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Abstract

Studies of environmental radiofrequency and microwave radiation, high power radiation sources, and source contributions to existing environmental nonionizing radiation levels have contributed to an understanding of the relative environmental significance of the major high power source categories. Analyses and measurements have produced information relating to radiation characteristics, potential hazard evaluations, and environmental radiation levels associated with high power source categories, which include satellite communication earth terminals, radars (military and civilian), and broadcast transmitters (UHF-TV, VHF-TV, and FM). These results when considered along with other factors such as number of sources in each category, relative numbers of persons possibly exposed, and general system operating characteristics and procedures, lead to the conclusion that broadcast transmitters constitute the most environmentally significant source category.

Introduction

This paper presents a view of the nonionizing radiation environment in terms of categories of high power sources of nonionizing radiation, their contributions to environmental levels, and the relative significance of the source categories considered. This is only one of a number of results which have come from a comprehensive measurement and analysis program whose objectives are to determine if a need exists for general population exposure standards and to define those standards if they are needed.

A program concerning the application of nonionizing radiation exposure standards to the environment requires an understanding of environmental nonionizing radiation (NIR) in terms of the intensities of existing electromagnetic fields as a function of frequency, identification of the sources and source categories which are important in producing these fields, and a determination of the quantitative relationships between sources and their contributions to environmental nonionizing radiation levels.

The nonionizing radiation environment consists of electromagnetic radiation which exists over a wide range of frequency (0-300 GHz). At any point in the environment the environmental power density at any frequency is dependent upon the sources in the general area and the geometry which exists relative to the source and that point in the environment. A high power source can be defined as one which is capable of producing a significant power density, arbitrarily chosen to be a minimum of 0.01 mW/cm^2, at a distance from the antenna where free access would ordinarily be possible, with inadvertent exposure of individuals, unless restrictions were intentionally imposed. With this definition, it is possible to differentiate between high power sources and potentially hazardous sources which are those capable of producing power densities above this threshold, and of the order of 10 mW/cm^2, but only at distances close to a system antenna where inadvertent exposure of an individual is highly unlikely.

The categories of high power systems studied, i.e., satellite communication earth terminals, search and tracking radars, and broadcast transmitters (UHF-TV, VHF-TV, and FM), are those which include systems capable of producing significant power densities in the environment.

High power source studies were undertaken to obtain information about the maximum power density capabilities of the sources studied, the variation of on-axis power density as a function of distance from the source, and to allow the development of models which could predict radiation characteristics useful in determining the significance of individual sources and source categories relative to the NIR environment. In addition, the radiation characteristics obtained are important in performing hazard evaluations of specific systems and facilities.

A realistic evaluation of a source of environmental RF or microwave radiation, in terms of whether or not it may create a hazardous or undesirable exposure situation, requires source and biological effects information. In the absence of sufficient biological effects information, a potential hazard evaluation can be used to identify and evaluate the sources which may be capable of producing radiation exposure levels defined to be significant relative to some selected exposure criterion. This evaluation is based upon calculation of the significant characteristics of a source under very basic conditions and neglects the factors which add realism to the situation. Examples of such criteria on which a potential hazard evaluation is possible are the maximum on-site power density which may exist at a specified distance, or the distance to which a specified power density could exist.

The evaluation of the relative environmental significance of these source categories is based not only on their potential for producing hazardous levels of nonionizing radiation, but includes factors such as number of sources in each category, relative numbers of persons possibly exposed to significant levels of power density, general system operating procedures, and NIR hazard awareness by operating personnel. The generally directional nature of the radiation distribution pattern of most high power source antennas may significantly mitigate the exposure problem; i.e., the power densities which exist at free access locations may be substantially less than on-axis or main beam power densities depending upon antenna height above ground, main beam orientation, locations in the environment to which persons may most closely approach the system, and the operational procedures employed. Enhancement of environmental levels of power density can occur if radiation is reflected from surfaces upon which it may be incident and interfere constructively with other radiation.

Generally, with the exception of a few unique systems, the anticipated power densities at distances of closest approach for individuals not occupationally involved are less than the occupational exposure threshold of 10 mW/cm^2 specified by current U.S. standards (1) for prolonged exposure times. However, environmentally significant power density levels, could exist in the environment at great distances from many of the sources considered.

Satellite Communication Earth Terminals

Satellite communication earth terminals have the functional requirement to communicate with earth orbiting satellites. Satellite communication (SATCOM) system antennas require very directional antennas which radiate power into collimated beams with very little divergence. The antenna diameter and maximum transmitter power are characteristics of particular interest from an environmental aspect since it is the combination of high transmitter power and large antenna diameter that is responsible for producing a region of significant power density which may extend over very large distances.

The antennas of all powerful satellite communication system earth terminals have paraboloidal surfaces, are circular in cross-section, and have Cassegrain geometries. In the Cassegrain antenna, Fig. 1, power is introduced to the antenna from the primary radiating source (power feed) located at the vertex of the paraboloidal reflector. The radiation is incident on a small hyperboloidal subreflector located between the vertex and the focus of the antenna. Radiation from the power feed is reflected from the subreflector, illuminates the main reflector as if it had originated at the focus, and is then collimated.

The empirical model(2) used to calculate the radiation characteristics of SATCOM earth terminals applies to antennas (reflectors) that are circular cross-section paraboloids. It expresses the on-axis power density, the maximum which exists for any given distance from the antenna, as a function of distance from the antenna in terms of basic characteristics; i.e., the reflector diameter, radiation frequency, aperture efficiency, and the maximum power which can be introduced into the antenna system for subsequent radiation into space. The on-axis radiation field characteristics for circular cross-section paraboloidal antennas based upon this model can be described using Eqs. 1-4.(2,3)

$$W_{nf} = \frac{16\eta P}{\pi D^2} \qquad (1)$$

W_{nf} = maximum (on-axis) near-field power density (W/cm^2)

η = aperture efficiency, typically $0.5 \leq \eta \leq 0.75$

P = power fed into antenna (W)

D = antenna diameter (cm)

$$\frac{W_{if}}{W_{nf}} = \left(\frac{R}{R_1}\right)^{-1} \qquad (2)$$

W_{if} = intermediate field power density (on-axis) at distance R (W/cm^2)

$R_1 \leq R \leq 2R_1$

$$R_1 = \frac{D^2}{5.66\lambda} \qquad (3)$$

R_1 = extent of near-field (cm)

λ = radiation wavelength (cm)

$$\frac{W_{ff}}{W_{nf}} = 2\left(\frac{R}{R_1}\right)^{-2} \qquad W_{ff} = \text{far field power density (on-axis) at distance R (W/cm}^2\text{)} \qquad R \geq 2R_1 \tag{4}$$

A characteristic necessary to the calculation of on-axis power density as a function of distance from an antenna is the extent of the near field, R_1 (Eq. 2); i.e., the distance over which the on-axis power density is a maximum before it begins to decrease with distance. The magnitude of the power density oscillates, as a function of distance from the antenna, in the near-field region, however the maximum value of on-axis power density (Eq. 1) is constant. 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, W_{ff}, in the far-field, where $R \geq 2R_1$, decreases inversely as the square of the distance from the antenna. In the intermediate field ($R_1 \leq R \leq 2R_1$), a transition region between the near- and the far-fields, the power density, W_{if}, (Eq. 3), decreases inversely with distance.

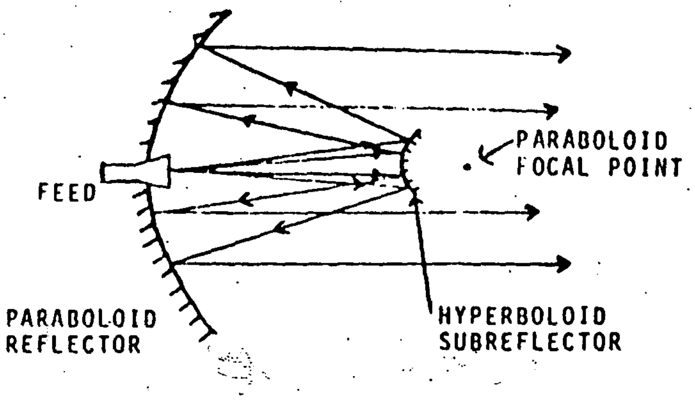

Fig. 1 Cassegrain Antenna

Comparisons between measured on-axis power density levels and predicted values for the systems measured are sufficiently good to provide confidence in the model used.

Anticipated Environmental Levels of Power Density for Selected Systems

Calculations have been made for the expected characteristics of several existing satellite communication systems operating at maximum transmitter power. In each case, the distances from the antenna at which power densities of 10 mW/cm², 1 mW/cm², 100 μW/cm², and 10 μW/cm² are expected have been determined. The results are given in Table 1.(4)

The factors which must be considered in realistically evaluating a system relative to the potential for exposure of persons at power density levels above a selected threshold, include the transmitter power used in its regular operations (generally much less than the maximum possible), the procedures employed in system operation, height above ground, terrain characteristics, antenna sidelobe-radiation characteristics, the minimum elevation angle of the antenna below which the system cannot operate, location and height of structures, and population characteristics within the area of interest. A system may produce significant power densities, and not constitute a hazard if there is no possibility for exposure of persons.

Table 1 Anticipated Characteristics of Selected Satellite Communication Systems

System	Antenna Diameter (ft)	λ^* (cm)	P_T (kW)	R_1 (m)	W_{nf} (max) (mW/cm²)	Distance (m) from Antenna for Power Densities of: 10 mW/cm²	1 mW/cm²	100 μW/cm²	10 μW/cm²
LET	15	3.7	2.5	9.98×10	30.4	2.46×10^2	7.79×10^2	2.46×10^3	7.79×10^3
AN/TSC-54	18(eff)	3.7	8	1.44×10^2	50.8	4.58×10^2	1.45×10^3	4.58×10^3	1.45×10^4
AN/MSC-46	40	3.7	10	7.10×10^2	8.56	-	2.94×10^3	9.29×10^3	2.9×10^4
AN/MSC-60	60	3.7	8	1.60×10^3	3.04	-	3.94×10^3	1.25×10^4	3.94×10^4
AN/FSC-9	60	3.7	20	1.60×10^3	7.61	-	6.23×10^3	1.97×10^4	6.23×10^4
Intelsat	97	4.8	5	3.22×10^3	.728	-	-	1.23×10^4	3.88×10^4
Goldstone Venus	85	12.6	450	9.43×10^2	97.3	4.16×10^3	1.32×10^4	4.16×10^4	1.32×10^5
Goldstone Mars	210	12.6	450	5.76×10^3	16.8	9.68×10^3	3.34×10^4	1.06×10^5	3.34×10^5

The systems analyzed consitute a potential hazard in that the maximum on-axis power densities capable of being produced range from 0.73 to 97.3 mW/cm^2 and the near-field distances range from 10^2 to $6x10^3$ m. These systems are able to produce on-axis power densities, ≥ 1 mW/cm^2, at distances ranging from $7.8x10^2$ to $3.3x10^4$ m. High power SATCOM systems are relatively unique, few in number, and have extremely well collimated beams. The very large and powerful sources such as the Goldstone Venus and Mars systems have extensive general population exclusion areas which includes the air space above them. The operational procedures employed were developed with safety as a consideration. In many cases, elevation angles less than minimum; i.e., 7.5 degrees above the horizon, are not possible during normal operation. An effort is made to avoid irradiation of persons and structures by the main beam of radiation because of mission objectives and safety considerations. It is of interest to see that for these systems having antenna diameters which vary from 15 feet to 210 feet, the near-field extent, R_1, increases from approximately 100 meters to almost $6x10^3$ meters. With the exception of the Intelsat system, the on-axis near-field power densities, W_{nf}, are of the same order of magnitude or exceed 10 mW/cm^2. Examination of the distances from the antenna at which various on-axis power densities occur, shows the increase in the spatial extent over which significant power densities exist, as the antenna diameter and near-field extent increase. Even for a small diameter, low power system such as the LET, 10 $\mu W/cm^2$ can exist as far as $7.8x10^3$ m from the antenna.

Radar Systems

Radar systems in the categories of acquisition and tracking radars have been studied. (3) Included were military systems, air traffic control (ATC) radars, and weather radars. The results are used to specify, for entire system categories where possible, the ranges of on-axis power density levels produced and the distances from the system for which significant environmental levels exist.

The variation of system characteristics is greatest in the categories of acquisition and tracking radars, resulting in a wide range of on-axis near-field power densities and effective near-field distances. The systems studied represent the majority of powerful radars used for civilian application and include examples of military systems considered to be among the most hazardous under worst-case operating conditions relative to power density levels and the distance over which those levels may occur.

The characteristic of primary interest in radar system radiation measurements is time-averaged power density, not peak power density. The radiation is pulsed, and, for most systems, the pulse width and repetition rate are such that the average transmitter power and power density created at any point are roughly 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 which might occur at a particular location.

An evaluation of peak radiation characteristics is appropriate when considering interference effects, as exist for the operation of certain electronic systems in a pulsed microwave radiation field, and any biological effects caused by pulsed fields.

All of the radars studied have antennas with paraboloidal surfaces. Those with circular cross-sections can be analytically treated by the model used in the analysis of SATCOM system antenna radiation characteristics. The acquisition and tracking radar category includes radars which have circular, rectangular, and ellipsoidal cross-sections. Noncircular cross-section antennas collimate radiation in a manner such that the radiation beam is better collimated in the plane which contains the antenna axis having the larger dimension, and has greater divergence in the plane containing the antenna axis of lesser length, the antenna axes being mutually orthorgonal.

The time-averaged system characteristics used in evaluation of radar hazards are dependent upon the transmitter power fed to the antenna, pulse duty cycle, antenna linear dimensions and area, aperture efficiency, radiation wavelength; and in the case of rotating antennas, the angle through which the scan occurs, the half-power beamwidth in the plane of scan, and the distance from the source to an on-axis field point of interest.

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, R_{1eff} is expressed as:

$$R_{1eff} = 0.318\ A/\lambda \qquad (5)$$

Antenna rotation further reduces the time-averaged power density which would be produced by a stationary (non-rotating) radar antenna. The power density produced at any point, by a system with a rotating antenna is:

$$W = W_s \cdot f \qquad (6)$$

where W_s is the time-averaged power density produced by the antenna if stationary and f is the rotational reduction factor which applies at the point of interest.

Anticipated characteristics of several types of radar systems are presented in Table 2 and Table 3(3) for acquisition and tracking systems, respectively. Shown are the distances from the antenna at which power densities of 10 mW/cm^2, 1 mW/cm^2, 0.1 mW/cm^2, and 0.01 mW/cm^2 are expected if the antennas were stationary.

Table 2 Acquisition Radar System Characteristics

System	FPN-40		ARSR	
Antenna Dimensions* (ft)	L_v=3, L_h=9 azim.	L_v=10, L_h=2.5 elev.	L_v = 18	L_h = 42
Frequency (GHz)	9.0		1.33	
Average Transmitter Power (W)	180		2.8x10^3	~2x10^4
Near-Field Extent (m)	22	17	31.2	
Near-Field Power Density (mW/cm^2)	12.8	13.9	15.5	111
Distance (m) to				
10 mW/cm^2	28.1	24.2	48.3	147
1 mW/cm^2	111	89.6	174	465
0.1 mW/cm^2	351	283	549	1.47x10^3
0.01 mW/cm^2	1.11x10^3	896	1.74x10^3	4.65x10^3
Rotational Reduction Factor (far-field)	3.8x10^{-2}	3x10^{-2}	3.75x10^{-3}	

*L_v = maximum vertical dimension
L_h = maximum horizontal dimension

Table 3 Tracking Radar System Characteristics

System	Hawk Hi Power	Weather	Others		
Antenna Diameter (ft)	4	5	31	52	86
Frequency (GHz)	9.8	34.5	2.85	2.85	1.30
Average Transmitter Power (W)	4.7x10^3	59.9	1.2x10^4	5.5x10^3	1.5x10^5
Near-Field Extent (m)	8.6	47.2	150	422	523
Near-Field Power Density (mW/cm^2)	800	6.6	34.2	5.58	55.7
Distance (m) to					
10 mW/cm^2	108	---	392	---	1.75x10^3
1 mW/cm^2	344	171	1.24x10^3	1.41x10^3	5.52x10^3
0.1 mW/cm^2	1.08x10^3	542	3.92x10^3	4.45x10^3	1.75x10^4
0.01 mW/cm^2	3.44x10^3	1.71x10^3	1.24x10^4	1.41x10^4	5.52x10^4

Although, the number of individual systems is small, the attempt was made to include widely used rotating antenna systems and those stationary antenna systems capable of producing significant power densities at large distance from the source. The far-field power densities shown can be reduced further for normally rotating systems by multiplication by the rotational reduction factors shown to obtain the time-averaged power density in the far-field of the antenna at the distances shown.

Of all radars operating in the U.S., the majority operate in a scanning mode and produce rotational time-average power densities less than 0.01 mW/cm^2 at ground level in the antenna far-field region. Tracking radars, being non-rotational, are generally capable of producing hazardous and environmentally significant on-axis power densities at much greater distances from the antennas. However, the systems with antennas of diameters greater than 5 feet are relatively few and unique, and generally located in areas where the possibility for exposure of large numbers of persons would be minimal. These systems, having the greatest potential for creating environmental hazards, could be operated in a manner which would minimize exposure in free access areas and consequently reduce their environmental significance relative to time-averaged biological effects.

If peak field effects related to interference with the operation of certain types of electronic systems were considered, all of the radar system categories considered would have greater environmental significance. The hazard evaluations could be performed analytically to determine hazard potential with off-axis characteristics being of great importance.

UHF-TV Transmitters

UHF television transmission has become a common and widespread radiation component of the environment to which millions of persons are exposed. Whereas satellite communication and radar systems are sources with very directional antennas radiating power into collimated beams with relatively little divergence compared to an isotropically radiating source, the UHF-TV antenna is an almost isotropic radiator, omnidirectional in the horizontal plane, but having some collimation in the vertical plane. It is designed to disseminate information and in the process irradiate very large areas in which great numbers of people may reside. UHF-TV transmitters comprise a significant number of the CW sources which have high effective radiated power, and are commonly located in urban areas.

The transmission frequencies range from 432 to 728 MHz, equivalent to a range of radiation wavelengths of 69.4 cm to 41.2 cm, respectively. The maximum effective isotropic radiated power (EIRP) allowed by the Federal Communications Commission for a single UHF-TV transmitter is 5.0 MW. There were 306 UHF-TV stations in operation in the United States as of December 1971.(5) There are 52 transmitters having an EIRP greater than 2 megawatts and approximately 100 transmitters with an EIRP greater than 1 megawatt.

It has become a common practice in certain very large urban areas to locate two or more powerful UHF-TV antennas at the same location, and in some instances atop the tallest buildings. The possibility that other buildings, of the same height may be located within close proximity to the antennas results in the possibility for exposure of many persons to microwave radiation at relatively high power density levels.

The field strength and power density for the general case of UHF-TV transmission (assuming no propagation losses) are described by the following equations:(6)

$$E = \frac{R_\alpha (30\ P_T)^{1/2}}{r} \tag{7}$$

$$W = \frac{E^2}{Z} = \frac{P_T R_\alpha{}^2}{4\pi r^2} \tag{8}$$

where E = field strength (volt/meter), R_α = relative field strength and is a function of the depression angle, α, relative to horizontal, P_T = total EIRP (W) for a transmitter for both visual and aural signals, and r = distance from antenna (meters). The geometry used in the model is shown in Figure 2. The distance to the antenna is given in terms of the relative vertical height, h, and horizontal distance, d. R_α, is determined from the vertical radiation pattern of the antenna. A typical radiation pattern, that of WDCA (Bethesda, MD), is shown in Figure 3.

The results of power density for several relative antenna/exposure point heights as a function of horizontal distance from the antenna for a transmitter/antenna EIRP of 1 megawatt are shown in Figure 4.(5)

The results can be applied to the case of a transmitter or transmitter complex, in order to estimate environmental power density levels and population exposed to power densities above any selected threshold. The

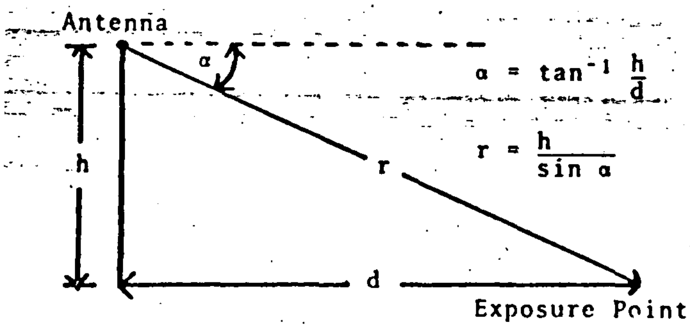

Fig. 2. Geometry Used in Calculation of Field Intensities for UHF-TV Transmission.

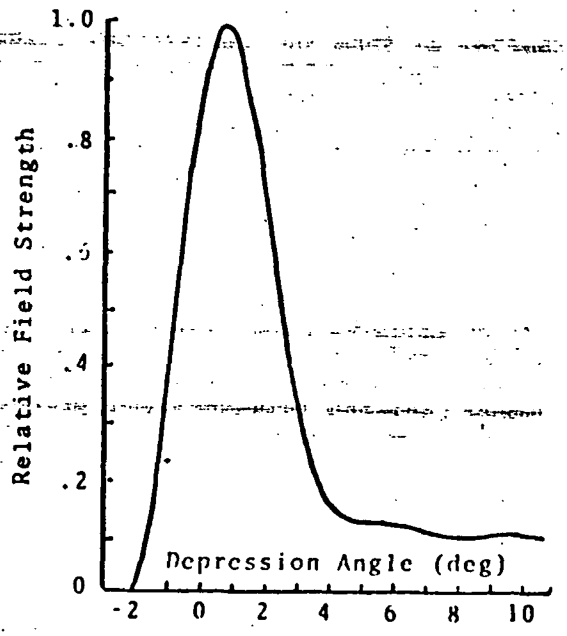

Fig. 3. Vertical Radiation Pattern, WDCA

power density characteristics for different transmitters will differ depending upon their individual antenna radiation patterns.

The results, assuming for simplicity that the radiation pattern (Fig. 3) is typical of all UHF-TV transmitters, have been applied to a worst-case prediction of population exposed to power densities equal to or greater than 1 $\mu W/cm^2$ and 4 $\mu W/cm^2$ from selected transmitter complexes in four urban areas. In this worst-case determination, the field strength was doubled to allow for reflections. The results of this estimate are presented in Table 4.(7)

In urban areas, where population distribution may vary greatly over relatively small distances, differences between predicted power densities and those which actually exist, especially in the region of the second power density maximum (Fig. 4) may be responsible for significant differences in the location and extent of the region in which a selected power density threshold may be exceeded, and subsequently responsible for large differences between the estimated exposured population and the number of persons actually exposed.

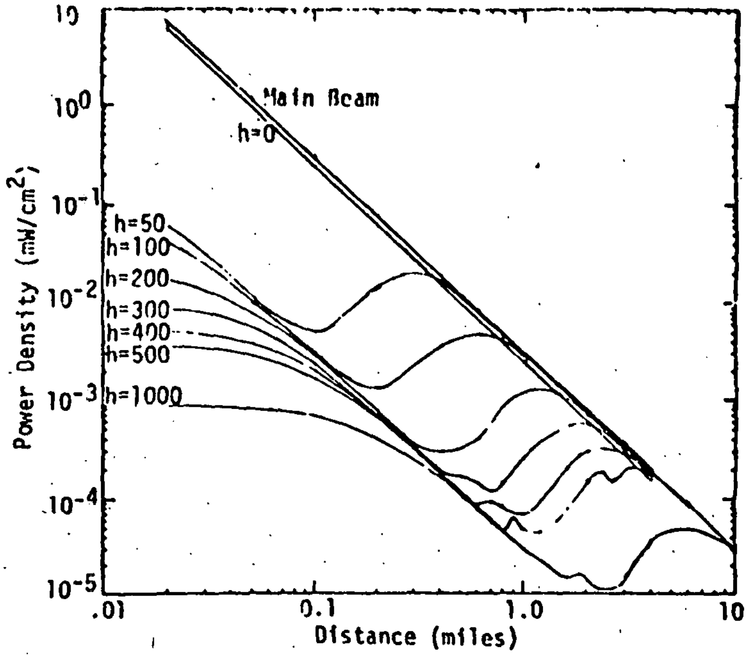

Fig. 4. UHF-TV Radiation Characteristics, 1 MW

Table 4 Approximate Population Exposure from Selected UHF-TV Transmitters

Station	Total EIRP (mW)	Location	Population Exposed (Thousands) to Power Densities of 1 $\mu W/cm^2$	4 $\mu W/cm^2$
WPHL	4.9	Philadelphia	1300	3
WDCA/WETA	5.7	Washington	800	20
WSNS/WFLD	6.0	Chicago	46	20
WSBK/WKBG	5.5	Boston	10	1

Discussion and Conclusions

Satellite communication earth terminals, tracking radars, and UHF-TV transmitters are categories of high power sources of nonionizing radiation capable of producing main beam time-averaged power densities considered hazardous; i.e., ≥ 10 mW/cm^2, at distances of the order of 100 meters from the system antenna. In general, all of these source categories contain systems which can generate environmentally significant, main beam power densities, defined in this paper to be ≥ 10 $\mu W/cm^2$ at distances on the order of 100 m from a source. However, significant differences between the radiation characteristics of these sources occur because of differences in beam collimation, antenna location relative to population centers, antenna height above ground, and system operational procedures. VHF-TV and FM broadcast transmitters have not been specifically discussed in this paper since environmental data and analyses are extremely recent and not yet available for presentation. However, similarities in environmental radiation characteristics of broadcast transmitters allow the discussion of UHF-TV transmitters to be generally applicable to the category of high power broadcast sources and indicate that VHF-TV and FM transmitters are environmentally significant sources.

SATCOM and tracking radar antennas produce very well collimated radiation beams and off-axis radiation levels are greatly reduced relative to main beam radiation levels. The ratio of off-axis power density to on-axis power density at any far-field location is generally less than 0.01 at angles greater than 5 degrees relative to the antenna axis for systems having small diameter ($\sim$10 ft) antennas. This ratio decreases as off-axis angle increases, and the angle at which a given ratio may exist decreases as antenna diameter increases and wavelength decreases. Radiation produced by a UHF-TV transmitter is collimated vertically, but for an exposure point out of the main beam at depression angles $\gtrsim 7$ degrees (refer to Fig. 2), the ratio of field intensity at that point to main beam field intensity at that same distance from the antenna is relatively constant and approximately equal to 0.1 (refer to Fig. 3).

A determination of the relative environmental significance of these source categories should include the differences in beam collimation characteristics, the fact that UHF-TV, VHF-TV, and FM antenna height above ground is much greater than that of tracking radar and SATCOM antennas, and that generally radar and SATCOM systems are located where access is restricted and population sparse when compared to the location of broadcast sources.

Tracking radar and SATCOM systems are considered to have a greater potential for the production of hazardous environmental power densities closer to the ground than UHF-TV sources. However, the number of persons that could be exposed to these levels and to environmentally significant levels would be expected to be very small because of (1) system location in sparsely populated areas, (2) operation generally in accordance with procedures to minimize the possibility for exposure of persons, and (3) the well collimated radiation beam.

UHF-TV and broadcast sources generally should be considered to have the greatest environmental significance. It has been shown that they have the capability to produce significant power densities outside of the main beam and irradiate large numbers of people. The number of transmitters and persons involved in situations where exposure levels should be reduced will ultimately depend upon verification of these predictions with measurements and the results of biological effects research in determining the threshold levels for exposure upon which standards would be based.

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