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Office of Air and Radiation
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The Radiofrequency Radiation Environment: Environmental Exposure Levels and RF Radiation Emitting Sources

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FOREWORD

The Office of Radiation Programs conducts a national program to evaluate the exposure of the population to ionizing and nonionizing radiation, to recommend radiation protection guidance for the use of Federal agencies, to publish environmental radiation standards and criteria, and to advise the States on radiation protection matters, so as to protect public health and to assure environmental quality.

The applications of radiofrequency radiation in communications, transportation, defense, industry, consumer products, security, science, traffic control, and medicine have produced a radiofrequency radiation environment to which the entire population is continuously exposed. Everyone in the United States is exposed to low levels of radiofrequency radiation, and some people who live or work near powerful sources are exposed to higher levels. As the number of radiofrequency radiation sources increases, the probability of public exposure to higher radiation levels also increases.

This document summarizes the radiofrequency radiation environment, discusses the sources and levels of radiofrequency radiation to which the public is exposed, and provides information pertinent to the development of radiofrequency radiation exposure guidelines.

Sheldon Meyers, Director
Office of Radiation Programs

ABSTRACT

This document summarizes the radiofrequency radiation environment to which the public is exposed. The contents consist of information on environmental levels of radiofrequency radiation produced by systems in common use such as AM and FM radio, VHF and UHF television, microwave communications, radar, and mobile radio. The exposure environment is discussed in terms of the system characteristics important to its creation.

The information presented in this document resulted from a nationwide exposure measurement program conducted by the Environmental Protection Agency (EPA) to determine typical and atypical public exposure levels and from modeling efforts to estimate environmental exposure levels. Most of this work has been documented in previously published technical reports and papers as referenced herein.

The exposure environment is examined from two aspects: the typical, relatively low-level environment to which most persons are exposed, occurring far from the sources of the radiation; and the higher-level environment to which relatively few persons are exposed, which occurs close to the radiation producing systems. The information acquired by EPA leads to the conclusion that the principal sources of the radiofrequency radiation environment to which the public is exposed in urban areas are radio and television broadcast systems. They produce most of the low-level radiofrequency radiation exposure to which the public is continuously subjected, and are the systems responsible for the majority of the higher-level exposure situations experienced by a smaller proportion of the public.

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SECTION 1
INTRODUCTION

This document provides a summary of our knowledge of environmental levels of radiofrequency (RF) radiation. The systems producing this radiation, i.e., broadcast radio and television, microwave communications, and radar, are discussed in this report. This knowledge has been developed from a comprehensive measurement and analysis program designed to define public exposure to radiofrequency radiation.

In 1982, EPA announced its intent to develop Federal Guidance to limit exposure of the public to RF radiation (ANPR 82). To support the development of this guidance, EPA published reports on the biological effects of RF fields (E184), and the potential impact, economic and otherwise, that the proposed guidance might have on affected RF sources and users of the electromagnetic spectrum (Ha85). In this document we will discuss the RF radiation environment in terms of environmental exposure levels and the RF sources producing these levels.

Before the production of radio waves by Heinrich Hertz in 1888, the earth's RF radiation environment resulted from natural phenomena such as lightning and solar radiation. With the introduction of radio communications in 1895, however, the RF radiation environment has been increasingly artificially produced. Although environmental levels of nonionizing radiation were negligible before the 1930s, the applications of RF radiation in modern society, i.e., communications, transportation, defense, industry, consumer products, security, traffic control, and medicine, have produced an RF radiation environment to which the entire population is continuously exposed (Te80a). The dramatic rise in the numbers and types of radiating sources has increased the magnitude of environmental levels, extended the frequency range to which members of the public are exposed, and increased the number of persons exposed. Table 1 lists some of the applications and common sources that produce the radiofrequency radiation exposure environment.

The Environmental Protection Agency's studies of radiofrequency sources and levels have characterized the radiofrequency radiation environment to which most of the population is exposed. These studies have also resulted in an understanding of the environmental significance of the major high-power source categories, which include satellite communications earth terminals, radars (military and civilian), and broadcast transmitters (UHF-TV, VHF-TV, and AM and FM radio). Information obtained through measurements and analyses, when combined with other factors such as number of sources in each category, general system characteristics and operating procedures, and relative numbers of persons possibly exposed and their exposure locations, indicates that broadcast transmitters are the most environmentally significant source category.

Table 1

APPLICATIONS AND SOURCES OF RADIOFREQUENCY RADIATION

Applications
Broadcast Communications
Microwave Communications
Military
Transportation
Science
Medicine
Crime Prevention
Consumer Products
Sources
AM and FM Radio
VHF and UHF Television
Radar
Satellite Communications
Microwave Radio
Land-Mobile Radio
Amateur Radio

SECTION 2

RADIOFREQUENCY RADIATION -- CONCEPTS AND CHARACTERISTICS

Radiofrequency (RF) radiation is a part of the electromagnetic radiation spectrum. The term RF radiation applies to electromagnetic radiation frequencies between 3 kilohertz (kHz) and 300 gigahertz (GHz). Figure 1 depicts the electromagnetic spectrum and shows the conventional partitioning of the radiofrequency spectrum into specific bands. For example, the microwave frequency band covers the range 300 megahertz (MHz) to 300 GHz, and the FM radio broadcasting service in the United States uses frequencies within the VHF or very-high-frequency band.

Energies associated with microwave radiation at its extreme of 300 GHz are about 10,000 times less than is needed to cause cellular damage by ionization. The ionization potentials of the principal components of living tissue (water, atomic oxygen, hydrogen, nitrogen, and carbon) are between 11 and 15 electron volts (eV). The lower limit for ionization in biological systems is approximately 12 eV, but some weak hydrogen bonds in macromolecules may have lower ionization potentials, possibly even as low as about 3 eV. For reference, an ultraviolet wavelength of 180 nanometers corresponds to an energy of about 7 eV. Thus, RF radiation having energies less than 10^{-4} eV is nonionizing radiation, as is infrared radiation, visible light, and lower frequency ultraviolet radiation.

However, RF and microwave radiation is absorbed and interacts with biological systems. Absorbed energy is converted to electronic excitation and to molecular vibration and rotation. The RF energy is primarily absorbed by increasing the kinetic energy of absorbing molecules. The amount of energy absorbed depends on the radiation intensity and wavelength, and the shape, size, and the electrical characteristics of the absorber. A complex structure such as the human body absorbs energy differently in specific parts, so that non-uniform absorption may result.

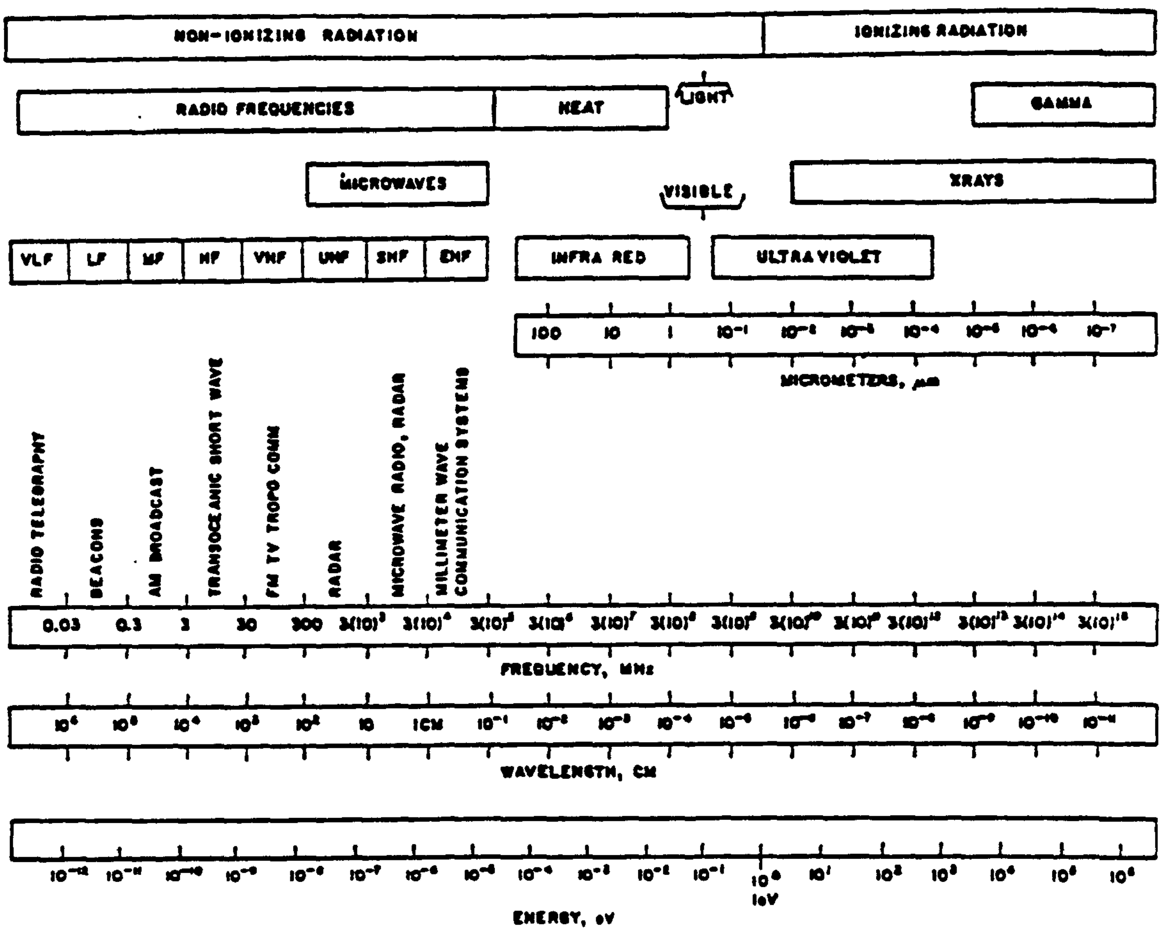

Figure 1. The electromagnetic spectrum

The characteristics of RF radiation, necessary to an understanding of the information presented in this document, are briefly summarized here. Textbooks and references are available for a more comprehensive description; see, for example, Chapter 6 in Si65.

Electromagnetic radiation is characterized by coupled electric and magnetic fields that oscillate periodically in time as the fields propagate away from the source of the radiation at the velocity of light, equal to 3×10^{10} cm/sec in vacuum or air. This radiation has a wavelength equal to the distance traveled by the wave during one complete cycle. The wavelength, λ, is expressed as:

$$\lambda = c/f = 3 \times 10^{10} \text{ cm/sec} \times T, \quad (1)$$

where f is the oscillation frequency of the electromagnetic wave, expressed in units of cycles per second or hertz (Hz), and T is the period of one oscillation, i.e., the time duration of one cycle, and is related to the frequency by the expression $T = 1/f$.

Radiofrequency electromagnetic fields are generated by the oscillation of electrons within a system's antenna. The frequency of the field is equal to the electron oscillation frequency. The field generated by any radiating system has two components: the induction field and the radiation field. The induction field occurs in the immediate vicinity of the radiating system; the energy in the induction field oscillates back and forth between the antenna and nearby space. At sufficiently large distances the induction field becomes negligible relative to the radiation field. The radiation field represents a continual flow of energy outward from the antenna. At a distance $r \gg \lambda/2\pi$, the radiation field becomes dominant, and the induction field can be neglected (Si65). This distance is generally taken to be equal to a few wavelengths.

All RF systems consist of a power source (transmitter) and an antenna. The transmitter produces the RF power by which information is transmitted through the application of selected amplitude/frequency/time modulation; the antenna radiates that energy, some of which impinges on another antenna or object at some distance.

The total emitted power is directly related to the transmitter power. The distribution of that power in space is determined by the antenna. Environmental levels at any location are determined not only by the transmitter power and the antenna, but also by the location and orientation of the antenna and other objects (such as structures that reflect emissions), and the operating characteristics of the system (including the time-dependent motion of rotating or nodding antennas and the on-off operation of the transmitter).

The primary function of the antenna is to emit power with a specific spatial distribution pattern. The radiation intensity at any location in free space is determined by the power radiated and the inherent ability of the antenna to radiate that power in a given direction relative to the antenna axis or center of radiation. This directive property of an antenna is its gain function. Antenna gain represents the increase in the power radiated in a given direction over that from an isotropic radiator emitting the same total power. At large distances from the source, the antenna can be considered to be a point source radiating power as a function of direction. The radiation propagates in space through a surface having an area equal to $4\pi r^2$, where r is the distance from the radiation source. The energy density varies inversely with the square of the distance. This can be understood by realizing that the power radiated by the antenna into space is propagating into an increasingly larger volume, with the surface area of the wavefront increasing as the distance from the source increases.

The propagation of the electromagnetic wave away from the antenna can be represented as the motion of a wavefront in space. As the wavefront (represented by simultaneously emitted, in-phase electric and magnetic components of the field) becomes more distant from the radiation source, its surface becomes progressively more planar. At a sufficiently great distance, the wavefront appears to be a perfect plane. Theoretically, this occurs when the distance from the source is infinite; practically, it occurs in what is known as the far-field (Fraunhofer) region, which begins at a finite distance from the antenna. For the purposes of describing the RF radiation environment, the electric and magnetic fields and the direction of wave propagation can be considered to be mutually orthogonal at a distance of a few wavelengths from the antenna (Si65), i.e., for distances much greater than $\lambda/2\pi$. From that distance through the far-field region, the electric and magnetic field vectors are perpendicular to each other and form a plane perpendicular to the direction of radiation propagation. The radiation field at any point is expressed in terms of the magnitude and direction of both the electric and magnetic fields at that point.

In free space or in air, at a distance from the antenna where E and H are essentially orthogonal, the absolute values of the electric field E and the magnetic field H are related as follows:

$$E(V/m)/H(A/m) = 377(ohms), \qquad (2)$$

where E has units of volts per meter (V/m), H has units of amperes per meter (A/m), and 377 ohms is the impedance of free space.

Another quantity commonly used to describe the intensity of RF radiation exposure is the power density, i.e., the RF power (in the direction of radiation propagation) incident on a unit area to which it is perpendicular. The magnitude of the power density, S, is expressed as the product

$$S = EH. \qquad (3)$$

The power density has the magnitude given by the following expression for S in units of watts per square meter (W/m^2):

$$S(W/m^2) = [E(V/m)]^2/337(ohms) = [H(A/m)]^2 \times 377(ohms). \qquad (4)$$

The power density value of interest is the energy flow over a cycle rather than the instantaneous flow. This time-averaged value is derived from the root-mean-square (rms) values of E and H.

The units in which power density is commonly expressed are watts per square meter (W/m^2), milliwatts per square centimeter (mW/cm^2), microwatts per square centimeter ($\mu W/cm^2$), and nanowatts per square centimeter (nW/cm^2). These are related as shown below:

$$\begin{aligned} 1\ W/m^2 &= 0.1\ mW/cm^2 \\ &= 100\ \mu W/cm^2 \\ &= 10^5 nW/cm^2. \end{aligned}$$

The general expression for radiation intensity, in terms of the power density, at a point in space at a distance, r, from the antenna at angles θ and Φ, in a spherical coordinate system centered at the antenna (Figure 2) is given by the expression

$$S = PG(\theta,\Phi)/4\pi r^2, \qquad (5)$$

where power density, S, is the radiated power from the antenna incident on a unit area at a distance, r, from the antenna, and the gain, $G(\theta,\Phi)$, is the ratio of the power radiated in a given direction per unit solid angle, $P(\theta,\Phi)$, to the average power radiated per unit solid angle, $P/4\pi$, where P is the total power radiated.

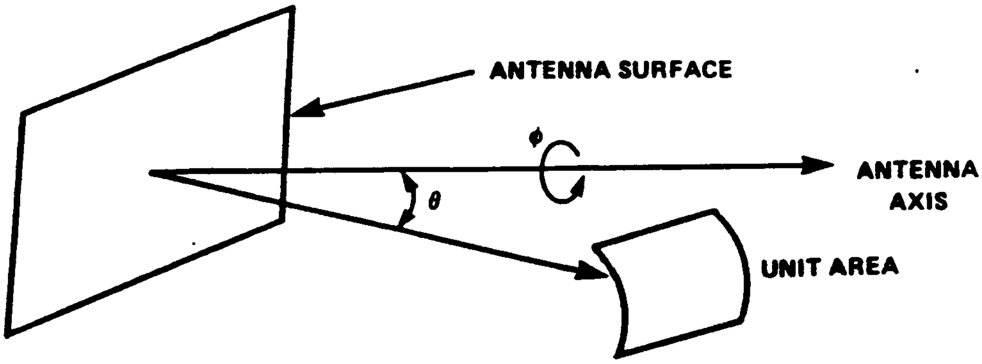

Figure 2. Spherical Coordinate System Used to Describe Antenna Radiation Characteristics

The total energy radiated by the antenna is never greater than the energy provided to it; however, the energy can be directed so that the resulting radiation distribution pattern can show intensity enhancement in preferred directions and intensity reductions in other directions. By comparison, an isotropic radiator produces a uniform spatial distribution pattern of equal radiation intensities in all directions at a specific distance. The radiation distribution pattern at a given distance from the antenna has the same angular dependence as the antenna gain. Figure 3 illustrates the general case for the spatial distributions of radiation from two antennas, one being an isotropic radiator and the other having a high-gain characteristic. Relative radiation intensity or antenna gain is shown as a function of angle in a polar coordinate system. An isotropic radiator has a gain equal to 1 in all directions.

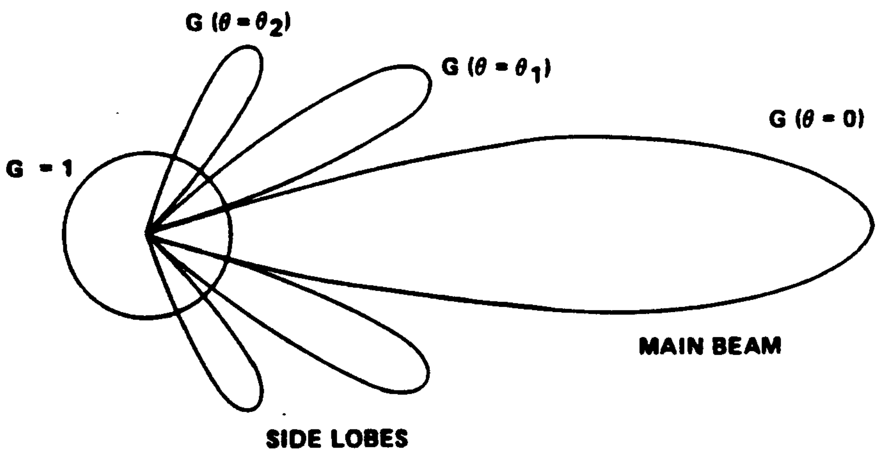

Figure 3. Representation of Spatial Distribution of Radiated Fields from Isotropic and High-Gain Directional Antennas. (For the Isotropic Antenna, G = 1 for any Direction and $S = P/4\pi r^2$.)

The gain, $G(\theta,\Phi)$, of an anisotropic antenna varies with angle and can be much greater than 1 for high-gain antennas at $\theta = 0$ degrees. In fact, $G(\theta=0)$ can exceed 10^6 for very large area reflector antennas that radiate energy with wavelengths that are very small compared to the antenna dimensions. The radiation intensity, in terms of power density, is generally a maximum at $\theta = 0$ degrees, i.e., in the direction of the antenna axis.

The electric field intensity, E, in free space far from an antenna, can be expressed in terms of transmitter power and antenna gain, using Equations (4) and (5) as follows:

$$E(V/m) = [30PG(\theta,\Phi)]^{1/2}/r. \qquad (6)$$

Radiation intensity enhancement in a preferred direction for anisotropic antennas is directly characterized by the gain. High-gain antennas concentrate more radiated energy into a main beam, which is generally symmetric about the antenna radiation axis, and distribute relatively little energy in other directions. Greater antenna gain results in greater radiation intensity in the main beam (which has a decreasing angular divergence as the gain increases) and less in the side-lobe radiation pattern.

High-gain antennas are typically used to produce usable signal intensities with available transmitter power at great distances from the transmitting antenna. They reduce the possibility of interference from other radiating systems, a result of having a main beam with small angular divergence and reduced intensity side lobes. Systems using high-gain antennas include satellite communications, microwave relay, and radar. Low-gain antennas are used in systems that must radiate energy in all directions to produce a more even intensity distribution, so that radiation can be received at every location in a given region. Such applications include AM and FM radio, VHF and UHF television, land-mobile radio, paging systems, and low-powered hand-held radio.

In general, for systems of equal power output, those employing high-gain antennas produce higher signal intensities in the main beam of radiation at a point at a given distance from the antenna than those using low-gain antennas. Because the radiation from high-gain RF radiating systems is intended for receivers that need not be near people, environmental exposures from these high-gain systems are usually relatively low. Systems using low-gain antennas generally distribute radiation into the environment where people wish to receive it, i.e., where radio and television receivers and their listeners and viewers are located. As a result, radio and television broadcast systems make the largest contribution to the RF radiation environment to which everyone is exposed.

The radiation intensity pattern of any antenna system can be represented in a manner similar to the mathematical expression for the signal intensity far from a broadcast antenna (Equation 5). While this expression can become very complex, depending upon the antenna and system operation, it is possible to estimate radiation intensities produced by the operation of any of the radiating systems previously identified. These analytically derived exposures can be used to estimate the environmental radiation levels produced by any system and to assist in implementing and assuring compliance with exposure guides and standards.

At distances close to an antenna, where the antenna does not appear to be a point source, the expressions for power density and the electric and magnetic field intensities are different from those shown in the equations previously used. They will be discussed later for specific antenna systems.

SECTION 3

GENERAL ENVIRONMENTAL EXPOSURES

BACKGROUND

The most common exposure to RF fields consists of a superposition of the fields from many different RF sources operating at different frequencies and occurs at distances far from individual radiation sources. To determine these general environmental exposures, EPA began measuring levels of RF radiation in urban areas in October 1975. Measurements have shown that the principal sources of environmental RF radiation are AM and FM radio and VHF and UHF television transmitters (Te74a, Ja77a, Ja77b, Ja79a, Te78a), with other bands making only minor contributions to general environmental exposure levels (Te74a, Ja77a, Ja77b, Te77a, Ha76a). Instrumentation was developed to measure general environmental exposure levels (Te76a) in the broadcast bands. The frequency bands initially measured included VLF communications and the standard AM broadcast band (0-2 MHz), the VHF television bands (54-88 and 174-216 MHz), the FM radio band (88-108 MHz), two land-mobile bands (150-162 and 450-470 MHz), and the UHF television band (470-806 MHz).

This multisource, multifrequency general RF radiation environment was measured at 486 sites in 15 large cities (Te80a, Te78a, Ja79b, At78, Ja80). The data represent approximately 14,000 measurements and have been used to estimate the RF radiation exposure within some 47,000 census enumeration districts for the 44 million people residing in these 15 cities. The estimate used 1970 census data and represents only outdoor residential (not occupational) exposures. The estimated residential exposure for more than 99 percent of the total population of those 15 cities is less than 1 microwatt per square centimeter ($1 \mu W/cm^2$) at AM, FM, and TV frequencies (Te80a, Ja79b, At78, Ja80). The estimated median residential exposure is $0.005\ \mu W/cm^2$ at FM radio and TV frequencies and $0.019\ \mu W/cm^2$ at AM radiofrequencies (Te80a, Ja80). (The median exposure level is the time-averaged power density that separates the exposed population into two groups, such that 50 percent of the population is exposed above that level and 50 percent is not.) Further analysis indicates that for frequencies above 806 MHz, negligible levels are found in the general environment.

The analytic approach used to estimate population exposure does not take into account the following: the normal daily movements of the population residing within an area, exposures at heights greater than 6 meters above ground (where exposures can be greater due to non-uniform antenna radiation patterns), attenuation effects of typical buildings, and periods of time when sources are not transmitting. The results are simply estimates for the population residing in areas where an unobstructed measurement 6 meters above ground would result in the indicated exposure values.

These estimates of population exposure represent general environmental exposures for the public residing far from RF radiation sources. Exposures occurring close to sources can be much greater; however, estimating population exposed at these greater levels is much more difficult.

METHOD OF DETERMINING POPULATION EXPOSURE

The RF radiation exposure levels measured at selected locations in the 15 cities were used to estimate the radiofrequency radiation exposure within 47,000 census enumeration districts (CEDs) out of the 257,000 CEDs in the 1970 census. Each CED is a small geographic area within which approximately 900 to 1,000 people reside. The data base provided a description of each CED, i.e., the geographical coordinates of the population centroid and the number of residents. In densely populated cities, a CED is a relatively small geographic area, while it is generally much larger in less densely populated suburban and rural areas.

The method used to determine population exposure included:

1. Selecting the sites at which to perform RF exposure measurements;
2. Measuring RF exposure power densities at these locations;
3. Estimating the exposures at each population centroid within the general urban area studied; and
4. Counting the number of persons residing in all of the CEDs (in that particular metropolitan area) who are exposed to specific power density intervals within the entire existing range of exposures.

The procedures used to predict residential exposures from exposures measured at a limited number of locations in a city are described by Tell and Mantiply (Te80a).

In the first seven cities, measurement sites were selected on the basis of population distribution within a city as inferred from city maps. For the remaining eight cities, a random selection process was adopted to specify the CEDs in which measurements were to be made. Each CED was assigned a weighting factor according to its population, so that all individuals in a city had an equally likely chance of having the centroid of their CED chosen as a measurement site. In addition to these locations, a few additional measurement sites very close to broadcast station antennas were selected to allow the full range of environmental exposure levels to be defined.

Typically, measurements of RF exposure power densities and their frequency dependence were made at one particular site within each of the CEDs chosen. The field intensities obtained for each broadcast station at each measurement site were used to develop a model describing electric field intensity variation as a function of distance from each specific station. This model was used to calculate the field intensity resulting from each broadcast source at each CED centroid. The exposure power density as a function of frequency at each CED centroid was summed to obtain the total power density within each frequency band and the total power density from all frequency bands. The predicted exposure levels at each CED centroid were assumed to apply to everyone residing within that CED. The population exposure for the entire metropolitan area under study was obtained by adding the number of persons exposed to the same intensities within each frequency band for all CEDs. Since most of the RF radiation sources in a metropolitan area are generally far from any CED centroid and the population assumed to reside there, these population exposure estimates represent general environmental exposures (far from sources) for the public. They therefore exclude population exposures for individuals living or working close to RF radiation sources.

POPULATION EXPOSURES

The method previously described to estimate population exposures was applied to the data obtained at each of the measurement sites in the 15 cities selected for the study of general population exposure to environmental RF radiation. The combined results of the analysis, presented as the cumulative fractions of population exposed within power density ranges defined by the values 0.001, 0.002, 0.005, 0.010, 0.020, 0.050, 0.100μW/cm^2, etc., are shown in Figure 4 for all 15 cities. Results of this type were obtained for the population of each city and for the total population of the 15 cities. A more complete description of the study and results is contained in references (Te80a, Te78a).

The cumulative population exposures shown in Figure 4 are derived from the percent of population exposed within various power density intervals, as presented in Figure 5.

The number of measurement sites and FM and TV transmitters, as well as the number of CEDs and the population for each city involved in the study, are summarized in Table 2.

The median population exposure and the percent of population exposed at and below 1 μW/cm^2 are presented in Table 3 for each of the 15 cities. The median exposure values vary from 0.002 μW/cm^2 in Chicago and San Francisco to 0.02 μW/cm^2 in Boston and Portland. The median exposure for all cities together is 0.005 μW/cm^2.

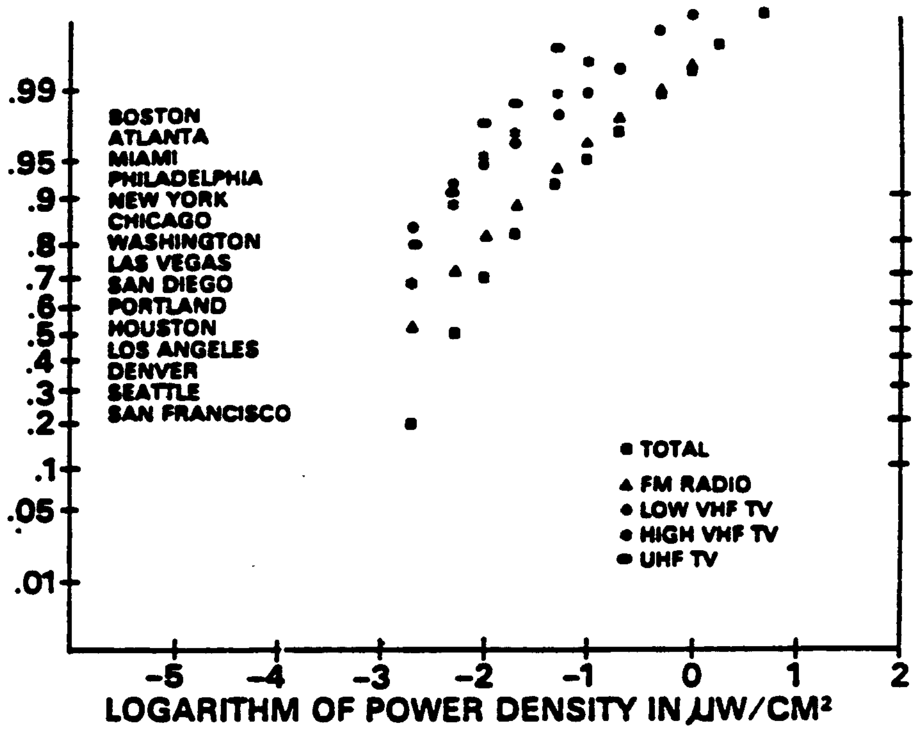

Figure 4. Cumulative Population Exposure for 15 Cities

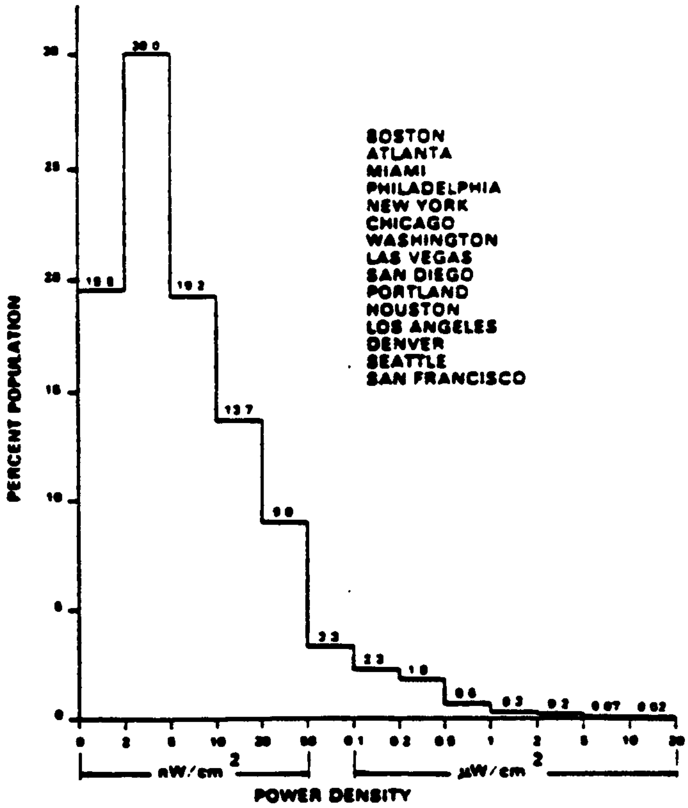

Figure 5. Differential Fraction of Population Exposed Within Given Power Density Intervals (15 Cities)

Table 2

SUMMARY OF INFORMATION RELEVANT TO ENVIRONMENTAL RF RADIATION MEASUREMENTS AND POPULATION EXPOSURE ESTIMATES FOR 15 CITIES

City	No. CEDs	Population	Number of Stations FM	Low VHF	High VHF	UHF	No. Sites
Boston	2,003	1,953,665	14	3	1	3	9
Atlanta	1,249	1,221,431	11	2	2	2	16
Miami	1,897	1,661,012	13	3	2	2	16
Philadelphia	3,606	3,407,059	17	2	2	3	31
New York	11,470	12,269,374	23	3	4	3	36
Chicago	4,646	4,743,905	20	2	3	3	39
Washington	2,291	2,516,917	17	2	2	3	37
Las Vegas	356	264,501	6	2	3	0	42
San Diego	1,113	1,071,887	17	1	2	2	38
Portland	1,194	818,040	12	3	3	0	38
Houston	1,127	1,265,933	14	1	3	2	33
Los Angeles	7,596	6,951,121	29	3	4	7	38
Denver	1,629	1,148,016	10	3	2	0	43
Seattle	1,315	872,422	16	2	2	0	35
San Francisco	5,297	3,959,893	26	3	2	3	35
TOTAL	46,789	44,125,176	245	34	37	34	486

Table 3

ESTIMATED POPULATION EXPOSURE IN 15 U.S. CITIES (54-806 MHz)

City	Median Exposure ($\mu W/cm^2$)	Percent Exposed <1 $\mu W/cm^2$
Boston	0.018	98.50
Atlanta	0.016	99.20
Miami	0.0070	98.20
Philadelphia	0.0070	99.87
New York	0.0022	99.60
Chicago	0.0020	99.60
Washington	0.009	97.20
Las Vegas	0.012	99.10
San Diego	0.010	99.85
Portland	0.020	99.70
Houston	0.011	99.99
Los Angeles	0.0048	99.90
Denver	0.0074	99.85
Seattle	0.0071	99.81
San Francisco	0.002	97.66
All Cities	0.0048	99.44

The general environmental exposure measurements (Te80a, Te74, Ja77a, Ja77b, Te78a, At78) demonstrated that the RF radiation exposure environment is dominated by the FM radio and VHF television frequencies. The contribution from UHF television transmitters is not as significant (Figure 4). In the frequency range 27 to 806 MHz, land-mobile radio contributes the least exposure. This is shown by the distribution of power densities, presented as the fraction of sites at which the total power density exceeds any given value (Figure 6). This distribution was derived from the data representing the total power density in each frequency band measured at each of the 193 measurement sites in the seven metropolitan areas first studied (At78). The value of total power density measured at each of the 193 measurement sites ranged from 0.0001μW/cm² to 10μW/cm², and the maximum exposure power densities are shown in Table 4 for each of the frequency bands measured.

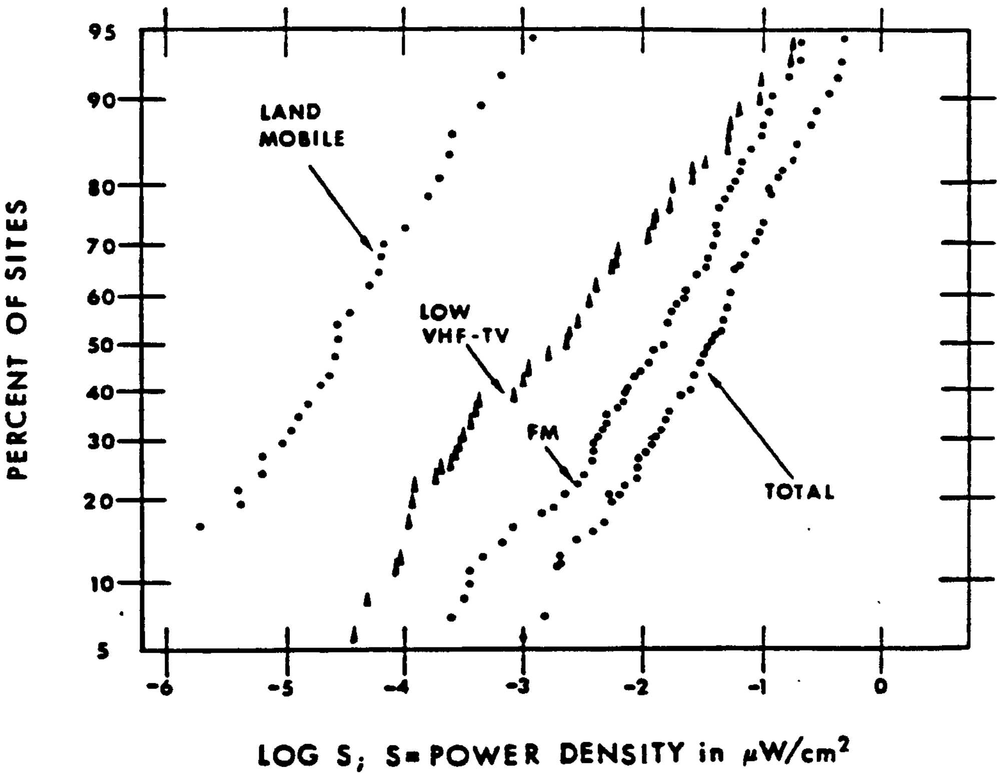

Figure 6. Cumulative Distribution of Power Densities at 193 Measurement Sites

Table 4

MAXIMUM EXPOSURE POWER DENSITY MEASURED FOR EACH FREQUENCY BAND IN DETERMINATION OF GENERAL ENVIRONMENTAL RF RADIATION EXPOSURES

Frequency Band	Location	Power Density (μW/cm²)
0-2 MHz	Atlanta	0.94
	Miami	0.94
Low VHF-TV	Washington, D.C.	1.49
High VHF-TV	Washington, D.C.	0.77
FM Radio	Chicago	10.9
UHF-TV	Washington, D.C.	0.40
Low Land-Mobile Radio	Washington, D.C.	0.029
High Land-Mobile Radio	Philadelphia	0.039
Total (for all bands)	Chicago	10.9

The FM radio band makes the largest contribution to the overall population exposure because of lower antenna height and greater relative intensity of the vertically directed radiation from FM antennas.

The population exposure estimates for the AM radio band are treated separately from those for the 54- to 806-MHz bands because of the large difference in absorption at these frequencies. The absorption rates differ by a factor of almost 4000; i.e., an exposure of 1 $\mu W/cm^2$ at AM radiofrequencies is required to produce the same rate of energy absorption as 0.00025 $\mu W/cm^2$ at FM frequencies (Ja80). Population exposure estimates for the AM radio band, using the measured electric field intensities, are shown in Table 5. The median exposure level is about 0.28 V/m. These results are based on measurements at 203 sites in seven cities.

Other RF radiation sources contribute very little to the general RF exposure environment. This is demonstrated by the contribution of radar systems in the San Francisco area. Measurements by the Institute for Telecommunications Sciences (Te77a) were used to estimate the exposures at three locations far from the radar sites. These estimates are presented in Table 6.

To develop a basis for comparison between the general environmental exposures measured in large metropolitan areas and an RF radiation environment with no nearby broadcast transmitters, measurements were made in a known RF radiation "quiet zone," Greenbank, West Virginia, where the power density in the broadcast frequency bands is on the order of 10^{-11} $\mu W/cm^2$.

Table 5

CUMULATIVE POPULATION EXPOSURE IN THE AM BROADCAST BAND (0.535-1.605 MHz)

Electric Field Strength (V/m)	Cumulative Percent of Population[a]
0.07	2.0
0.12	5.9
0.16	19.2
0.20	33.5
0.25	44.8
0.28	51.2
0.35	66.0
0.45	75.9
0.50	81.3
0.63	87.7
0.79	92.6
1.00	97.0
2.51	99.9

(a) For example, 2% are exposed to less than 0.07 V/m, 33.5% are exposed to less than 0.2 V/m, etc.

Table 6

TYPICAL URBAN RADAR ENVIRONMENTS IN SAN FRANCISCO, CALIFORNIA

Exposure Location	Number of Radars Detected	Average Power Density ($\mu W/cm^2$)
Mt. Diablo	8	0.000026
Palo Alto	10	0.00027
Bernal Heights	10	0.0011

SECTION 4

EXPOSURES FROM SELECTED RF RADIATION SOURCES

BACKGROUND

Exposures at locations in the immediate vicinity of a particular source can be considerably higher than those in the general RF environment and are dominated by the source or sources at those locations. The exposure situations to be discussed here occur at distances from antennas that range from the near field (Fresnel zone) to the beginning of the far field (Fraunhofer region). The information describing this "specific source" environment consists of exposure measurements and of estimates obtained through analyses for the most common categories of both high- and low-power systems; i.e., broadcast transmitters, satellite communications earth stations, radars, microwave radio, land-mobile radio, and low-power hand-held radio. Exposure measurements and estimates are given for locations close to sources within these categories.

Measurements have been performed for a number of different types of RF sources including FM radio and VHF and UHF television antennas (Te79, Te78b, Te76b, Te77b), satellite communications systems (Ha74a), military acquisition and tracking radars (Ha76a, Ha74b, Te74b), civilian air traffic control radars (Te74c), aircraft weather radars (Te76c, Te74d), microwave relay systems used in communications and data transmission (Te80b), police radar units (Ha76b), microwave ovens (Te78c), and land-mobile and hand-held radio (La78, Te76e, Ru79). Many of these studies provided data useful in developing analytical techniques to calculate the power densities and peak electric field intensities produced by most sources. Analytical models predicting power densities produced by sources having parabolic reflector antennas have been described by Hankin (Ha76a, Ha76c, Ha77) and Lewis (Le85).

Analytical methods used to predict exposure power density at distances close to antennas are presented here for the systems of greatest interest, i.e., broadcast FM and TV, microwave communications, and radar. The on- and off-axis power density characteristics of systems will be presented for locations in the Fresnel region as well as for locations farther from the antennas. Analysis of broadcast radiation sources has been given by Tell and others (Te72, Te78d, Te74e, Te76d, Ga85). Satellite communications earth terminals have been analyzed by Hankin (Ha74a), air traffic control radars by Hankin (Ha76a, Ha76d), and airborne radars by Tell and Nelson (Te74d), Tell, Hankin, and Janes (Te76c), and Hankin, Tell, and Janes (Ha74b). The overall impact of high-power sources based upon measurements and theoretical analyses has been discussed by Hankin and others (Ha76a, Ha74b).

Broadcast sources are usually located near densely populated areas so that the radio and television signals can be received by a large audience. The radiation patterns for broadcast antennas are not highly collimated, and exposure of persons to main-beam radiation intensities near the radiating antennas is not uncommon. Relatively high exposures compared to those in the general environment can occur at ground level close to broadcast station antennas and at higher elevations, e.g., in hilly terrain and on the upper floors of high-rise buildings, where exposure locations are in or close to the axis of the main beam.

Measurements and observations have shown that exposures to these higher fields are not unusual, although the total number of persons exposed is likely to be relatively small. The extent to which such exposures occur and the size of the exposed population remain to be determined.

Radiofrequency radiation emitting systems with highly directional (high-gain) aperture antennas used for satellite communications, radar, and microwave radio, ordinarily are used in ways that preclude possibilities of main-beam exposure at locations close to the antenna systems. Exposures that occur close to high-power sources are usually due to the antenna side-lobe radiation patterns rather than main-beam radiation (refer to Figure 3). Public exposure at locations close to the antenna (in the Fresnel region) usually occurs far from the antenna axis, i.e., at an "off-axis" distance of at least several antenna diameters as measured along a line perpendicular to the axis, where "off-axis" exposure intensities are very likely to be at least three orders of magnitude ($x10^{-3}$) less than Fresnel region on-axis exposure. At exposure locations beyond the Fresnel region in the far field (Fraunhofer region), main-beam divergence results in a decrease of power density proportional to $1/r^2$ as the distance, r, from the antenna increases. Main-beam divergence in the far field increases the probability of population exposure to main-beam radiation for some systems, but usually at distances very far from the antenna, where intensities are low.

Although high-power microwave sources such as radar and satellite communications earth terminals are capable of producing intense main-beam radiation levels at considerable distances from the source antenna, actual exposure levels (due to side-lobe radiation) have been found to be considerably lower. Many of these RF radiation sources are remotely located and are surrounded by an exclusion area that further limits the probability of exposure. Some sources are mechanically or electrically equipped to limit the pointing directions of antennas or to reduce or shut off power when occupied areas are scanned. The rotational motion of many radar antennas further reduces the average exposure.

While fewer persons are exposed to main-beam radiation produced by systems having very directive antennas and high-powered transmitters (relative to broadcast systems), some radars and satellite communications earth terminals can produce main-beam power densities of 10 mW/cm^2 and greater (Ha76a, Ha74a, Ha74b). Individuals near airports and military bases may be exposed to side-lobe radiation from systems having stationary or slowly moving antennas or to main-beam radiation from many types of radars with rapidly moving antennas, where exposure to the main beam is short but repetitive. The results of analysis indicate that continuous or time-averaged power densities in the range 10 to 100 $\mu W/cm^2$ may occur at distances up to 0.5 mile from some of these systems (Ha74a, Ha77a). Associated instantaneous peak electric field intensities can be on the order of 2,000 V/m.

Other short-term, intermittent exposures to relatively strong electric fields occur when persons are close to transmitting land-mobile radio or citizens-band radio antennas (La78, Te76e, Ru79).

FM RADIO AND TELEVISION

FM radio and VHF and UHF television are treated together in this discussion because of similar antenna radiation patterns and roughly equivalent effective radiated powers (ERP), with ERP being the product of the transmitter power and the antenna gain. ERP is used as a combined characteristic for broadcast stations in place of transmitter power and antenna gain. The frequency and maximum power characteristics for FM radio and television broadcasting are presented in Table 7.

The exposure levels produced by the radiation from FM radio and VHF and UHF television antennas depend on the location of the exposure site relative to that of the transmitting antenna. Antenna height strongly influences exposure power density. An FM or TV antenna generally consists of a vertical arrangement of radiating elements, the exact configuration being determined by the desired radiation pattern. A more complete discussion of FM and TV antenna structure and the related radiation pattern is contained in reference (Ga85). To provide good reception over a large area, antennas are often placed atop mountains, tall buildings, or tall antenna towers. Frequently, a single tower may support several FM and TV antennas.

Table 7

GENERAL CHARACTERISTICS OF FM AND TV BROADCASTING

Service	Frequency (MHz)	Maximum ERP (kW)
FM Radio	88-108	100 (may use 100 kW in both horizontal and vertical planes)
Low VHF-TV	54-72 (Channels 2-4) 76-88 (Channels 5-6)	100 visual 22 aural
High VHF-TV	174-216 (Channels 7-13)	316 visual 69.5 aural
UHF-TV	470-806 (Channels 14-67)	5000 visual 1100 aural

The FM or TV antenna has a radiation pattern that is uniform around the axis of the vertically oriented array of elements. While the primary beam of radiation is in the horizontal direction, a significant amount of power may be concentrated into a beam with a relatively small angular divergence in the vertical plane. The major difference between FM and TV transmission, with regard to RF radiation exposures, lies in the antenna radiation pattern at locations close to the antenna at large angles from the direction of maximum gain, i.e., near the base of the antenna support structure.

An example of a vertical plane radiation pattern for a typical FM antenna with six dipole elements, having a 1.0 wavelength separation between elements, is shown in both rectangular and polar coordinates in Figures 7a and 7b. A visual representation of the pattern is shown in Figure 7c. The vertical radiation lobe, called the grating lobe, occurs at about 90° relative to the horizontal. The maximum antenna gain for the primary beam and the maximum antenna gain in the grating lobe may in some cases be approximately equal, i.e., $G(\theta=0°) = G(\theta=90°)$, although the primary beam is generally narrower than the grating lobe.

The vertical plane radiation pattern for a typical UHF-TV transmitting antenna is shown in Figure 8 (Te76d). This graph does not show the intensity for large vertical plane angles out to 90°. The maximum intensity, where $G(\theta)$ is a maximum, occurs just below the horizontal plane (0.5°) to optimize the coverage. For UHF-TV and VHF-TV antennas, the E field at large depression angles is approximately 10 percent and 20 percent, respectively, of the maximum intensity (main beam) E fields (Ga85).

The previously introduced Equations 4, 5, and 6 for electric field intensity and power density at a few wavelengths from the antenna, change slightly for FM and TV when effective radiated power, $P_{ERP}(\theta)$, is

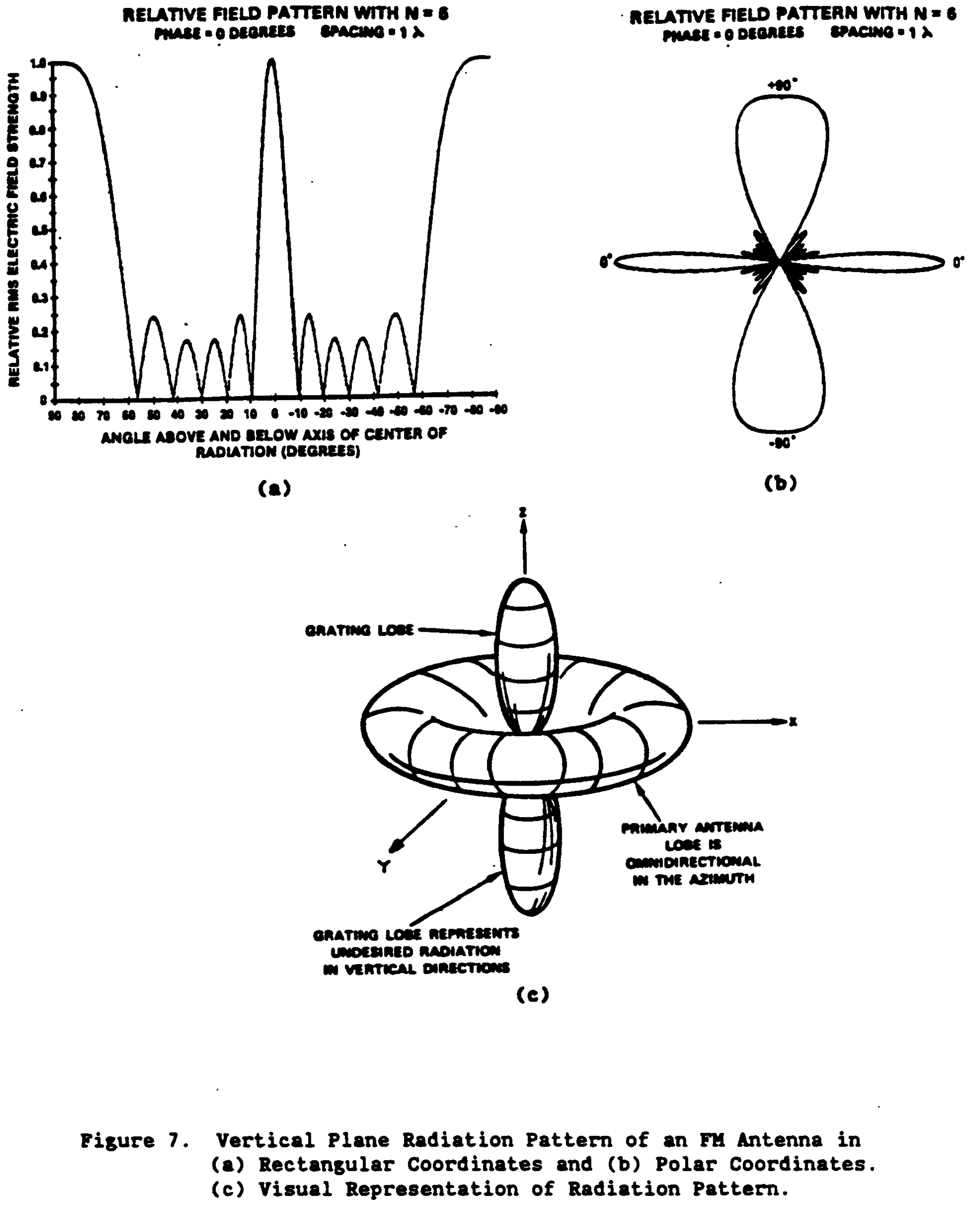

Figure 7. Vertical Plane Radiation Pattern of an FM Antenna in (a) Rectangular Coordinates and (b) Polar Coordinates. (c) Visual Representation of Radiation Pattern.

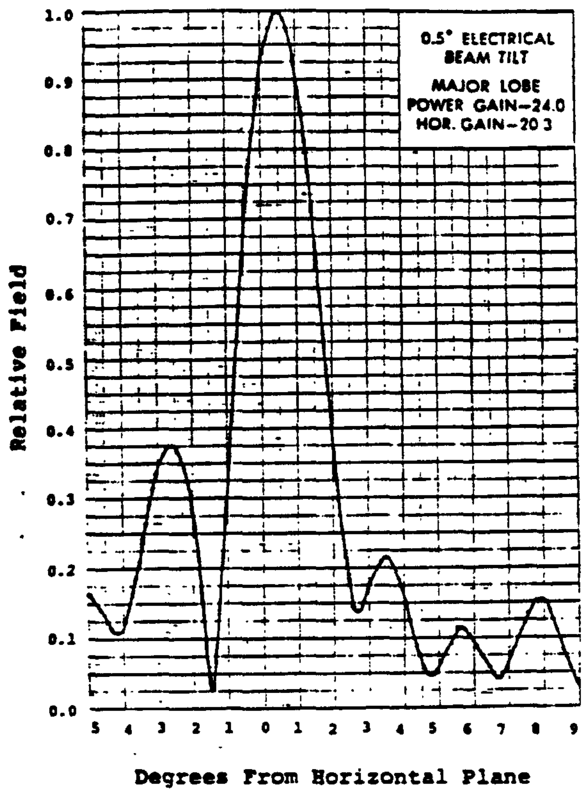

Figure 8. Vertical Plane Radiation Pattern of a Typical UHF-TV Transmitting Antenna

used to characterize the system instead of antenna gain and radiated power. The equation for power density at an angle θ,

$$S_\theta = PG(\theta)/4\pi r^2, \quad (5)$$

becomes

$$S_\theta = P_{ERP}(\theta)/4\pi r^2, \quad (7)$$

and the electric field strength at an angle θ,

$$E_\theta(V/m) = [30PG(\theta)]^{1/2}/r, \quad (6)$$

becomes

$$E_\theta(\text{V/m}) = [30P_{ERP}(\theta)]^{1/2}/r. \tag{8}$$

However, $P_{ERP}(\theta)$ can be expressed as $R_\theta^2 P_{ERP}(0°)$ for FM and TV antennas, where R_θ is the relative field strength and is a function of θ, and $P_{ERP}(0°)$ is the maximum value of $P_{ERP}(\theta)$. Then,

$$E_\theta = R_\theta[30P_{ERP}(0°)]^{1/2}/r \tag{9}$$

and

$$S_\theta = R_\theta^2 P_{ERP}(0°)/4\pi r^2. \tag{10}$$

An example of exposure power density variation with distance from the antenna support tower, calculated at ground level, is shown in Figure 9 for the FM antenna pattern depicted in Figure 7. It is assumed that the E field is reflected from the ground and adds to the incident field, so that the exposure E field is approximately twice that of the incident E field.

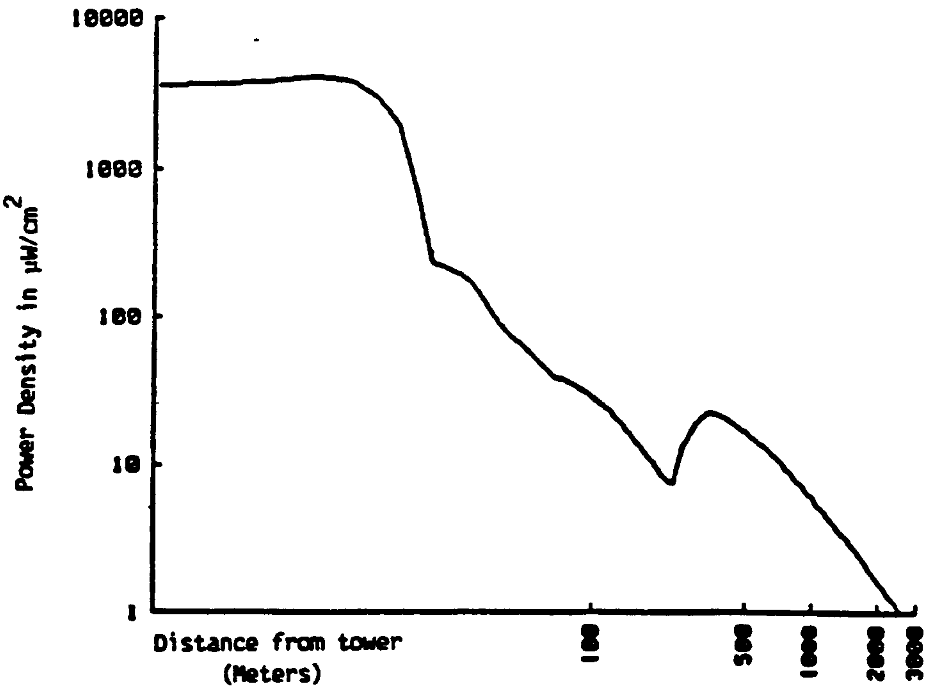

Figure 9. Ground-Level Power Density vs. Distance for an FM Antenna

Figure 9 illustrates why high-intensity exposures can be found near the base of a tower supporting an FM antenna and at elevated locations (in the main beam) such as the upper stories of high-rise buildings or at high elevations in hilly terrain.

The power density variations for a UHF-TV station for various heights below the center of the antenna are presented in Figure 10. Again, the pattern of exposure is similar to that for FM antennas. Intensities are generally greatest near the base of the support tower and decrease with horizontal distance from the antenna for constant height below the antenna. Because the grating lobe gain for TV antennas is generally not equivalent to the main-beam gain, however, relatively higher intensity exposures are more likely to occur at locations farther away from the antenna tower than is the case for FM antennas, where high-intensity exposures can occur near the base of the antenna support tower. These locations are generally at upper floors of nearby high-rise buildings.

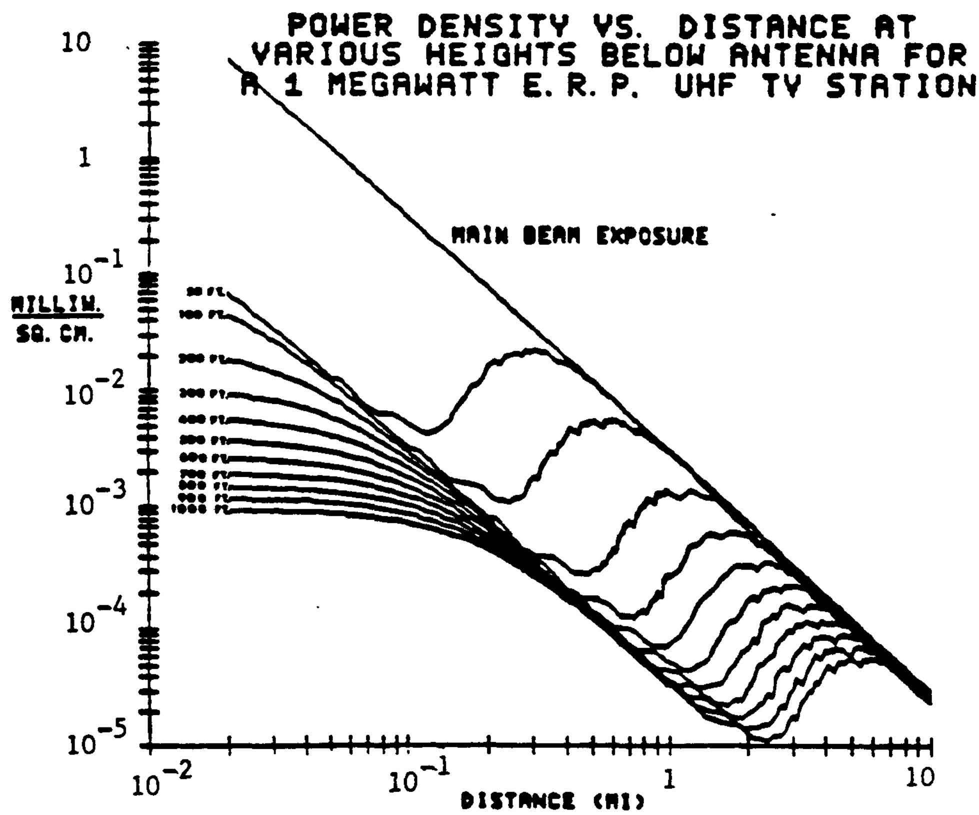

Figure 10. Power Density vs. Distance for a 1 Megawatt (ERP) UHF-TV Station

Several series of measurements verify the analytical predictions illustrated in Figure 9. At Mt. Wilson, California, where 12 FM radio and 15 TV antennas are located in a relatively small area, measured exposure levels ranged from 1.0 to 7.2 mW/cm^2 beneath the FM antennas (Te77b). Maximum power densities in a nearby post office building were about 120 $\mu W/cm^2$. Power densities of 55.9 $\mu W/cm^2$, with 29.5 $\mu W/cm^2$ from FM radio, 14.2 $\mu W/cm^2$ from VHF-TV, and 12.2 $\mu W/cm^2$ from UHF-TV were measured in a nearby parking lot. At other sites close to FM radio antennas, ground-level exposures ranging up to more than 700 $\mu W/cm^2$ were found in publicly accessible locations near residential areas (Te85a, Te85b). An analytical assessment of exposures near a residential area predicted exposures of nearly 3 mW/cm^2 (Te84).

To investigate the relative number of FM antennas exhibiting strong grating lobes, electric field intensities were measured near the bases of 58 FM radio antennas (Te79). The results for five of these antennas are presented in Table 8 (Ja80) for power density measured at locations 3 feet above ground level, directly below the antennas out to horizontal distances of 61 m (200 feet). The values range from almost 20,000 $\mu W/cm^2$ to less than 1 $\mu W/cm^2$ to within 200 feet of the support tower. The station characteristics are included in Table 8.

The expectation that exposures at higher elevations would increase as the vertical distance between the main-beam axis and the exposure locations decreased, as predicted by the FM and TV radiation patterns shown in the preceding figures, was supported by the results of a series of measurements made in high-rise buildings in several cities (Te78b, Te85a). The results of these measurements are summarized in Table 9.

The exposures at the Empire State Building and the roof of the Sears Building were due to the antennas mounted on those buildings. The exposures at the Pan Am Building and the World Trade Center in New York City were caused by the transmitting antennas on the Empire State Building located

Table 8

POWER DENSITIES IN THE GRATING LOBE FOR 5 FM RADIO ANTENNAS AT 3 FEET ABOVE GROUND LEVEL

Distance (m)	Distance (ft)	Power Density ($\mu W/cm^2$) KXLU	KFAC	KRTH	KPRI	KWVE
0.3	1	27	—	106	19,337	—
1.5	5	—	52	—	5,199	—
3	10	223	60	106	2,652	—
4.6	15	193	—	—	2,394	—
6.1	20	166	—	239	1,413	—
7.6	25	86	60	106	862	1,300
9.1	30	32	—	—	—	—
12.2	40	0.3	165	424	—	106
15.2	50	—	60	—	—	166
30.5	100	—	—	—	—	38
61	200	—	—	—	—	27

Station	Frequency (MHz)	Effective Radiated Power (kW)	Antenna Height (ft)
KXLU	88.9	2.9	32
KFAC	92.3	39	157
KRTH	101.1	58	144
KPRI	106.5	50	60
KWVE	107.9	50	98

Table 9

POWER DENSITY MEASUREMENTS AT HIGH-RISE BUILDINGS

LOCATED NEAR FM AND TV BROADCAST ANTENNAS

Location	Power Density (μW/cm²) FM	TV	Total
EMPIRE STATE BUILDING (New York City)			
86th Floor Observatory	15.2	—	15.2
102nd Floor Observatory			
Near Window	30.7	1.79	32.5
Near Elevator	1.35	—	1.35
WORLD TRADE CENTER (New York City)			
107th Floor Observatory	0.10	1.10	1.20
Roof Observatory	0.15	7.18	7.33
PAN AM BUILDING (New York City)			
54th Floor	3.76	6.52	10.3
ONE BISCAYNE TOWER (Miami)			
26th Floor	6.69	—	6.69
30th Floor	5.24	—	5.24
34th Floor	62.1	—	62.1
38th Floor	96.8	—	96.8
Roof (shielded location)	134	—	134
Roof	148	—	148
SEARS BUILDING (Chicago)			
50th Floor	31.7	34.2	65.9
Roof	201	29.0	230
FEDERAL BUILDING (Chicago)			
39th Floor	5.74	.73	6.47
HOME TOWER (San Diego)			
10th Floor	18	—	18
17th Floor	0.22	—	0.22
Roof	119	—	119
Roof	180	—	180
MILAM BUILDING (Houston)			
47th Floor	35.8	31.6	67.4
ALA MOANA AMERICANA HOTEL (Honolulu)			
Observation Deck	57	254	311
COTY TOWER (Honolulu)			
Rooftop	—	—	375

some distance from both structures. The measured exposures at the other buildings, with the exception of the roof of the Sears Building in Chicago, were produced by antennas on other high-rise buildings located within 100 to 1,000 meters. Total power densities measured inside the buildings ranged from less than 1 $\mu W/cm^2$ (in a shielded location) to 97 $\mu W/cm^2$.
A building in Miami, One Biscayne Tower, illustrates the effect of approaching the main-beam radiation axis, where antenna gain increases to its maximum value. The power density measurement at the 17th floor of the Home Tower, San Diego, was less than expected because of attenuation of the FM field by a transparent metallized film used to cover the windows above the tenth floor. The film is used to reduce solar heat input by reflecting the sun's rays. Since these measurements were first reported in 1978, many TV and FM antennas in New York City have been relocated, undoubtedly significantly affecting the building exposures reported. This may also be true for other cities.

More recently, measurements of RF exposure levels were conducted in Honolulu, Hawaii, where most broadcast antennas are located on or very near tall buildings that in some cases have rooftop recreational areas (Te85a). Exposures on rooftop recreational and observation areas on buildings in Honolulu ranged up to 300 to 400 $\mu W/cm^2$.

AM RADIO

AM radio transmission is very different from FM radio and VHF and UHF television transmission. The AM broadcast band covers the frequency range of 535 to 1605 kHz. The associated wavelengths, 560 m to 190 m, are 100 to 1,000 times longer than those of the FM radio and television broadcast bands. The antennas used are vertical monopoles with lengths that vary from 0.1 to 1.0 wavelength. The entire tower structure acts as the antenna and, in general, the antenna tower height varies with the transmission frequency. Most AM antenna towers are 0.1 - 0.25 wavelength tall.

The primary mode of AM radio transmission is not line-of-sight, as in FM radio and television, but through propagation of a vertically polarized "groundwave" that follows the contour of the ground in an omnidirectional pattern. At night, radiation that propagates upward, called skywaves, is reflected back to earth by the electrically charged particles of the ionosphere, resulting in radiation being detected at greater distances at night than during the day. Daytime reception is largely dependent upon groundwaves, a more reliable AM radio transmission process. The skywave effect produces possibilities for interference with reception from other AM stations. To prevent nighttime interference, stations operating at night with transmitted powers of 50 kW (the power range for AM broadcast is 100 W to 50 kW) typically use a multiple-tower configuration to minimize radiation in some particular direction instead of enhancing the signal in a given direction.

Because the earth acts as a ground plane for the vertical antennas used in AM radio transmission, ground conductivity plays an important role in determining the strength of the emitted signals. The greater the soil conductivity, the greater the signal strength at a given point for a fixed power. Other factors that affect the intensity of an AM radio signal are the tower height (some heights are more effective than others in maximizing field strengths), the radiation frequency, the terrain characteristics immediately around the antenna site, and the power being transmitted.

The calculated ground-level field strengths near two AM radio towers are shown in Figure 11. These two curves represent the extremes in field strength for variations in ground conductivity, antenna tower height, and frequency, and were determined through application of the FCC rules and regulations as used in reference (Te76d). Each curve is computed for a transmitter output power of 50 kW and assumes that the power is delivered to the antenna without loss. A maximum field strength of 22 V/m is obtained at 100 meters for the 550 kHz case and decreases approximately with the inverse of the distance. Two qualifications need to be placed on these results: (1) the indicated field strength values are not valid at distances closer than 100 meters due to near-field effects, and (2) it is possible that some particular station with an optimum tower height for its operating frequency and an excellent ground system might produce slightly higher field strengths. The two cases selected here are intended to be representative of typical but not necessarily absolute extremes. A field strength of 22 V/m is equivalent to a plane-wave power density of 0.13 mW/cm^2 in free space (refer to Equation 4).

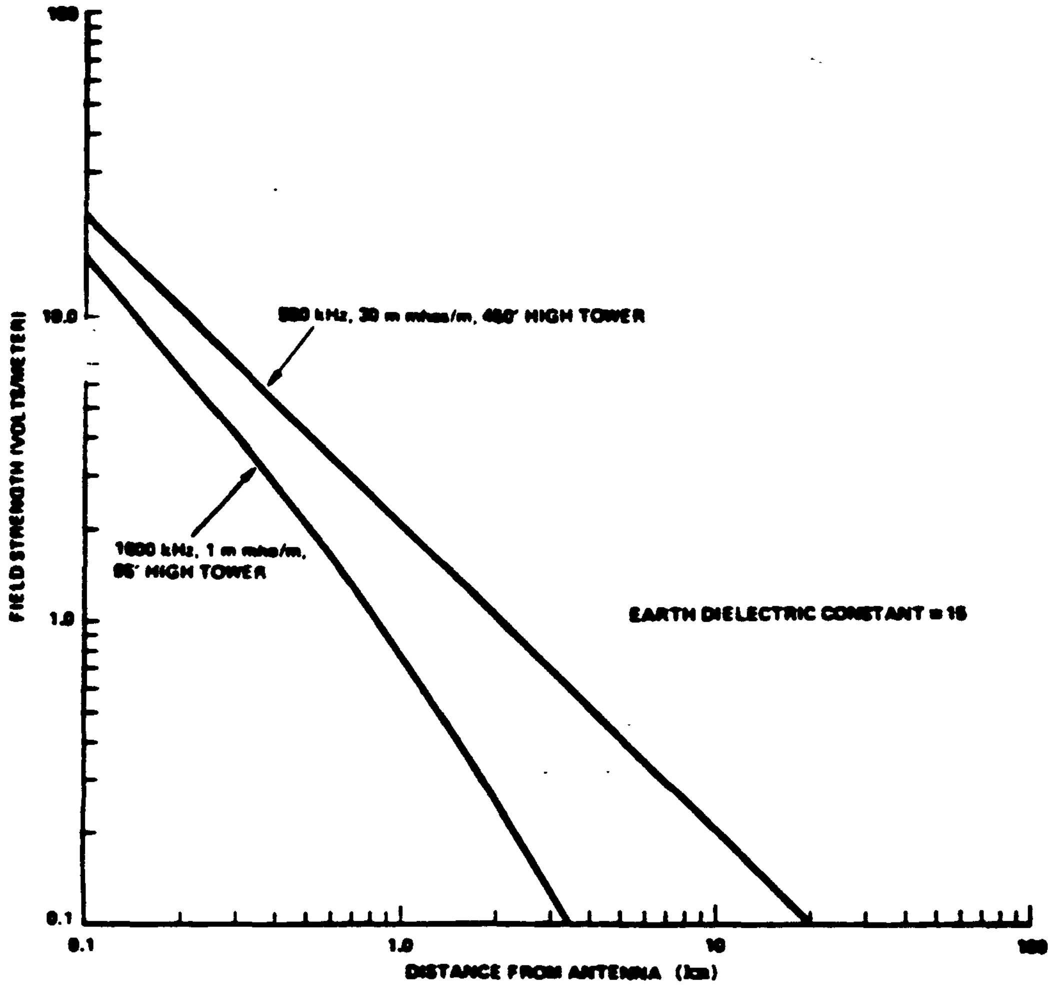

Figure 11. Groundwave Field Strengths for 50 kW Single Monopole AM Radio Broadcast Stations

A description of the methods used to calculate fields for AM radio stations is contained in reference (Ga85). Table 10 presents the calculated electric field intensity over a wide range of distances for a 50-kW station using one of the methods described (Jo68).

In this example (Table 10) the field strength varies from 56 V/m near the tower (4.6 meters) to 11 V/m at 93.8 meters (308 feet) to 1 V/m at 1,757 meters (1.1 mile). Measurements made by the Federal Communications Commission (Wa76) at two different 50-kW stations are consistent with the values in Table 10. Both stations consisted of three antenna towers arranged in an in-line configuration with only one tower radiating during the day and all three operating at night. The electric field intensity at a distance of 300 feet from the antennas of the 1,500 kHz station was 17.3 V/m; at 295 feet from the antenna of the station operating at 1,090 kHz, it was 40.8 V/m. An electric field intensity of 1.7 V/m was measured at a distance of 1 mile from a 50 kW, 720 kHz station (Ha77b).

Ground-level exposures from AM transmitters have been found to be as great as 300 V/m (electric field) and 9.0 A/m (magnetic field), corresponding to equivalent plane-wave power densities of 24,000 $\mu W/cm^2$, and $3x10^6 \mu W/cm^2$, respectively, in publicly accessible locations. Measurements of the exposures at recreational areas on the roofs of high-rise buildings (Te85a) revealed AM electric field intensities of 100 to 200 V/m (equivalent plane-wave power density of 2,650 to 10,600 $\mu w/cm^2$).

HIGH-FREQUENCY (HF) RADIO

Exposures from transmitting systems operating in the HF band, 3 to 30 MHz, have been investigated. Radio transmission in the HF band is used for international communications. Transmitter powers can vary considerably, with effective radiated power (ERP) being restricted to a minimum of 50 kW for FCC-licensed international broadcast stations. Other communication systems using the HF band operate at much lower ERP values.

Table 10

ELECTRIC FIELD STRENGTH AT VARIOUS DISTANCES

FROM A 50 kW AM RADIO BROADCAST STATION

Distance (m)	Electric Field Strength (V/m)
4.6	56.2
8.8	.32.7
20.9	27.2
46.4	12.7
93.8	11.2
121	12.7
147	9.3
202	6.8
479	3.0
1,000	1.9
1,757	1.0
2,021	.7
5,275	.4
10,000	.2
20,000	.1

Measurements of environmental magnetic field intensities (Te78e) for an international broadcast station operating at 5.980 MHz with an ERP of 250 kW and at 9.615 MHz with an ERP of 50 kW found maximum H field intensities of 0.251 A/m and 0.112 A/m, respectively, at generally accessible locations near the antennas. Corresponding plane-wave equivalent power densities would be 2.38 mW/cm^2 at 5.980 MHz and 0.47 mW/cm^2 at 9.615 MHz.

Another international broadcast system proposed to operate at 9 MHz with an ERP of 100 kW was analyzed; for this system an equivalent plane-wave power density of 0.11 mW/cm^2 was predicted at a distance of 750 feet and at a height of 30 feet above ground (Te82).

The environmental exposure levels produced near a facility with a number of HF transmitters were determined by an analysis of the radiating systems (Ha78a). Systems operating simultaneously with frequencies varying over a range of 3 to 17.4 MHz, having ERPs of 10 kW (for seven of the systems) and 12 kW (for two of the systems), were predicted to produce a total plane-wave equivalent exposure power density of 81 $\mu W/cm^2$ at a distance of 100 meters and 0.3 $\mu W/cm^2$ at 1 mile.

The results of the three studies are consistent and indicate that exposure power densities in accessible areas close to high-power (ERP on the order of 100 kW) HF systems can be equal to or greater than 1 mW/cm^2.

SATELLITE COMMUNICATIONS EARTH TERMINALS (SATCOMS)

Satellite communications earth terminals communicate with earth-orbiting satellites that are used for communications, scientific research, weather forecasting, national defense, and geological exploration of earth resources. These SATCOM systems can produce significant power densities at greater distances from the antenna than is possible for other types of radiating systems. Exposure of people to radiation from SATCOM earth terminal antennas, when it occurs, is not to main-beam radiation, but to the lower intensity side lobes (refer to Figure 3). These side lobes may irradiate a particular region of the environment for long periods of time while the earth terminal antenna is in contact with satellites in various earth orbits out to geostationary (synchronous) orbits at a height of 22,300 miles above earth.

Satellite communications (SATCOM) systems use high-gain antennas that radiate power into well collimated main beams with very little angular divergence. The need to transmit power over great distances and the number of communications channels involved determine the transmitter power to be used with an antenna having a diameter usually determined on the basis of reception requirements. Generally, as systems are required to provide higher data transmission rates over great distances, the earth terminal transmitter power and antenna diameter increase. The combination of high transmitter power and antenna diameter is responsible for producing a region of high power density (in the main beam) that extends over very large distances. Two of the highest power systems included in this discussion, located at Goldstone, California, are used to communicate with space probes performing research many millions of miles from earth.

The antennas of satellite communications system earth terminals have paraboloidal surfaces and circular cross sections. Many have Cassegrain geometries (Figure 12) where power is introduced to the antenna from the primary radiating source (power feed) located at the center of the paraboloidal reflector. The radiation is incident on a small hyperboloidal subreflector located between the power feed and the focal point of the antenna. Radiation from the power feed is reflected from the subreflector, illuminates the main reflector as if it had originated at the focal point, and is then collimated by the reflector. While the reflector surface can be illuminated by means other than Cassegrain geometry, the example shown illustrates the general radiation characteristics of circular cross-section paraboloidal reflectors.

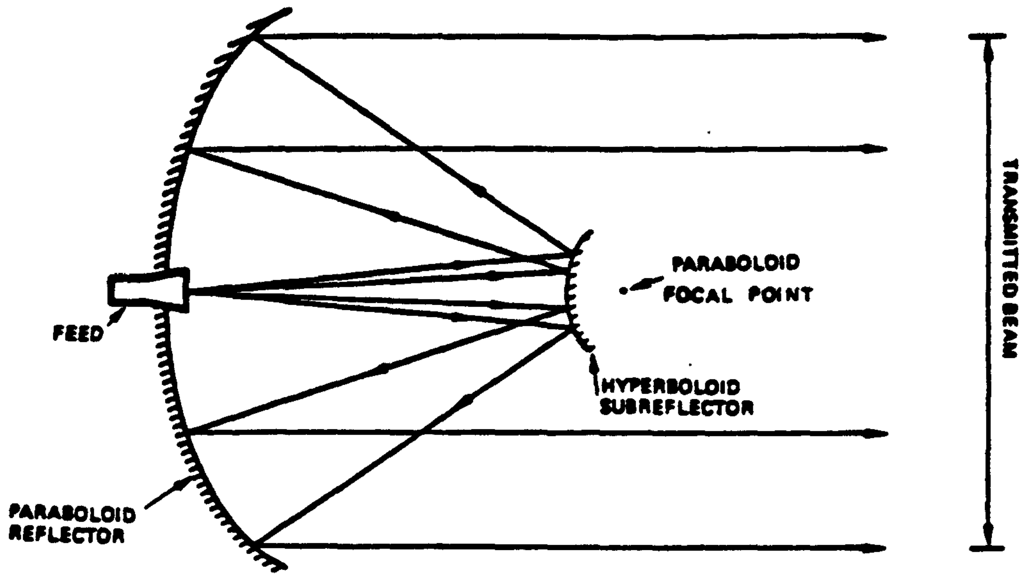

Figure 12. Cassegrain Paraboloidal Antenna

The radiation frequencies used by SATCOM systems usually range from about 2 to 14 GHz (14×10^9 Hz), with some special systems employing frequencies in the range of 20 to 94 GHz. The high frequencies used and the relatively large antenna diameters result in the antenna being highly directional (high gain); the ratio of wavelength (λ) to diameter (D) is the determining factor. The generally directional nature of the radiation distribution pattern of the antennas of most high-power systems significantly reduces the probability of exposure to high levels; i.e., the power densities at locations accessible to the public are usually substantially less than on-axis or main-beam power densities. The exposures depend upon antenna height above ground, main-beam orientation, location of the system in relation to public access areas, and operational procedures used, in adddition to transmitter power, antenna diameter, and wavelength.

Selected SATCOMS were studied analytically and by measurement of on-axis power densities to determine methods of estimating potential environmental exposure levels and to determine the relative environmental significance of this category of radiation sources.

An empirical model, based upon aperture-antenna theory (Si65, Ha76a, Ha74a, Ha76c, Ha77) and many measurements (Ha74a, Ha74b, Te74b, Te76c, Te74d, Ha76b), has been developed and used to calculate the characteristics of satellite communications earth terminals and to evaluate potential environmental exposures. The model applies directly to antennas (reflectors) that are circular cross-section paraboloids. It expresses the on-axis power density, the maximum existing at any given distance from the antenna, as a function of distance from the antenna in terms of basic characteristics; e.g., the reflector diameter, radiation wavelength, aperture efficiency, and the power that can be introduced to the antenna system. An earlier version of the model was used in a study of SATCOM systems (Ha74a); the results have been updated and included in this section.

An in-depth treatment of paraboloidal antennas is given by Silver (Si65). General characteristics are presented here to enable the reader to better understand the information provided. In general, the reflector is illuminated so that beyond a specific distance from the antenna, in the Fraunhofer (far-field) region, power is distributed in a series of maxima and minima as the off-axis angle (defined by the antenna axis, the center of the antenna, and the specific fieldpoint) increases. For constant phase over the aperture, there is one maximum that is much greater than the others, i.e., the main beam. The power distribution is characterized by the gain function, $G(\theta)$. For the special case of uniform illumination, the main-beam gain is the maximum possible, $G_o(\theta=0^o) = 4\pi A/\lambda^2$, where A is the antenna area, and λ is the radiation wavelength. In general, for any other field distribution over the aperture, the gain is less than $G_o(\theta=0^o)$. If the illumination decreases in magnitude from the aperture center toward the edge, then the gain decreases, the beam width (of the main beam) increases, and the intensities (gains) of the side-lobe maxima decrease relative to the peak intensity (gain) in the main beam. An important characteristic of an illuminated aperture is the efficiency of the aperture in concentrating the available energy into the peak intensity of the main beam. The maximum gain occurs with uniform illumination, and the efficiency is equal to 1. In practical use, side-lobe gain is reduced so that interference may be reduced, illumination is not uniform, and the efficiency is less than 1. The overall gain of the antenna and the efficiency also include the fraction of the total power to the antenna that illuminates the aperture. The overall antenna efficiency is called the aperture efficiency, and for Cassegrain antennas is usually equal to about 0.55.

The on-axis radiation field characteristics for circular cross-section paraboloidal antennas can be described using Figure 13 (Ha76c). The magnitude of the on-axis power density oscillates as a function of distance in the near field (Fresnel region) of an antenna due to the integrated contribution from adjacent Fresnel zones to the field at a point on the antenna axis; the maximum value of the near-field on-axis power density, S_{nf}, is given by Equation 11. The beam of radiation is collimated so that most of the power in the near field is contained in a region having approximately the diameter of the reflector. The power density in the far field, S_{ff} (Equation 15), decreases inversely as the square of the distance from the antenna. The intermediate-field region is a transition region between the near and far fields in which the intermediate-field power density, S_{if} (Equation 14), decreases inversely with distance. The extent of the Fresnel region is defined by the point on the axis for which the entire aperture is a single Fresnel zone; the extent of the Fresnel region, R_{nf}, is equal to $D^2/4\lambda$.

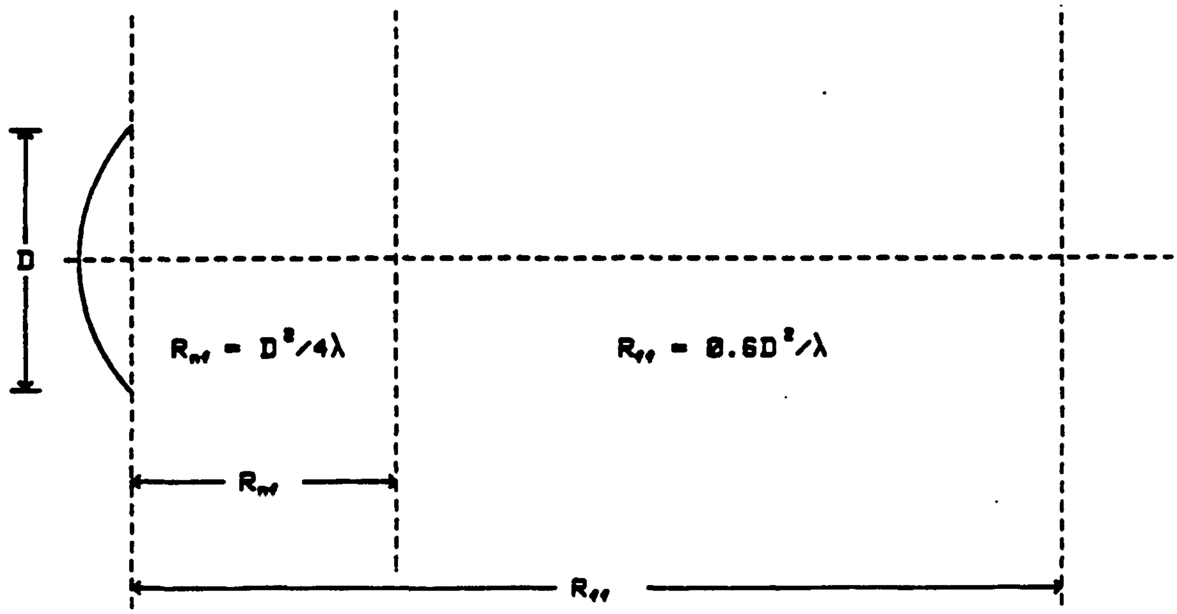

Figure 13. Radiation Field Regions for a Circular Cross-Section Reflector Antenna

$$S_{nf} = 16\eta P/\pi D^2 \tag{11}$$

$$R_{nf} = D^2/4\lambda \tag{12}$$

$$R_{ff} = 0.6D^2/\lambda \tag{13}$$

$$S_{if} = S_{nf}(R/R_{nf})^{-1} \qquad \text{for } R_{nf} \le R < R_{ff} \tag{14}$$

$$S_{ff} = 2.47S_{nf}(R/R_{nf})^{-2} = PG/4\pi R^2 \qquad \text{for } R \ge R_{ff} \tag{15}$$

where:
- S_{nf} = maximum near-field power density (on-axis)
- η = aperture efficiency, typically $0.5 < \eta < 0.75$
- P = power fed to antenna
- D = antenna diameter
- R = distance from antenna (on-axis)
- R_{nf} = extent of near field
- R_{ff} = distance to the onset of the far-field region
- S_{if} = power density (on-axis) in transition (crossover) region
- S_{ff} = power density (on-axis) in the far field.

To calculate on-axis power density as a function of distance from an antenna, the extent of the near field, R_{nf}, must be determined, i.e., the distance over which the power density can be a maximum before it begins to decrease with distance. This parameter and the maximum power density in the near field determine the on-axis power density at any distance from the antenna. Although these equations are applicable to circular paraboloidal antennas, they show that in general the important system parameters are antenna diameter, power delivered to the antenna, radiation wavelength, and aperture efficiency.

The on-axis radiation field characteristics presented for circular paraboloidal antennas yield the maximum power density the system can produce at any distance from the antenna. This provides the basis for an assessment of the potential environmental exposure levels that can be produced. Exposure at distances closer to the antenna than the onset of the far field are generally at off-axis locations where relative intensities are much less than on-axis power densities at the same horizontal distance from the antenna. The radiation pattern and relative intensities close to the antenna, out to a distance of D^2/λ along the antenna axis and out to an off-axis distance of four antenna diameters, are presented in Figure 14 for an aperture antenna having a diameter/wavelength ratio > 30 (Le85). These radiation patterns have been determined for off-axis distance up to four antenna diameters for a range of D/λ ratios appropriate for practical microwave communications antennas.

The anticipated exposure power densities have been calculated for many communications systems operating at normal transmitter powers. A comparison of measured and predicted values is presented in references (Ha74a, Ha74b, Te76c), showing good agreement with the model. The results for systems having typical SATCOM characteristics are presented in Table 11. Shown are basic system characteristics that include the

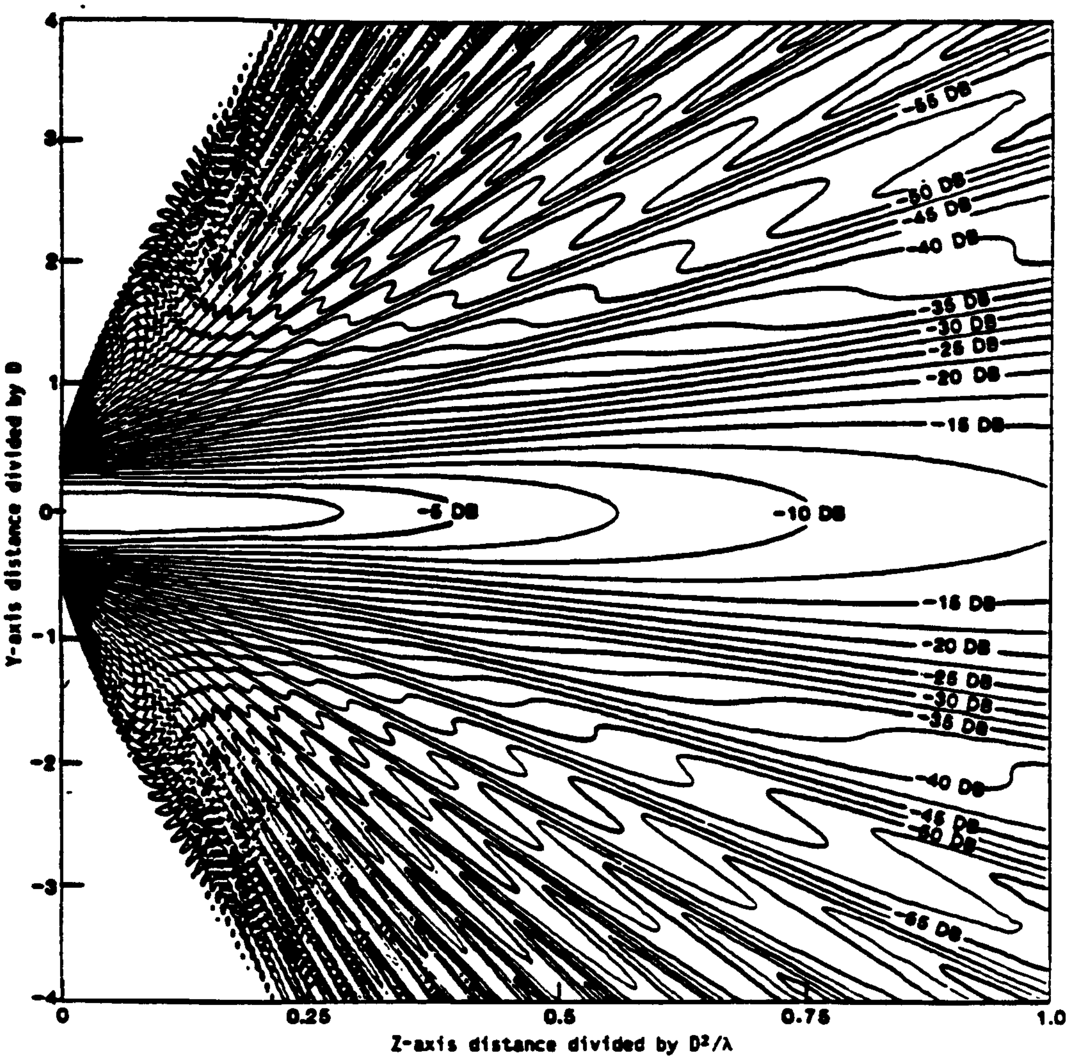

Figure 14. Relative Power Density Contours for a Circular Aperture Antenna. Contours are Shown in the y-z Plane for the Case $D \geq 30\lambda$, where $-4D \leq y \leq 4D$ and $0 \leq z \leq D^2/\lambda$. The Aperture Illumination is $[1-(\rho/a)^2]^2$, where ρ is the Radial Distance Variable, $0 \leq \rho \leq a$, and $a = D/2$. Each Contour Corresponds to an Increment of -2.5dB.

Table 11

RADIATION CHARACTERISTICS OF SOME EXISTING SATELLITE COMMUNICATIONS SYSTEMS

Diameter (ft)	Diameter (m)	Frequency (GHz)	λ (cm)	Gain (dB_i)	P (W)	R_{nf} (m)	R_{ff} (m)	η	S_{nf} ($\mu W/cm^2$)	$S_{100m} \times 10^{-3}$ ($\mu W/cm^2$)
60	18.3	8.15	3.68	60.8	4×10^3	2.27×10^3	5.45×10^3	0.5	3.0×10^3	3.0
60	18.3	8.15	3.68	60.8	10×10^3	2.27×10^3	5.45×10^3	0.5	7.5×10^3	7.5
97	29.6	6.25	4.8	62.7	2.5×10^3	4.55×10^3	1.09×10^4	0.5	7.2×10^2	0.72
85	25.9	2.38	12.6	53.8	225×10^3	1.33×10^3	3.20×10^3	0.57	9.81×10^4	98.1
210	64.0	2.38	12.6	61.9	225×10^3	8.13×10^3	1.95×10^4	0.61	17.0×10^3	17.0
105	32.0	14.25	2.1	69.0	5×10^3	1.22×10^4	2.92×10^4	0.35	8.66×10^2	0.87
105	32.0	6.18	4.86	64.0	5×10^3	5.27×10^3	1.26×10^4	0.57	1.46×10^3	1.46
42.6	13.0	6.0	5.0	56.4	2.6×10^2	8.45×10^2	2.03×10^3	0.65	5.19×10^2	0.52
42.6	13.0	7.98	3.76	58.0	80	1.12×10^3	2.70×10^3	0.53	1.29×10^2	0.13
40	12.2	8.15	3.68	57.3	5×10^3	1.01×10^3	2.42×10^3	0.5	8.5×10^3	8.5
39.4	12	6.42	4.69	55.4	5×10^3	7.71×10^2	1.85×10^3	0.54	9.5×10^3	9.5
36.1	11.0	6.40	4.69	55.0	2×10^3	6.45×10^2	1.55×10^3	0.58	4.9×10^3	4.9
32.8	10	5.96	5.03	53.6	2×10^2	4.97×10^2	1.19×10^3	0.59	6.0×10^2	0.60
17.9	5.45	8.15	3.68	52.1	4×10^3	2.02×10^2	4.84×10^2	0.75	5.15×10^4	51.5
15	4.57	8.15	3.68	48.8	1.26×10^3	1.42×10^2	3.41×10^2	0.5	1.53×10^4	15.3
10	3.05	14.0	2.14	50.0	1.4×10^3	1.08×10^2	2.6×10^2	0.5	3.84×10^4	38.4

calculated on-axis, near-field power density; on-axis power density at 100 meters (usually in the near field); and maximum off-axis power density at 100 meters from the antenna (along the antenna axis) with the relative intensity (the ratio of off-axis power density to on-axis power density) taken to be 10^{-3}.

Although the maximum on-axis power densities that can be produced range from 1.29×10^{2} to 9.81×10^{4} $\mu W/cm^{2}$, the maximum exposure power density at a distance of 100 meters is less than 100 $\mu W/cm^{2}$, because the relative intensity in the off-axis radiation region where exposure could occur is less than 10^{-3}.

RADAR SYSTEMS

Radar systems use microwave frequencies, with the radiation emitted and received in pulses that are generally short in duration compared to the time interval between the emission of succeeding pulses. The reflected pulse must be detected before the next pulse is emitted, thus determining the maximum time interval between pulses and affecting the distance range for which the system is used.

The power radiated per pulse for radars is generally much greater than the average power transmitted by continuously radiating systems, and thus the values of peak radiated fields are greater than those of equivalent gain systems that radiate power continuously. The analysis of potential environmental impact due to radar systems may involve use of peak transmitter power to determine near-field, on-axis peak power density; the variation of peak on-axis power density as a function of distance from the source; or the distance from the source at which specific values of peak on-axis power density levels may exist. This type of an evaluation is appropriate when considering the potential for interference effects on the operation of certain electronic systems in a pulsed microwave radiation field. It would also be the correct approach in evaluating the potential for the occurrence of certain kinds of effects, such as "microwave hearing," that are caused by pulsed fields. In such cases, the appropriate physical radiation field parameter to be determined is peak field intensity rather than time-averaged power density.

Exposure evaluation analysis involving time-averaged values of transmitter power to determine the corresponding time-averaged field characteristics is appropriate when considering exposure in relation to effects that depend upon time-averaged power density (or more directly, time-averaged specific absorption rate).

Selected radar systems have been studied, and the results have been used to specify the range of exposure levels produced. The systems studied, analytically and by measurement, are military acquisition and tracking radar, civilian and military air traffic control (ATC) radar, and weather radar. The variation of system characteristics is greatest for acquisition and tracking radars, resulting in a wide range of on-axis, near-field power densities and effective near-field distances.

Time-averaged power density is the characteristic of primary interest in radar system radiation exposure measurements, although peak-power density is certainly important. The radiation emissions are pulsed, and, for most systems, the pulse width and repetition rate are such that the time-averaged transmitter power and power density at any point are two to four orders of magnitude less than the peak value. In addition, many radar system antennas rotate, further reducing the time-averaged power density. The results of measurements and analysis of radar system exposure characteristics are presented in Tables 12 to 19. Power density measurements at the indicated distances are time-averaged values for stationary mode operation and are based on time-averaged transmitter power. The scan reduction factor is shown for those antennas that normally rotate.

Most of the radars studied have antennas with paraboloidal surfaces. Those with circular cross sections can be analytically treated by the model used for analysis of SATCOM system antenna radiation characteristics. The acquisition and tracking radar category includes radars having circular, rectangular, and ellipsoidal cross sections. Noncircular cross-section antennas collimate radiation so that the radiation beam is better collimated in the plane containing the larger of the antenna axes. The beam has greater divergence in the plane containing the smaller antenna axis, the axes being mutually orthogonal.

The system characteristics used in evaluating radar systems depend upon the peak power delivered to the antenna, pulse duty cycle, antenna dimensions and area, aperture efficiency, and radiation wavelength. For rotating or rapidly moving antennas, these characteristics also include the angle through which the scan occurs and the half-power beam width in the plane of scan.

The model, used to determine on-axis, time-averaged power densities at a distance beyond the near field of the antenna, has been modified for paraboloidal antennas that have other than circular cross sections. The effective near-field distance (assuming an aperture efficiency equal to 0.5) is expressed as:

$$R_{nf\ eff} = 5.07 \times 10^{-2}\ G\lambda. \qquad (16)$$

The differences between peak values of transmitter power and on-axis near-field power density and the corresponding time-averaged characteristics are determined by the pulse duty cycle, (i.e., the ratio of the pulse width to the time interval between pulses), and is equal to the pulse width, Δt, (in units of time) mutiplied by the pulse repetition frequency, PRF.

$$\text{Duty cycle} = \Delta t \times \text{PRF}. \qquad (17)$$

The average transmitter power is then $P_{av} = P_{peak}$ x duty cycle = P_{peak} ($\Delta t/T$), where T, the time interval between pulses, = 1/PRF.

Simplified exposure evaluation models used to estimate exposures for radar systems are basically the same as those used for circular cross-section paraboloidal antennas, previously described for SATCOM system antennas. This assumes that the noncircular cross-section antenna can be represented by a circular aperture of the same physical area and gain. The on-axis power density equations applicable to noncircular cross-section paraboloidal antennas are described below with $\eta = 0.5$.

$$S_{nf} = 12.6\ P_{av}/G\lambda^2 \qquad \text{For } R \leq 5.07 \times 10^{-2}\ G\lambda \qquad (18)$$

$$(\text{when } R_{nf\ eff} = 5.07 \times 10^{-2}\ G\lambda)$$

$$S_{if} = S_{nf}(R/R_{nf\ eff})^{-1} \qquad \text{For } 5.07 \times 10^{-2}\ G\lambda \leq R \leq 1.22 \times 10^{-1}\ G\lambda \qquad (19)$$

$$S_{ff} = 2.47\ S_{nf}(R/R_{nf\ eff})^{-2} \qquad R \geq 1.22 \times 10^{-1}\ G\lambda \qquad (20)$$

$$S_{ff} = P_{av}\ G/4\pi R^2 \qquad (21)$$

Antenna rotation further reduces the time-averaged power density produced by a stationary (nonrotating) radar antenna, because exposure to main-beam or side-lobe radiation (in the far field) is not continuous. Therefore, time-averaged exposures include a reduction factor compensating for variation in radiation intensity with time due to antenna motion. The power density produced at any point by a system with a rotating antenna is:

$$S = S_s\ f, \qquad (22)$$

where S_s is the time-averaged power density produced by the antenna if it were stationary, and f is the rotational reduction factor applying at the exposure point of interest.

In practice, the rotational reduction factor depends on the antenna radiation pattern (main-beam and side-lobe structure), antenna motion, and location of an exposure point relative to the antenna. For main-beam exposure, the factor, f, is defined as the fraction of time the radiation beam is incident at some point relative to the time interval required for the beam to return to the same point during the next rotation. For rotating antennas it is equivalent to the ratio of the length of the arc that contains the beam at a distance, R, compared to the total arc length at distance, R, for the angle through which the antenna rotates.

In the near field, the beam is considered to have a dimension in the plane of rotation equal to the length of the antenna axis, L, in that plane. The near-field rotational reduction factor, f_{nf}, at R is given by

$$f_{nf} = L/R\theta_s, \qquad (23)$$

where L equals the antenna dimension in the plane of rotation, R is the distance from a point in the near field to the antenna, and θ_s is the scan angle in radians. The power density calculated in the near- and intermediate-field region for a scanning antenna, using the reduction factor determined by the method described, is an overestimate, but it is consistent with the conservative approach employed in exposure evaluations.

The reduction factor used in determining the time-averaged power density produced in the far field of a scanning antenna is given by

$$f = \theta_{1/2}/\theta_s, \qquad (24)$$

where $\theta_{1/2}$ is the half-power beam width of the antenna and has the same units as θ_s.

Acquisition and Tracking Radars

The results of measurements of on-axis power density for acquisition and tracking radars are shown in Table 12. For the first three systems, a point was found at which an on-axis power density of 10 mW/cm^2 occurred, and the distance from that point to the antenna was measured. The remainder of the systems were evaluated at distances of closest approach to the systems, i.e., at the boundaries of the facility. The power densities listed in Table 12, measured while the antennas were stationary, can be reduced further for the normally rotating systems by using the scan reduction factors to obtain the time-averaged power density at the specified distances from the antenna. The scan reduction factors presented are applicable in the near field and result in overestimating the average power densities that would exist in the far field. For these systems, all of which are military radars, those operating in a scanning mode produce time-averaged power densities of less than 1 mW/cm^2 at distances beyond the near field of the antenna.

The tracking radars (nonscanning) are capable of producing time-averaged, main-beam power densities much greater than 1 mW/cm^2, depending upon the transmitter power, duty cycle, and antenna dimensions. Since these system characteristics are defined by the function for which a specific system has been designed, there is a great variation in the resulting near- and far-field, time-averaged power densities.

Because of the variety of system specifications, acquisition and tracking radars cannot be described by categorical radiation field characteristics. This conclusion is supported by measurement results (Table 12) and an analytical study of a number of tracking systems having circular cross-section paraboloidal antennas (Table 13).

Table 12

ACQUISITION AND TRACKING RADAR MEASUREMENTS (ON-AXIS)

System	Antenna Dimensions (ft)		Freq. (GHz)	P(av.) (kW)	S (mW/cm^2)	R Calc. (m)	R Meas. (m)	Scan Reduction Factor
TPN-18[a]	4x6.5	azim	9.0	0.192	10	22.2	24.4	?
	2x8	elev.			10	11.8	10.7	?
FPN-40[a]	3x9	azim	9.0	0.180	10	28.1	28	3.8×10^{-2}
	2.5x10	elev.			10	24.2	24	3×10^{-2}
TPS-1D[a]	4x15		1.3	0.492	10	10	7.6	1.1×10^{-2}
M-33 Acq.[b]	3.92x14.33		3.1-3.5	1.39	6	65	61	1×10^{-2}
LOPAR[b]	-		-	-	4	-	94	1×10^{-2}
M33-C Band[b]	8 (diam.)		5.45-5.82	3.8×10^{-2}	0.2	-	95	-
M33-X Band[b]	6 (diam.)		8.50-9.60	4.8×10^{-2}	0.65	-	95	-
SCR-584[b]	6 (diam.)		2.70-2.90	2.9×10^{-1}	0.65	-	81	-
TTR	-		-	-	7.5	-	85	-

Measurements performed with antennas stationary

(a) Fort Monmouth, New Jersey.

(b) Grumman ECM Site, Calverton, New York.

Table 13

TRACKING RADAR CHARACTERISTICS

Source Diameter (ft)	Gain (dB)	Frequency (GHz)	Wave-length (cm)	Transmitter Power		Maximum Near Field Power Density, (mW/cm^2)		Near Field Distance (m)	Distance (m) to		
				Peak (kW)	Average (W)	Peak	Average		10 mW/cm²	1 mW/cm²	0.1 mW/cm²
4.0	39.0	9.8	3.06	---	4.67×10^3	---	800	8.6	108	343	10.8
5.0	51.9	35.0	0.857	80.0	40.0	8.8×10^3	4.38	47.9	---	141.8	448.4
5.0	51.8	34.5	0.869	120.0	59.9	13.2×10^3	6.57	47.2	---	171.1	541.0
6.65	54.0	33.4	0.898	100.0	2400	6.2×10^3	148.8	80.8	440.8	1.39×10^3	4.41×10^3
28.8	45.5	2.90	10.3	10^4	3.28×10^3	33.0×10^3	10.8	131.6	142.6	612.8	1.94×10^3
31.0	46.0	2.85	10.5	500	12×10^3	1.43×10^3	34.2	149.8	392.1	1.24×10^3	3.92×10^3
34.7	53.2	5.84	5.14	2.5×10^3	100	5.69×10^3	0.23	384.7	---	---	820.9
36.5	53.2	5.55	5.40	2.8×10^3	448	5.76×10^3	0.92	404.9	---	---	1.74×10^3
37.5	53.2	5.40	5.56	3.0×10^3	120	5.85×10^3	0.23	415.5	---	---	899
47.2	60.0	9.38	3.20	10^3	640	1.23×10^3	0.79	1.14×10^3	---	---	4.54×10^3
52.0	50.5	2.85	10.5	2×10^4	5.5×10^4	2.03×10^4	5.58	421.6	---	1.41×10^3	4.45×10^3
68.6	52.8	2.82	10.6	5×10^3	3.52×10^3	2.91×10^3	2.05	726.1	---	1.47×10^3	4.65×10^3
85.94	48.0	1.30	23.2	5×10^3	1.5×10^3	1.86×10^3	55.7	523.3	1.75×10^3	5.52×10^3	17.5×10^3
112.8	66.0	7.84	3.83	700	210	151	0.04	5.45x10	---	---	---

In general, the tracking systems presented in Table 13 are either unique systems, some of which can produce on-axis, time-averaged power densities of 1 mW/cm^2 or greater at great distances from the antenna, or relatively low-power radars with a limited region of influence. The rotational mode acquisition radars studied are expected to be typical of this source category in that the time-averaged power densities produced in the far field should be a factor of approximately 100 less than the stationary mode power density produced at the same point. Thus, tracking radars with high average transmitter powers would constitute the group capable of producing the greatest time-averaged power densities.

Air Traffic Control Radars

Some air traffic control (ATC) radars, used to track aircraft flights and control landings at airports, have been studied. Measurements were made at the Federal Aviation Administration (FAA) Aeronautical Center, Oklahoma City, Oklahoma, on three types of systems installed at and around airports in the United States (Te74c). These systems are scanning radars with antennas that rotate through a 360° sector. Measurement results, system characteristics, and corresponding predictions made through use of the model previously discussed are presented in Table 14.

The results of the measurements (Table 14) are off-axis power densities at specified distances from the antenna, time-averaged to include transmitter modulation but not reduced to compensate for rotation of the antennas. The table includes the horizontal and vertical dimensions (L_h and L_v), the operating frequency, and both peak and time-averaged transmitter power. The extent of the near field; the maximum near-field, on-axis, time-averaged power density; and the distance where on-axis, time-averaged power densities of 10 and 1 mW/cm^2 occur have been calculated for stationary antennas. In addition, the on-axis, time-averaged power density has been calculated at the point of measurement for each system along with the corresponding power density, which includes the

Table 14

PREDICTED AND MEASURED CHARACTERISTICS OF ATC RADARS

	ASR-7	ASR-4B			ARSR-1D		
Dimensions (ft.)	L_v=9.0, L_h=17.5	L_v=9.0, L_h=17.5			L_v=18.0, L_h=42.0		
Frequency (GHz)	2.820	2.720			1.335		
Transmitter Power							
Peak (kW)	425	425			500	4000	
Av (W)	336	402			360	2880	
Near-Field Extent (m)	22.6	18.6			31.2	31.2	
Near-Field Power Density, (mW/cm²)	4.15	5.82			1.94	15.5	
Distance (m) for							
10 mW/cm²	---	---			---	48.3	
1 mW/cm²	65.0	63.4			60.5	174	
Power Density (mW/cm²) at	880'	750'	1480'	1800'	1000'	1000'	1240'
Stationary							
Measured (off-axis)	0.016	1.37×10^{-4}	8.80×10^{-5}	3.2×10^{-5}	5.42×10^{-3}	0.165	1.2×10^{-3}
Calculated (on-axis)	0.059	7.71×10^{-2}	1.98×10^{-2}	1.34×10^{-2}	4.05×10^{-2}	0.324	0.211
Rotating							
Calculated (on-axis)	2.3×10^{-4}	3.0×10^{-4}	7.69×10^{-5}	5.21×10^{-5}	1.52×10^{-4}	1.22×10^{-3}	7.9×10^{-4}
Rotational Reduction Factor (far field)	3.89×10^{-3}	3.89×10^{-3}				3.75×10^{-3}	

far-field rotational reduction factor. When rotational reduction factors are considered, the time-averaged power densities produced are much less than 0.1 mW/cm^2 at distances of 100 meters or greater from the antenna, for all of the systems included in Table 14. Even the air route surveillance radar (ARSR) systems, having peak transmitter powers of 10,000 kW, would also produce time-averaged power densities of less than 0.1 mW/cm^2 at distances of 100 meters or greater under conditions of rotation.

The ARSR-1 system and the more powerful ARSR-3 were analyzed to predict environmental exposures that could exist in two actual situations (Ha76d). The system characteristics and exposure conditions are summarized in Table 15. Actual distances at which exposures could occur were used. The relatively large main-beam divergence in the vertical plane is responsible for producing ground-level exposures, for typical antenna elevation angles, that are about a factor of 10 less than on-axis exposures.

Height-Finder Radars

Height-finder radars can produce environmental exposure power densities that range from greater than 1 mW/cm^2 in the far field to about 17 mW/cm^2 in the near field. The primary antenna motion associated with the height-determining operation is a periodic nodding motion in the vertical plane. The angular excursion is limited, and the far-field reduction factors used to derive time-averaged, exposures for vertical beam motion are on the order of 10^{-2}. However, because the nodding motion can direct the beam axis toward the ground at distances relatively close to the antenna, high-intensity exposure to on-axis radiation can readily occur.

The exposure characteristics of two military height finders are presented in Table 16 (Ha78b). It should be noted that time-averaged exposures, including reduction for beam motion, at the beginning of the far field (roughly 100 meters from the antenna) can be as high as 500 to 1,200 $\mu W/cm^2$. Prolonged public exposures would depend on accessibility.

Table 15

PREDICTED EXPOSURES FROM ARSR RADARS

System Characteristics	ARSR-3	ARSR
Antenna dimension (m)	12.8 horizontal 6.86 vertical	12.8 horizontal 5.49 vertical
λ (cm)	22.2	22.2
R_{nf} (m)	35.2	29.8
R_{ff} (m)	84.5	71.5
G (dB_i)	34.2	34.2
η	0.42	0.49
P_{av} (kW)	4.38	3.6
$S_{nf\ av}$ ($\mu W/cm^2$)	29.9×10^3	34.3×10^3
S_{ff} ($\mu W/cm^2$)	5.83×10^2 at 396m	16.8×10^3 at 61m
Relative off-axis intensity	0.1	0.1
Beam motion reduction factor	3.06×10^{-3}	3.6×10^{-3}
S_{av}, off-axis, ($\mu W/cm^2$)	1.78×10^{-1}	6.05

Table 16

HEIGHT-FINDER RADAR SYSTEM CHARACTERISTICS

System Characteristic	FPS-26A		FPS-90
Antenna Gain (dB_i)	43		38.5
Frequency (GHz) Wavelength (cm)	5.9 5.08		2.9 10.34
Aperture Efficiency (assumed)	0.5		0.5
Near-Field Extent (m) (ft)	51.4 169		37.1 121
Distance to Onset (m) of Far Field (ft)	123 405		89.1 292
Half-Power Beam Width (deg) - Vertical	0.56		1.02
Half-Power Beam Width (deg) - Horizontal	2.30		3.30
Beam Motion Reduction (vert) Factor	1.65×10^{-2}		3.00×10^{-2}
Pulse Width (μsec)	4.4		2.0
Pulse Repetition Frequency (sec^{-1})	333.3		400
Duty Cycle	1.47×10^{-3}		8.00×10^{-4}
Peak Power to Reflector (kW)	2383 [a]	4766 [b]	2780
Average Power to Reflector (kW)	3.495	6.990	2.224
On-Axis Near-Field Power Density, Average (mW/cm^2)	85.13	170.3	37.0
On-Axis Power Density at Start of Far-Field, Average (mW/cm^2)	36.4	72.8	15.9
Power Density at Start of Far-Field, Corrected for Beam Motion, (mW/cm^2)	0.601	1.20	.477

(a) Normal mode.
(b) Power add mode.

Weather Radars

Table 17 (Ha79, Ha82) presents radars used in meteorological activities, their characteristics, and time-averaged, on-axis power densities (including rotation), at two specific distances. The large diameter radars are unique systems located at the National Severe Storms Laboratory at Norman, Oklahoma. The small diameter radar is typical of those used by local television stations for their weather reports. On-axis, time-averaged power densities at distances of several hundred feet are on the order of 1 to 10 $\mu W/cm^2$. Off-axis exposures are expected to be on the order of 1 to 10 nW/cm^2 (1 nW/cm^2 = 10^{-3} $\mu W/cm^2$) or less.

Special High-Power Radar Systems

A radar system that has received considerable attention from the public and EPA is the PAVE PAWS, a phased-array radar system. The PAVE PAWS system, four of which are to be operating in the continental United States, was evaluated analytically to determine its potential for creating environmental exposures (Ha77a). The basic system is characterized in Table 18.

The antenna was treated as a circular cross-section aperture in the analysis, the results of which are contained in Table 19. In the near field, any exposure is likely to be less than 0.87 mW/cm^2. At the beginning of the far field, the maximum exposure possible is 37 $\mu W/cm^2$. The closest community is approximately 1 mile away, with the predicted maximum possible exposure being 2.9 $\mu W/cm^2$. A detailed description of the system, analytical procedures, and environmental impact evaluation for the system located in Massachusetts is contained in reference (Ha77).

Table 17

WEATHER RADAR CHARACTERISTICS

D (ft)	D (m)	λ (cm)	R_{nf} (m)	R_{ff} (m)	G (dB_i)	η	P (kW) peak	P (kW) average	S_{nf} ($\mu W/cm^2$) peak	S_{nf} ($\mu W/cm^2$) average	Beam Motion Reduction Factor	$S_{average}$ ($\mu W/cm^2$) at R_{ff}	$S_{average}$ ($\mu W/cm^2$) at 1 mile
30	9.14	10.4	200	4.81×10^2	46.8	0.63	596	1.79	2.29×10^6	6.88×10^3	2.22×10^{-3}	6.33	0.584
12	3.66	10.4	32	7.69×10	38	0.52	312	0.205	6.18×10^6	4.05×10^3	5.56×10^{-3}	9.62	0.022
16	4.88	5.45	109	2.62×10^2	46.4	0.55	500	0.651	5.89×10^6	7.67×10^3	2.61×10^{-3}	8.62	0.227
1.83	0.56	5.56	1.40	3.37	28	0.63	-	0.060	-	6.18×10^4	2.3×10^{-2}	6.11×10^2	0.0027

D = antenna diameter

λ = wavelength

R_{nf} = near-field extent

R_{ff} = distance to onset of far field

G = antenna gain

η = aperture efficiency

P = power to antenna, $P_{average} = P_{peak}$ x duty cycle

S_{nf} = on-axis power density

$S_{average}$ = on-axis, time-averaged power density incorporating beam motion reduction factor.

Table 18

PAVE PAWS SYSTEM CHARACTERISTICS

System Characteristics	Basic System	Growth Option
Peak Power (kW)	582.4	1164.8
Duty cycle (max)	0.25	0.25
Scan mode	0.11	0.11
Track mode	0.14	0.14
Time-averaged transmitter power (kW)	145.6	291.2
Gain (dB_i)	37.92	40.9
Antenna diameter (ft)	72.5	102
Frequency (MHz)	420-450	420-450
Beam width (-3dB), (degrees)	2.2	1.5
Main beam null (degrees)	2.6	1.8
First side lobe - max. (degrees)	3.4	2.4
First side lobe relative power (max.), (dB)	-20	-20
First side lobe null (degrees)	4.8	3.3
Secondary side lobe relative power (max.), (dB)	-30	-30
Angle of antenna relative to vertical (deg)	20	20
Minimum elevation angle (deg)	+3	+3

Table 19

PAVE PAWS ENVIRONMENTAL EXPOSURE CHARACTERISTICS

System Characteristics	Basic System	Growth System
Antenna area, cm^2	3.84×10^6	7.59×10^6
Aperture efficiency	.571	.573
Near-field extent, R_{nf}, cm, (ft)	1.83×10^4 (601)	3.62×10^4 (1189)
Near-field on-axis time-averaged power density, S_{nf}, mW/cm^2	86.7	87.9
Far field begins, $.6D^2/\lambda$ cm, (ft)	4.39×10^4 (1442)	8.69×10^4 (2854)
On-axis power density at $.6D^2/\lambda$, mW/cm^2	37.2	37.7
First side lobe max. power density, mW/cm^2	.372	.377
Second side lobe max. power density, mW/cm^2	.037	.038

Traffic Radars

Traffic radar systems are small portable units used by police (in both moving or stationary modes) to determine the speed of vehicles relative to that of the police vehicles in which the units are mounted. The system operation is based on measuring the Doppler shift in the fundamental frequency transmitted, the shift in frequency being directly related to the relative velocity of the target vehicle and the microwave radiation source. The systems analyzed emit radiation in a nonpulsed, continuous mode (Ha76b).

Traffic radars are low-power devices, 0.1 W or less, using a conical horn antenna for which the far field starts at distances of less than 2 feet from the antenna for the radiation frequencies typically used. As a result, traffic radars are incapable of producing environmental levels of microwave radiation greater than 1 $\mu W/cm^2$ at distances at which a member of the public would normally be exposed during the use of such systems. The maximum power density produced, determined by calculation, is 3.6 mW/cm^2 and occurs at distances 9 centimeters (3.6 inches) or less from the antenna. Exposure levels decrease rapidly at distances greater than 2 feet from the antenna, where the maximum power density is less than 0.4 mW/cm^2. At a distance of 14 feet, the maximum exposure level is less than 10 $\mu W/cm^2$ and decreases to less than 1 $\mu W/cm^2$ at 44 feet. Vehicular shielding would further reduce the microwave radiation level inside a vehicle. The occupants of a moving vehicle being irradiated by a traffic radar are unlikely to be exposed to a power density as great as 1 $\mu W/cm^2$.

MICROWAVE RADIO

Microwave radio systems are used for voice and video communications and data transmission. They link transmitting and receiving points within line-of-sight of each other. A series of transmitters and antennas can be used for long-distance communications or data transfer and are commonly used in telephone communications. These microwave relay or point-to-point systems are probably the most numerous of all RF emitting systems using high-gain antennas. They are conspicuous on rooftops of tall buildings in metropolitan areas or when mounted in clusters on tall support towers.

The antennas are high-gain, circular cross-section paraboloid reflectors or conical horn reflectors and are highly collimating. The power radiated is very low, generally ranging from less than 1 watt to 40 watts. Persons are exposed to secondary side-lobe radiation in the far field, or at far off-axis locations if exposure occurs at distances not yet in the far field. Relative exposures are at least a factor of 10^{-3} less than on-axis power densities at the same horizontal distance from the antenna. Exposure estimates and system characteristics for some commonly used systems are presented in Table 20. Results of a few measurements are included at the end of the table. Estimated exposure power densities are well below microwatt per square centimeter levels. Measured exposures are on the order of or less than 10^{-3} $\mu W/cm^2$ (Pe80).

MOBILE COMMUNICATIONS

Mobile communications equipment is in common use for both personal and business applications. Measurements of electric and magnetic field intensities in and around vehicles equipped with such systems have been reported (La78, Te76e, Ru79). The greatest exposures typically encountered by persons in and close to vehicles so equipped are summarized here. The transmitter powers for these systems varied from 4 watts for Citizens Band (CB) radios operating at 27.12 MHz to 35 to 100 watts for systems using nominal frequencies of 37, 39, 41, 64, 150, 154, 450, and 458 MHz.

Table 20

CALCULATED RADIATION CHARACTERISTICS OF SOME COMMONLY USED MICROWAVE RADIO SYSTEMS

Antenna Diameter (ft)	Antenna Diameter (m)	Freq. (GHz)	λ (cm)	G (dBi)	R_{nf} (m)	R_{nf} (ft)	R_{ff} (m)	R_{ff} (ft)	η (calc)	P (W)	S_{nf} (μW/cm²)	10^{-3} S_{nf} (μW/cm²)	10^{-3} S_{100m} (μW/cm²)
2	0.61	2.0	15	19.2	0.62	2.0	1.48	4.88	.51	10	6.99×10^{3}	6.99	6.6×10^{-4}
4	1.22	12.95	2.32	41.5	16.0	52.6	38.5	126	.52	1.58	2.81×10^{2}	0.28	1.8×10^{-2}
4	1.22	12.34	2.43	41.1	15.3	50.2	36.7	120	.52	.93	1.65×10^{2}	0.16	9.5×10^{-3}
4	1.22	2.0	15	25.2	2.48	8.13	5.95	19.5	.51	10	1.74×10^{3}	1.74	2.6×10^{-3}
6	1.83	12.95	2.32	45.1	36.1	118	86.6	284	.53	1.58	1.27×10^{2}	0.127	4.1×10^{-2}
6	1.83	6.0	5.0	39.0	16.7	54.9	40.1	132	.60	.60	5.50×10	0.055	3.8×10^{-3}
6	1.83	11.305	2.65	44.0	31.5	103	75.6	248	.54	1.19	9.72×10	0.097	2.4×10^{-2}
6	1.83	6.865	4.370	39.8	19.1	62.8	45.9	151	.55	.415	3.49×10	0.035	3.2×10^{-3}
8	2.44	6.855	4.376	42.1	34.0	111	81.5	267	.53	.195	8.84	0.0088	2.5×10^{-3}
8	2.44	1.865	16.1	31.1	9.24	30.3	22.2	72.8	.57	.275	1.34×10	0.0134	2.8×10^{-4}
8	2.44	2.175	13.8	32.2	10.8	35.4	25.8	84.8	.54	1.0	4.62×10	0.046	1.3×10^{-3}
8	2.44	6.425	4.67	41.6	31.8	104	76.4	251	.54	3.15	1.45×10^{2}	0.145	3.6×10^{-2}
8	2.44	12.95	2.32	47.6	64.2	210	154	505	.53	1.58	7.14×10	0.071	4.6×10^{-2}
9.42	2.87	6.0	5.0	43.5	41.2	135	98.9	324	.69	15.9	6.78×10^{2}	0.68	2.8×10^{-1}
9.5	2.90	6.0	5.0	43.5	41.9	138	101	330	.68	25.2	1.04×10^{3}	1.04	4.3×10^{-1}
10	3.05	12.95	2.32	48.8	100	329	241	789	.44	1.58	3.86×10	0.039	3.9×10^{-2}
10	3.05	6.425	4.67	43.6	49.7	163	119	392	.55	3.15	9.41×10	0.094	4.7×10^{-2}
10	3.05	11.0	2.73	48.5	85.2	279	204	671	.57	2.5	7.87×10	0.079	6.7×10^{-2}
10	3.05	11.7	2.56	48.3	90.6	297	217	713	.48	.12	3.18	0.003	2.9×10^{-3}
10	3.05	6.425	4.67	43.6	49.7	163	119	392	.55	10	2.99×10^{2}	0.299	1.5×10^{-1}
10	3.05	11.2	2.68	48.4	86.7	284	208	683	.54	18.3	5.43×10^{2}	0.54	4.7×10^{-1}
10	3.05	6.175	4.86	43.2	47.8	157	115	376	.54	25.6	7.55×10^{2}	0.76	3.6×10^{-1}
10	3.05	6.424	4.67	43.6	49.7	163	119	392	.54	40	1.19×10^{3}	1.19	5.9×10^{-1}
12	3.66	11.2	2.68	49.5	125	410	300	983	.48	1.5	2.76×10	0.028	2.8×10^{-2}
12	3.66	6.425	4.67	45.2	71.6	235	172	564	.55	10	2.08×10^{2}	0.21	1.5×10^{-1}
12	3.66	6.175	4.86	44.8	68.8	226	165	542	.54	14.7	3.02×10^{2}	0.302	2.1×10^{-1}
12	3.66	6.0	5.0	45.0	66.9	219	160	527	.60	20	4.56×10^{2}	0.456	3.0×10^{-1}

The following values were measured at ground level:

Antenna Dia. (ft)	Antenna Dia. (m)	Freq. (GHz)	Power Density (μW/cm²)	
10	3.05	11.0	2.0×10^{-3}	within 300 ft. off to the side
10	3.05	11.2	1.1×10^{-3}	100 ft. from antenna
?	--	2.1	1.0×10^{-2}	less than 100 ft. from antenna
?	--	4.0	6.2×10^{-4}	about 300 ft. from antenna

The exposures depend greatly on antenna type, antenna location on the vehicle, and the type of vehicle, as well as on transmitter power. All systems can produce large electric fields very near the antennas. However, the electric field strength decreases rapidly with distance from the antenna and the systems transmit intermittently. Four-watt CB systems can produce fields ranging from 225 V/m to 1,350 V/m at a distance of 2 inches from the antenna. At a distance of 2 feet from the antenna, 60 V/m fields can exist. The free space (plane-wave) equivalent power density for 60 V/m is 0.95 mW/cm^2. Exposure to persons inside or outside of vehicles generally would occur at greater distances so that exposures are even lower.

The more powerful mobile communications systems can produce exposures up to 200 V/m (10 mW/cm^2 free space equivalent power density) near the exterior surface of the vehicle and in the interior where the driver and passengers are exposed. Measured 100 $\mu W/cm^2$ power density contours for 50- and 100-W transmitters are shown in Figure 15.

HAND-HELD RADIO

Hand-held radios are low-power devices having maximum output transmitter powers of 5 watts. The systems are held close to the head in normal use, creating the possibility that the antenna might be placed close to the eyes. These systems normally operate with the same frequencies as mobile communications systems. The electric fields at a distance of 2 inches from the antenna have been measured to be 150 to 960 V/m (La78, Ru79). Exposures to the eye can be greater than 200 V/m. At distances of 2 feet from the antenna, exposure fields of 40 V/m have been found. The significance of these exposures to the user of the radio is not known; exposure durations can vary from a few seconds to several minutes during a single use interval. Whole-body-average specific absorption rates are extremely small since the power radiated is so low.

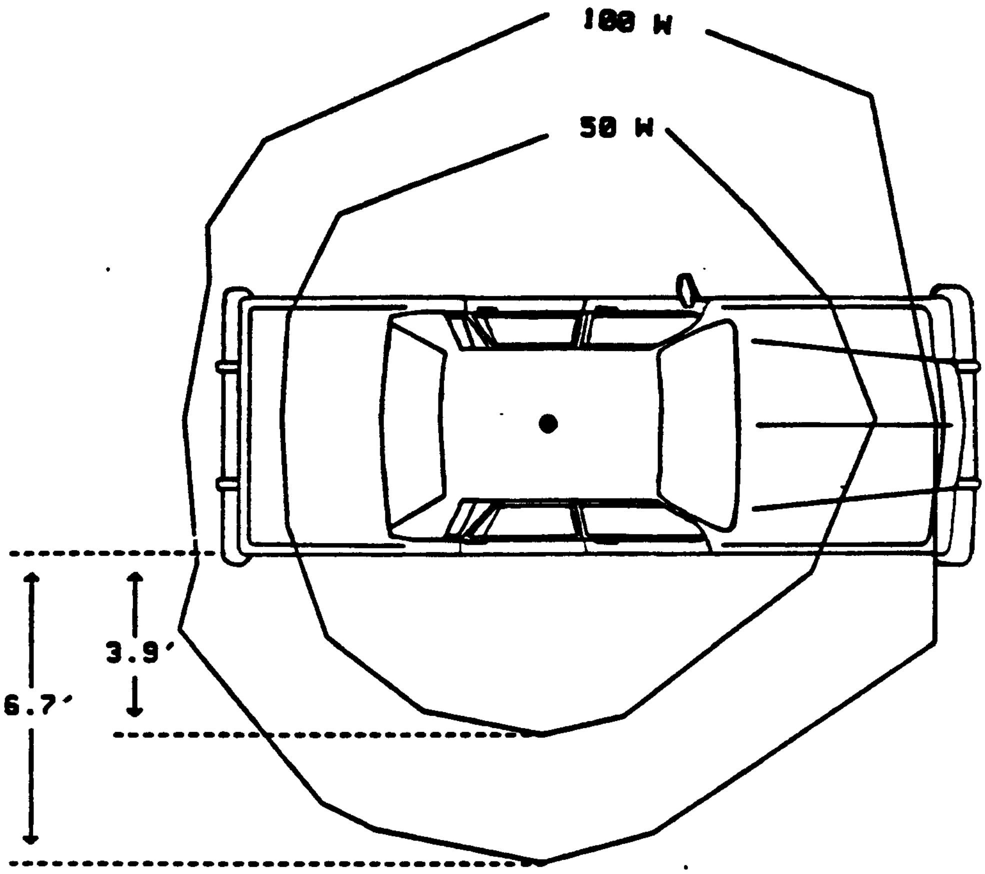

Figure 15. Measured 100 μW/cm² Contours for 50- and 100-Watt Mobile Transmitters at 164.45 MHz

SECTION 5
SUMMARY

The information presented in this report has focused on exposure at locations relatively close to the antennas of RF-emitting systems, because it is at such locations that exposures of public health significance might occur. All of the high-power source categories discussed in this report are capable of producing on-axis power densities on the order of or greater than 10 mW/cm^2. However, the normal operation of most systems, with the exception of broadcast transmitters and height-finder radars, makes it unlikely that people would be exposed to time-averaged power densities above 10 $\mu W/cm^2$. Radio and television broadcast systems generally use antennas with radiation patterns designed to expose the public to the transmitted RF radiation; RF radiation produced by these systems dominates the multisource, multifrequency, general RF radiation environment to which everyone is exposed.

It is estimated that over 99 percent of the population is continuously exposed to levels not greater than 1 $\mu W/cm^2$ for FM radio and television frequencies between 54 and 806 MHz and less than 2.5 V/m for AM radiofrequencies between 0.5 and 1.6 MHz. These population exposure estimates represent exposures far from RF sources and exclude population exposures for individuals living or working close to RF sources.

Measurements made close to broadcast transmitters, or at locations where exposures to main-beam or near-main-beam radiation from broadcast antennas occur, have found exposure power densities that range up to 10 mW/cm^2. Ground-level exposures from AM transmitters have been found to be as great as 300 V/m (electric field) and 9.0 A/m (magnetic field). Measurements made inside high-rise office buildings, in or near the main beams of nearby FM and TV transmitters, have shown exposure levels of up to 97 $\mu W/cm^2$. Measurements of the exposures at recreational areas on the roofs of high-rise buildings revealed AM electric field intensities of 100 to 200 V/m and exposure from FM transmitters of up to 375 $\mu W/cm^2$. Other measurements and observations have shown that possibilities for exposure of these magnitudes are not unusual and that although the total number of persons exposed is likely to be relatively small, the extent of such exposures and the size of the population exposed are yet to be determined.

Mobile communication systems and much lower powered hand-held radios can produce exposures in excess of 200 V/m to the occupants of a vehicle or the system user. The possibility for exposures lasting more than a few seconds exists usually only for the occupants of a vehicle equipped with a mobile communication system or the user of a hand-held radio. Exposures at distances of several feet are less than 20 V/m.

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