \frac{\pi (80)^2}{4}$$

$$A_p = 5,100 \text{ Feet}^2$$

From Figure (2):

$W_{\max} < 1 \text{ mw/cm}^2$ (There is no hazardous area in the vicinity of the antenna, therefore, no further analysis is necessary.)

The analysis does not include the possibility of reflections from ground or other objects in the field. Theoretically, the power density may be quadrupled at some point where reinforcement occurs between direct and reflected radiation. Such a condition occurs for perfectly conducting reflectors and is seldom realized in practice. One reference (Reference 17) shows that the power density is multiplied by a factor less than two when reflections exist. Assuming the possibility of reflection exists at some installation, and the power density is increased by a factor of two, R_1 and R_{10} as determined for any specific problem should be increased by the factor $\sqrt{2}$.

CONCLUSIONS

It is concluded that:

1. Aircraft transiting radio and radar beams of average power density 10 mw/cm^2 or less are safe, provided no electroexplosive devices are aboard. For guaranteed crystal protection, avionics items equipped with T-R (Transmit-Receive) tubes must be kept in POWER ON condition.
2. Aircraft carrying electroexplosive devices are safe in fields of average power density 1 mw/cm^2 or less when proper wiring procedures and maximum shielding efforts are used.
3. With regard to electroexplosive devices, progress by the military gives promise of yielding less restrictive limits in the near future.
4. The variety of high power installations precludes setting a single distance limit, and charts included in this report provide a rapid and simple means of converting from power density to distance along the antenna beam axis.
5. Power density calculations indicate that ATC radars have maximum power densities less than 10 mw/cm^2 (Appendix II).

RECOMMENDATIONS

It is recommended that:

1. Aircraft (not carrying electroexplosive devices) be prohibited from transiting electromagnetic fields in excess of average power density 10 mw/cm^2 . For guaranteed crystal protection, avionics items equipped with T-R (Transmit-Receive) tubes must be kept in POWER ON condition.
2. Aircraft carrying electroexplosive devices, which are properly wired and shielded, not be permitted to transit radio and radar fields in excess of average power density 1 mw/cm^2 .
3. Future progress of the military services on electroexplosive devices be monitored by the Research Division by attendance at, and limited participation in, meetings of the HERO (Hazards of Electromagnetic Radiation to Ordnance) Program with a view to establishing less restrictive limits as soon as possible.
4. Future studies in the area of radiation hazards should investigate the possibility of hazard to transistorized (solid state) avionics items being introduced into aircraft.
5. Experimental data be provided on the avionics items containing crystal rectifiers, using operational configurations. Tests should be made with T-R (Transmit-Receive) tubes in both active and quiescent states with frequencies compatible with tube bandwidth characteristics.
6. Experimental verification be made of the power density values calculated for the ATC radars in Appendix II.

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APPENDIX I

POSSIBLE RADIATION HAZARDS WHEN BLASTING NEAR AIRPORTS

A problem related to aircraft and electroexplosive devices is given as follows:

Blasting operations are taking place near a runway and an aircraft with transmitters operating passes overhead causing an electromagnetic field to which the EED on the ground is exposed. Determine the possibility of accidental ignition of the EED under such circumstances.

The body of this report suggests 1 mw/cm^2 average power density to which aircraft with EEDs may be safely exposed, provided precautions as per Reference 11 are taken. The situation in the problem being considered here indicates that precautions may not be taken, and the possibility exists that lack of knowledge of the radio frequency energy hazard may lead to setting up the blasting cap in a configuration which would be very effective in extracting energy from a radio field.

In calculating an estimate of power density required for accidental ignition, conditions which make ignition more likely are assumed:

1. The EED is sensitive - current for firing is .25 amperes and bridge wire resistance is .5 ohms.
2. The blasting cap is attached to wires with a configuration of a half-wavelength dipole.
3. The wires are oriented to match the field polarization.

$$\text{Now: } W = \frac{P}{A} \text{ (For any receiving antenna)}$$

where: W is the field power density

P is the power received

A is the effective area of the antenna for absorption

$$\text{Now: } P = I^2 R$$

where I is the squib firing current
R is the squib resistance

$$P = (.25)^2 (.5)$$

$$P = 31.25 \text{ milliwatts (required for cap ignition)}$$

If matched conditions prevailed; that is, if the bridge wire resistance were 72 ohms, rather than 0.5 ohms, the effective area would be:

$$A = \frac{3\lambda^2}{8\pi} \quad (\text{For half-wavelength dipole})$$

where λ is the wavelength of the radiation.

For any receiving antenna

$$P = A W$$

The power received under unmatched conditions can be determined from:

$$\frac{P_u}{P_m} = \frac{A_u W}{A_m W}$$

$$P_u = P_m \frac{A_u}{A_m}$$

where:

P_u is power received under unmatched conditions

P_m is power received under matched conditions

A_u is the effective area under unmatched conditions

A_m is the effective area under matched conditions.

In general:

$$A = \frac{d^2 R_o k}{(2\pi f L - 1/2 \pi f C)^2 + (R_o + R_r)^2} \quad (\text{Reference 16})$$

where:

R_r is the antenna resistance

R_o is the load resistance

k is the characteristic impedance of the medium

L is the antenna inductance

C is the antenna capacitance

f is the frequency

d is the antenna length

For a resonant antenna, the reactive part of the equation vanishes and

$$\frac{A_u}{A_m} = \frac{d^2 k \frac{R_o}{(R_o + R_r)^2}}{d^2 k \frac{R_r}{(R_r + R_r)^2}}$$

$$\frac{A_u}{A_m} = \frac{\frac{R_o}{(R_o + R_r)^2}}{\frac{R_r}{(R_r + R_r)^2}}$$

$$\frac{A_u}{A_m} = \frac{R_o (2R_r)^2}{R_r (R_o + R_r)^2}$$

$$\frac{A_u}{A_m} = \frac{4 R_o R_r}{(R_o + R_r)^2}$$

$$\text{Now: } P_u = P_m \frac{4 R_o R_r}{(R_o + R_r)^2}$$

$$\text{Therefore: } P_u = \left(\frac{4 R_o R_r}{(R_o + R_r)^2} \right) \left(\frac{3 \lambda^2}{8 \pi} \right) (W)$$

$$\text{and } W = \frac{2 \pi (R_o + R_r)^2}{3 R_o R_r \lambda^2} P_u$$

$$\text{Since } \lambda f = c$$

where f = operating frequency

c = velocity of light

$$\text{then } W = \frac{2 \pi (R_o + R_r)^2 f^2}{3 R_o R_r c^2} P_u$$

For the specific problem given:

$$R_r = 72 \text{ ohms}$$

$$R_o = 0.5 \text{ ohms}$$

$$P_u = 31.25 \text{ milliwatts}$$

Therefore:

$$W = \frac{2 \pi (0.5 + 72)^2 (31.25) f^2}{3 (0.5) (72) (9) (10^{20}) \text{ cm}^2} \text{ milliwatts}$$

$$W = 1.05 \times 10^{-17} f^2 \frac{\text{mw}}{\text{cm}^2}$$

The power density required for ignition is proportional to the square of the frequency.

The lowest frequencies present the most dangerous conditions. As a practical matter, however, the wires attached to the EED in a dipole configuration probably would be limited in length. Assume a 15 foot dipole is attached to the EED, then:

$$f = \frac{c}{\lambda}$$

$$\lambda / 2 = 15 \text{ feet}$$

$$\lambda = 30 \text{ feet}$$

$$\lambda = 360 \text{ inches}$$

$$\lambda = (2.54) (360) \text{ cm}$$

$$f = \frac{3 \times 10^{10} \text{ cm}}{2.54 \times 360 \text{ cm}}$$

$$f = 33 \text{ mc.}$$

For 33 mc:

$$W = 1.05 \times 10^{-17} \times 11 \times 10^{14} \frac{\text{mw}}{\text{cm}^2}$$

$$W = .0115 \frac{\text{mw}}{\text{cm}^2} \text{ (required for ignition)}$$

Aircraft transmitters in the high frequency bands may be rated as high as 2 kilowatts.

The power density produced at the electroexplosive device, from a half-wavelength antenna aboard the aircraft, is given by:

$$W = \frac{PG}{4 \pi r^2}$$

where P is the transmitted power

G is the antenna gain.

r is the distance between aircraft and the EED.

$$\text{If: } W = .0015 \frac{\text{mw}}{\text{cm}^2} = .115 \frac{\text{w}}{\text{m}^2}$$

$$r = \left(\frac{PG}{4 (0.115) \frac{\text{w}}{\text{m}^2}} \right)^{1/2} \text{ meters}$$

$$r = 3.28 \left(\frac{2 \times 2000}{4 \times .115} \right)^{1/2} \text{ feet}$$

$$r = 172 \text{ feet}$$

The aircraft transmitting 2 kilowatts at 33 mc. must be within 172 feet to produce a power density required for accidental ignition of a sensitive EED attached to a 15 foot half-wavelength dipole.

A somewhat more realistic case is the consideration of very high frequencies (since EED wires can more easily be placed in sensitive configurations). At 300 mc:

$$\lambda = \frac{c}{f} = \frac{3 \times 10^{10} \text{ cm}}{3 \times 10^8} = 10^2 \text{ cm}$$

$$\frac{\lambda}{2} = 50 \text{ cm (20 inches)}$$

For 300 mc.

$$W = 1.05 \times 10^{-17} \times 9 \times 10^{16} \frac{\text{mw}}{\text{cm}^2}$$

$$W = .95 \frac{\text{mw}}{\text{cm}^2}$$

About 1 mw/cm² is required for accidental ignition at 300 mc. Aircraft may carry VHF transmitters capable of producing 200 watts:

$$W = \frac{PG}{4\pi r^2}$$

$$r = \frac{PG}{4\pi W}$$

$$r = \left(\frac{200 \times 2}{40\pi} \right)^{1/2} \text{ meters}$$

$$r = 3.28 \left(\frac{10}{\pi} \right)^{1/2} \text{ feet}$$

$$r = 5.8 \text{ feet}$$

For an aircraft transmitting 200 watts on its VHF circuit (half-wavelength dipole) and an EED attached to a 20 inch dipole, also half-wavelength, the plane must be within 5.8 feet to cause accidental ignition. The greatest danger seems to be in the high frequency range (frequencies between 3 and 30 megacycles).⁶ Aircraft should stay about 250 feet above blasting operations in which EEDs are being used. For blasting operations not using electroexplosive devices, no danger exists from radio waves (Reference 10).

⁶Below the H-F range transmitter powers decrease and the antenna efficiencies decrease radically.

APPENDIX II

CHARACTERISTICS OF SOME AIR TRAFFIC CONTROL RADARS

A number of Air Traffic Control radars are designed with shaped beams to improve vertical coverage. Since the most efficient antennas (high k) have uniformly illuminated apertures, the shaped beam antennas with non-uniformly illuminated apertures have lower power densities along the line of maximum gain. To compute the maximum power density in the field along the line of maximum gain, use the formula:

$$W_{\max} = k \frac{4P_t}{A_p}$$

where: P_t = Transmitted (or transmitter power)

A_p = Physical area of antenna

and $k = \frac{G_a}{G_t}$ where G_a = actual antenna gain
 G_t = theoretical antenna gain

The antennas considered in this appendix have published G_a values which will be used with calculated G_t (equal to $4\pi A_p^2/c^2$) values to determine specific k values.

Using published data, W_{\max} is calculated for each antenna type, and a tabulation made. One complete calculation will be made explicitly on the ARSR-1A:

Given:

G_a = 34.2 decibels

f = 1300 megacycles

P_t = 3920 kilowatts (peak)

Pulse Recurrence Freq. = 360 pulses per second

Pulse Width = 2 microseconds

Reflector Dimensions = 40 x 11 square feet

Required:

G_a , G_t , k , P_t (average), and A_p .

a. $G_a = 34.2$ decibels

$$34.2 = 10 \log G_a$$

$$G_a = 2630$$

b. $G_t = \frac{4\pi A_p f^2}{c^2}$

$$G_t = \frac{4\pi \times 40 \times 11 \times (2.54)^2 \times (12)^2 \times (1.3)^2 \times 10^{18}}{9 \times 10^{20}}$$

$$G_t = 9640$$

c. $k = G_a / G_t$

$$k = 2630 / 9640$$

$$k = .273$$

d. P_t (average) = P_t (peak) x Pulse Recurrence Freq.
x Pulse Width

$$= 3920 \times 10^3 \times 360 \times 2 \times 10^{-6} \times 10^3$$

milliwatts

$$= 2.82 \times 10^6 \text{ milliwatts}$$

e. $A_p = 40 \times 11 \times (2.54)^2 \times (12)^2$

$$= 4.07 \times 10^5 \text{ (centimeters)}^2$$

Using the information from calculations (3) through (5)

$$W_{\max} = \frac{.273 \times 4 \times 2.82 \times 10^6}{4.07 \times 10^5} \frac{\text{mw}}{\text{cm}^2}$$

$$W_{\max} = 7.58 \frac{\text{mw}}{\text{cm}^2}$$

1. Circular Aperture. For a uniformly illuminated circular aperture, the power density (W) is oscillatory from the antenna to some distance (R_0) where the function begins to fall with distance (R) according to the $1/R^2$ law. The function has a number of maxima (all equal) and a number of minima (all zero). Figure (4) is a sketch of the function.

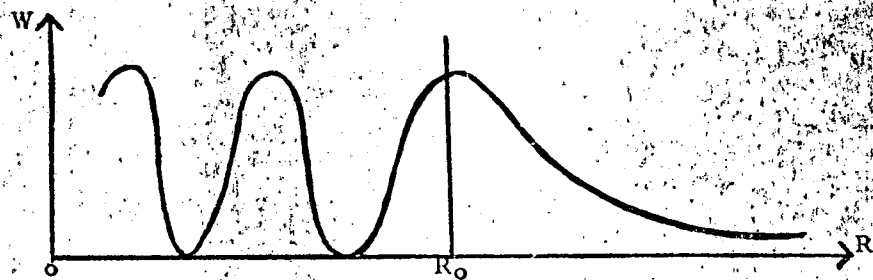


Figure (4). The power density (W) as a function of distance (R) for a uniformly illuminated circular aperture. R_0 is the distance at which the far field begins. R_0 can be found as follows:

In the near field

$$W_{\max} = k \frac{4P_t}{A_p}$$

In the far field

$$W = \frac{G_a P_t}{4\pi R^2}$$

At R_0 the far field function is a maximum and is equal to the near field function. Therefore,

$$\frac{4kP_t}{A_p} = \frac{G_a P_t}{4\pi R_0^2}$$

with $k = G_a / G_t$

and $G_t = \frac{4\pi A_p f^2}{c^2}$

where A_p = physical antenna
and c = velocity of light

$$\frac{4c^2 G_a P_t}{4\pi A_p^2 f^2} = \frac{G_a P_t}{4\pi R_o^2}$$

thus $R_o^2 = \frac{A_p^2 f^2}{4c^2}$

and $R_o = \frac{A_p f}{2c}$

Since the aperture is circular, $A_p = \frac{\pi d^2}{4}$ where d is the antenna diameter. Therefore,

$$R_o = \frac{\pi d^2 f}{8c}$$

2. Rectangular Aperture. For a rectangular antenna, the following description holds: very near the antenna to a distance R_{o1} the power density function is purely oscillatory. In the far field the power density falls with distance as $1/R^2$. In between a combined oscillatory and $1/R^2$ function exists. Figure (5) is a sketch of the function.

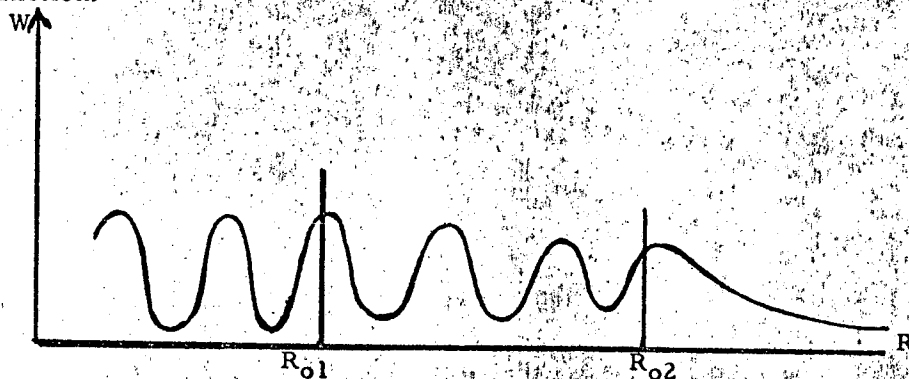


Figure (5). The power density as a function of distance for a rectangular aperture. To R_{o1} the power density function is purely oscillatory. From R_{o1} to R_{o2} the function is a combination of an oscillatory and a $1/R^2$ function. From R_{o2} the function follows the $1/R^2$ law.

Since for a circular aperture

$$R_o = \frac{\pi d^2 f}{8 c}$$

where d is the antenna diameter, it is assumed that

$$R_{o1} = \frac{\pi d_1^2 f}{8 c}$$

and

$$R_{o2} = \frac{\pi d_2^2 f}{8 c}$$

where d_1 and d_2 are the smallest and largest linear antenna dimensions respectively. For the ARSR-1A

$$R_{o1} = \frac{\pi \times 11 \times 11 \times 1.3 \times 10^9 \times 2.54 \times 12}{8 \times 3 \times 10^{10}}$$

$$R_{o1} = 63 \text{ feet}$$

The maximum power density anywhere in the field of the ARSR-1A radar is 7.58 mw/cm^2 and this value exists at points between the antenna and 63 feet from the antenna along the line of maximum gain.

Now:

$$R_{o2} = \frac{\pi d_2^2 f}{8 c}$$

$$R_{o2} = \frac{\pi \times 40 \times 40 + 11 \times 11 \times 1.3 \times 10^9}{8 \times \frac{3 \times 10^{10}}{12 \times 2.54}}$$

$$R_{o2} = 892 \text{ feet}$$

The power density at R_{o2} can be determined from

$$W = \frac{G_a P_t}{4\pi R_{o2}^2}$$

$$W = \frac{2630 \times 2.82 \times 10^6}{4\pi \times 892 \times 892 \times 12 \times 12 \times 2.54 \times 2.54}$$

$$W = .8 \text{ mw/cm}^2$$

Although it is not possible in this case to determine the exact distance at which $W = 1 \text{ mw/cm}^2$ the analysis shows that the distance is less than 892 feet. When W at R_{o2} is greater than 1 mw/cm^2 it is possible to find the distance (R_1) at which the power density is 1 mw/cm^2 from

$$\frac{W_{R_{o2}}}{W} = \frac{R_1^2}{R_{o2}^2}$$

$$\text{that is } R_1^2 = R_{o2}^2 \frac{W_{R_{o2}}}{W}$$

$$\text{where } W = 1 \text{ mw/cm}^2$$

$$R_1 = R_{o2} (W_{R_{o2}})^{1/2}$$

Table 1 gives W_{max} , R_{o1} , R_{o2} , $W_{R_{o2}}$ (power density at R_{o2}) and R_1 for a number of ATC radars. For the ARSR-1A the maximum power density is 7.58 mw/cm^2 from the antenna to 63 feet. From 63 to 892 feet the maximum power density varies from 7.58 to $.8 \text{ mw/cm}^2$. For all the antennas, the region between the feed horn and the reflector is a hazardous one since power densities greater than 10 mw/cm^2 will exist there.

TABLE I

Radar	W_{\max} ($\frac{mw}{cm^2}$)	R_{01} (ft.)	R_{02} (ft.)	$W_{R_{02}}$ ($\frac{mw}{cm^2}$)	R_1 (ft.)
ASR-2	2.58	112	272	1.01	272
ASR-3	5.90	112	300	2.08	432
ASR-4	3.12	63	366	0.72	$R_1 < 366$
ARSR-1A	7.58	63	892	0.80	$R_1 < 892$
ARSR-2	0.97	289	1592	0.02	$W_{\max} < 1$
FPS-8	1.95	102	425	0.58	$R_1 < 425$
FPS-20	6.58	133	964	1.26	1080
FPS-20A	6.58	133	964	1.26	1080
FPS-35	5.53	244	2720	0.74	$R_1 < 2720$
FPS-37	6.56	112	1126	0.21	$R_1 < 1126$
FPS-64	6.58	133	964	1.26	1080
FPS-66	6.58	133	964	1.26	1080
FPS-67	6.58	133	964	1.26	1080

TABLE I. Some characteristics of Air Traffic Control radars where

W_{\max} is the maximum power density in the field.
 R_{01} is the distance at which the field becomes part near and part far field. W_{\max} exists at points between the antenna and R_{01} .
 R_{02} is the distance at which the field becomes purely far field.
 $W_{R_{02}}$ is the power density at R_{02} .
 R_1 is the distance at which the power density is $1 \frac{mw}{cm^2}$.

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<p>exposed, under some conditions, to power densities of 1 mw/cm^2. This report contains charts, and procedures for using them, which give distances along the antenna beam axis at which the aforementioned limits are reached. It is recommended that experiments be undertaken to verify analyses in this report and that progress of the military services on electroexplosive devices be monitored to assure the earliest possible implementation of less restrictive limits.</p>	<p style="text-align: center;">UNCLASSIFIED</p> <p style="text-align: center;">UNCLASSIFIED</p>	<p>exposed, under some conditions, to power densities of 1 mw/cm^2. This report contains charts, and procedures for using them, which give distances along the antenna beam axis at which the aforementioned limits are reached. It is recommended that experiments be undertaken to verify analyses in this report and that progress of the military services on electroexplosive devices be monitored to assure the earliest possible implementation of less restrictive limits.</p>	<p style="text-align: center;">UNCLASSIFIED</p> <p style="text-align: center;">UNCLASSIFIED</p>

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