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Population Exposure to VHF and UHF Broadcast Radiation in the United States

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Abstract—The U.S. Environmental Protection Agency (EPA) has been collecting broadcast signal field intensity data for over three years to estimate population exposure to this form of nonionizing radiation. Measurement data have been obtained at 486 locations distributed throughout 15 large cities and collectively represent approximately 14 000 measurements of VHF and UHF signal field intensities. The VHF and UHF broadcast service is the main source of ambient radiofrequency (RF) exposure in the United States. A computer algorithm has been developed which uses these measurement data to estimate the broadcast exposure at some 47 000 census enumeration districts within the metropolitan boundaries of these 15 cities. The results of computations provide information on the fraction of the population that is potentially exposed to various intensities of RF radiation. Special emphasis has been placed on determining the uncertainty inherent to the exposure estimation procedure and details are provided on these techniques. A median exposure level (that level to which half of the population is exposed greater than) of 0.005 μW/cm^2 time averaged power density has been determined for the population of the 15 cities studied, the cumulative population of which represents 20 percent of the total U.S. population. The data also suggest that approximately 1 percent of the population studied, or about 441 000, are potentially exposed to levels greater than 1 μW/cm^2, the suggested safety guide for the population in the USSR. Alternative techniques of using the measurement data to estimate population exposure are examined and future extensions of this work are discussed.

Background

THE U.S. Environmental Protection Agency (USEPA) is presently gathering information pertinent to the development of guidance to Federal agencies within the U.S. concerning limitations on radio-frequency (RF) and microwave exposure of the general population. This information consists of both detailed descriptions of the biological effects of RF and microwave energy in experimental test animals and man, and normally encountered environmental exposure levels throughout the country. This report provides detailed information on the latest results of our environmental measurements program and presents our most current estimates of population exposure based on these measurement data. It is pertinent to describe the general approach used by the USEPA in collecting these data; in the first instance, numerous and widely distributed measurement points, generally selected on the basis of population distributions, located throughout many U.S. high density metropolitan areas have been used to determine ambient exposure levels of RF and microwave energy. These measurement data are then used in conjunction with a computer automated algorithm which contains census data to provide estimates of the fraction of the studied population exposed to various intensities of RF and microwave radiation. Via this method, good estimates of exposure of most of the population are obtainable. In the second instance, many field intensity measurements are conducted without regard to population distributions but rather from the viewpoint of determining the maximum or highest intensities of exposure that are possible to be found in the environment. The principle purpose of this report is to provide the results of our efforts in the first instance.

Previous discussions of USEPA activites in this area are available (Janes *et al.* [1]; Athey *et al.* [2]; Tell and Mantiply [3]). This report contains new and more extensive data and results for U.S. cities and uses an improved propagation modeling technique for generating estimates of population exposure. Additionally, a technique is discussed which provides insight to the consideration of the accuracy with which exposure estimates are obtained.

Method of Measurements

Detailed discussions of the development of a specially instrumented mobile electromagnetic radiation analysis van used in the collection of the environmental exposure data are available elsewhere (Tell [4]). The instrumentation approach, illustrated in Fig. 1, involves spectrum analysis techniques coupled with on-line computer assisted data acquisition for purposes of recording, correcting, and processing of the acquired spectral intensity data. A series of calibrated antenna systems appropriate to the frequency bands of primary consideration are used to provide signal input to the spectrum analyzer. Appropriate account is taken for the polarization of the impinging waves in certain bands by the use of orthogonal dipolar antenna systems. The minicomputer system provides various features including signal averaging whereby fluctuating signal amplitudes are processed to obtain time-averaged values of field intensity, and the capability to retain instantaneous peak signal intensity excursions during the overall observation period. Extensive efforts resulted in our ability to specify the measurement system uncertainties as outlined in Table I. It is noted that the mobile measurement system has been designed to principally operate in the bands assigned to domestic broadcasting within the U.S.; this was done because of the generally higher environmental levels of RF and microwave energy being the result of the broadcast service. Several changes in the mobile measurement system are currently underway which include a new super broad-band antenna system capable of a flat response over the 50–900-MHz region and a spectrum analysis system which will result in an enhanced capability for measurement of pulse radar field intensities.

Use of more portable instrumentation has been made in different studies of unique exposure situations, such as the main beam illumination of tall buildings and other locations not generally accessible by the mobile van system. Some of this instrumentation, the applicable studies involving its use, and discussions of accuracy limitations have been described in

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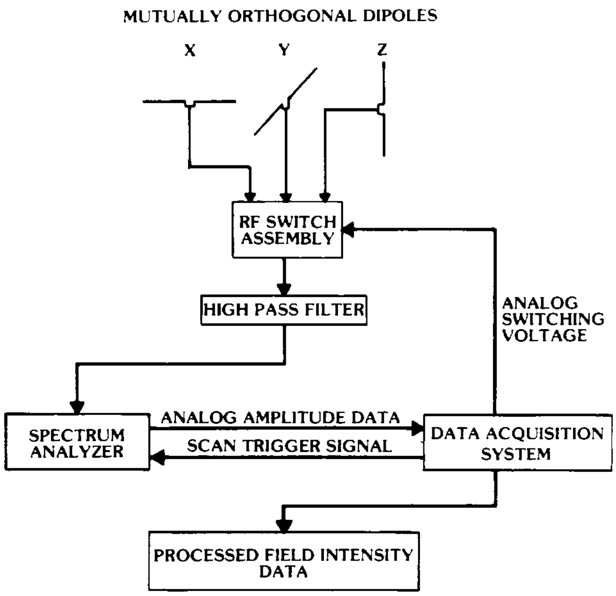

Fig. 1. Block diagram of environmental RF measurement system.

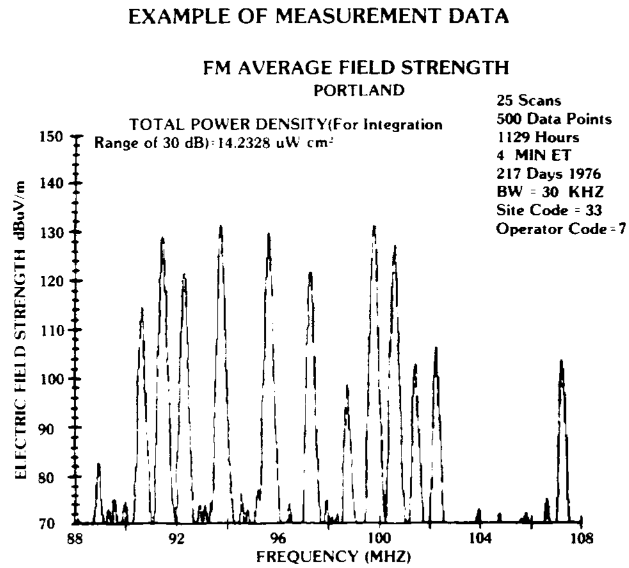

Fig. 2. Measured FM radio broadcast field intensity spectrum in Portland, OR.

TABLE I
MEASUREMENT SYSTEM UNCERTAINTIES IN VHF AND UHF BROADCAST BANDS

Band	Frequency Range (MHz)	RMS System Error (dB)
Low VHF TV	54 - 88	2.5
FM Radio	88 - 108	2.1
High VHF TV	174 - 216	2.3
UHF TV	470 - 806	2.0

previous reports (Tell and Nelson [5], [6]; Tell [7]; Tell and Hankin [8]).

APPROACH USED TO DETERMINE POPULATION EXPOSURE

The method used for our assessment of population exposure incorporates a) identification of sites representative of the population distribution in a given metropolitan area, b) measurement of the ambient field intensities existing at these representative sites, and c) subsequent use of a model, to estimate the exposure that would have been measured at many other locations throughout the city. The results of this modeling phase are then analyzed to determine the fraction of the population potentially exposed to different intensities of RF and microwave radiation.

An important underlying factor in our approach is the availability of detailed census data for the entire U.S. suitable for machine processing. These census data, based on the 1970 census of the U.S., represent the number of persons residing in specific geographical cells called Census Enumeration Districts (CED's) and the geographical coordinates of the centroid of each CED. A CED is a relatively small geographic area, consisting of, for example, a few city blocks within densely populated areas such as cities, but may be larger in rural regions wherein the population is more sparsely distributed. The entire U.S. population is contained within some 257 000 such CED's.

We have developed a method for selecting environmental measurement sites which are representative of the population within a city. First, general boundaries are defined for a city which include essentially all of the metropolitan area population, and all corresponding CED's within these boundaries are then selected for subsequent processing from the overall census data base. In effect, each of these CED's is assigned a weighting factor, according to the population within each CED. We then use a random process to select any desired number of these CED's to use as measurement sites. Thus, we use a technique which incorporates an equal likelihood of choosing any particular CED, except that those CED's having a greater population are weighted in such a way as to increase their chances of being selected as measurement sites. Out of this process, we obtain those sites which are deemed to be most representative of the total city population. Field measurements are then accomplished at each of the selected sites, usually between 30 and 40, from which subsequent propagation models are generated. In addition to these sites, selected irrespective of RF and microwave source locations, a few measurement sites are also included very near to selected transmitters to ensure a comprehensive approach to defining the full range of environmental levels.

Field measurements are then performed at each selected site using the aforementioned mobile measurement van. This field activity is normally accomplished during an intensive two-week period of time. The actual measurement process is performed by situating the measurement van at a specific stationary location. No attempt is routinely made to evaluate standing wave phenomena in the vicinity of each measurement site and thus seek out either maximum or minimum field intensities which are characteristically present in such measurements. The extent to which such immediate location variability affects the resulting measurements is reflected in the scatter of the final data and is inherent in the variance with which we subsequently predict field intensities via a model.

The results presented in this report are the product of USEPA field measurements conducted in 15 U.S. cities which include, in the order that they were studied, Boston, Atlanta, Miami, Philadelphia, New York, Chicago, Washington, Las Vegas, San Diego, Portland, Houston, Los Angeles, Denver, and San Francisco. The total population studied in these 15 cities is 44 125 176 and includes 46 789 CED's yielding a mean population per CED of 943 persons. From these field studies, approximately 14 000 individual signal field intensities were determined from a total of 486 measurement sites. Fig. 2 illustrates the type of field intensity data collected; in this case, the spectral data show one of the measurements of FM

TABLE II
SUMMARY OF INFORMATION RELEVANT TO ENVIRONMENTAL RF AND MICROWAVE FIELD INTENSITIES

City	No. CED's	Population	No. of Field Strength Values	Number of Stations FM	Low VHF	High VHF	UHF	Total	No. of Sites
Boston	2003	1953665	252	14	3	1	3	21	9
Atlanta	1249	1221431	396	11	2	2	3	18	16
Miami	1897	1661012	448	13	3	2	2	20	16
Philadelphia	3606	3407059	941	17	2	2	3	24	31
New York	11470	12269374	1426	23	3	4	3	33	36
Chicago	4646	4743905	1378	20	2	3	3	28	39
Washington	2291	2516917	1107	17	2	2	3	24	37
Las Vegas	356	264501	632	6	2	3	0	11	42
San Diego	1113	1071887	956	17	1	2	2	22	38
Portland	1194	818040	816	12	3	3	0	17	38
Houston	1127	1265933	810	14	1	3	2	20	33
Los Angeles	7596	6951121	1801	29	3	4	7	43	38
Denver	1629	1148016	766	10	3	2	0	15	43
Seattle	1315	872422	820	16	2	2	0	20	35
San Francisco	5297	3959893	1372	26	3	2	3	34	35
TOTAL	46789	44125176	13921	245	34	37	34	350	486

broadcast band obtained in Portland. Here each spectral peak observed is a single FM radio station signal. In this particular case the measurement site was near a multiple broadcast transmission center and the measured power density was 14 μW/cm^2. Table II summarizes the relevant information pertaining to each city investigated.

MODELING METHOD

Athey *et al.* [2] described a method whereby the actual measurement data were used to modify a presumptive propagation model for calculation at all CED sites thoughout a city. Athey's report made use of a propagation model form which was obtained by analyzing measured field intensity data obtained in Miami which suggested a classically recognized decrease in electric-field intensity with increases in distance between FM broadcast stations and measurement sites. This form for the model was then applied to data obtained in all VHF and UHF broadcast bands to determine exposure. In the present case, we have developed an enhanced method for predicting exposure at the various CED's by taking into consideration the fact that each city and individual station possess their own distinctive propagation characteristics.

The method we have used includes the following features. For each station under consideration, the field intensity obtained for the station at each measurement site is used to obtain a linear least square fit of the data. This provides a functional form describing the way by which the electric field strength varies as a function of distance from the station. Since this model is generated from actual measurement data for each station, note that no specification of transmitter power or antenna height is necessary. If, by chance, because of poor data, i.e., high variability in measured values of field strength, the resulting computed slope of the least square fit is positive, the slope is changed arbitrarily to be equal to zero. This in general is not a common problem, occurring in only 13 instances for the entire set of measurements reported. Next, the straight line model is used to calculate the field intensity which would be expected at each CED within the cities' bounds. From extensive tests we determined that maximum accuracy was usually obtained in the modeling procedure by using the predetermined slope of the line model but shifting this line model vertically to form a least square fit with the measurement data obtained in the neighborhood of the calculational point (a CED location). We observed that this shifting process was effective in reducing uncertainty whenever the particular station was closer than 5 km to the CED. Thus we incorporated this feature of appropriately shifting the line model to best fit the measurement data obtained at the two nearest measurement sites. Tests revealed a nonsignificant reduction in uncertainty by shifting the model to best fit more than the two nearest sites. The effect of this process is to lend weight to the local measurement data in improving estimates primarily of high intensity exposures. It was found that the shifting technique produced little, if any, apparent improvement in other than the higher exposure levels. If in the calculational process a CED was identified as being within 100 m from a nearby station, then the actual distance was arbitrarily changed to correspond to 100 m. This was accomplished to protect against the erroneous computation of very high exposure levels when the CED-station distance was very short.

An important feature in the development of our work was the construction of a test program that would be used to estimate the uncertainty associated with the modeling method. In lieu of performing additional measurements to examine the accuracy of the method, we elected to make use of the metropolitan area measurements themselves in a special way. The process consists of starting at one specific measurement site where data has been obtained and then creating the least squares line model for each station based on the measurements obtained at all other measurement sites, but not including the site under test. The exact calculational process described above is then used, always rejecting any data obtained at the test site, to arrive at the estimated field strength for each station. Then, a direct comparison is made between the predicted field and the field strength actually measured at the site. This is accomplished for each station involved and in addition to individual signal field strength differences, a comparison is made between the predicted total power density of exposure and that actually measured and being the result of exposure from all signals present at the site. The process is then repeated at each other measurement site to obtain an indication of the goodness of the modeling procedure. Once the process has been completed for all measurement sites in a city, the results are assessed statistically by determining the mean deviation between actual and predicted field strengths and the mean deviation between actual and predicted total power densities of all signals. These results are then used as an indicator of the quality of the more comprehensive calculations performed at all CED's within a city. Undoubtedly, the variances of the deviations apparent in this process are partly due to the immediate location variability discussed previously. Longely [9] has discussed this subject in detail.

Repeated application of the test program, using different criteria for shifting, provided the insight by which the final modeling criteria were determined. Extensive computer time was spent before arriving at the optimum criteria.

Population Exposure Results

The aforementioned modeling method was applied to the measurement data obtained in each of the 15 cities. Exposure levels were computed at each CED location and the resulting exposure was assumed to apply to all of the population associated with each CED. After calculation of the exposures the number of persons associated with various ranges of intensities was determined; in particular, approximately one-third decadic power density ranges were used to classify exposure, i.e., 0.001, 0.002, 0.005, 0.010, 0.020, 0.050, 0.100 μW/cm^2, etc. The final results of the analysis are presented in terms of the accumulative fraction of the population which are potentially exposed equal to or less than these different one-third decadic power density intervals. Results for Atlanta, Washington, and Los Angeles are presented in Figs. 3–5 wherein the exposure level is plotted logarithmically and the population fraction follows a near normal distribution. Fig. 6 provides the results for all cities taken together.

Each figure provides the population exposure determined for each band separately and for all measured bands together. The results suggest that the exposure levels are approximately normally distributed and reveal the interesting finding that of the exposure contributed by the various VHF and UHF broadcast bands, the FM radio broadcast band is clearly discernable as being most responsible for overall exposure, particularly at the highest exposure levels. This finding supports the earlier proposition offered by Tell and Janes [10], implicating FM radio broadcast transmissions as generally dominant in creating the highest ground levels of RF fields. Despite the lower effective radiated powers authorized for FM broadcasting compared to other VHF and UHF television emissions, a combination of relatively low tower heights and broad vertical antenna radiation patterns for FM transmission conspire to produce these relatively high fields. It is also interesting to note the relatively low contribution provided by the UHF TV band in as much that UHF television stations in the U.S. carry the maximum power authorizations.

In our experience we have found it informative to discuss these results using two different indices. The first is the median exposure level, i.e., that power density at which 50 percent of the population are exposed less than and 50 percent are exposed greater than. The second is the measure of the fraction of the population potentially exposed above 1 μW/cm^2. The data for total band exposure for each city have been summarized from the point of view of these two indices in Table III. The most significant results are for the accumulative population of all the cities in which a median exposure of 0.005 μW/cm^2 was determined while something less than 1 percent of the population are apparently exposed at intensities greater than 1 μW/cm^2. It is worthy to reemphasize that these data apply only to the domestic broadcast service in the U.S. and cannot account for population mobility. Though the population data base itself is dated, we feel that the results are probably representative for the actual present distribution of population. Fig. 7 presents the accumulative data of Fig. 6 in a differential form; i.e., the population fraction with exposures within approximately one-third decadic intervals. Clearly while greater than 99 percent of the population receive exposures less than 1 μW/cm^2, 95 percent are exposed to less than even 0.1 μW/cm^2.

The results of the test program designed to estimate the uncertainty associated with exposure calculations are presented in summary form for the 15 cities in Table IV. The tabulated

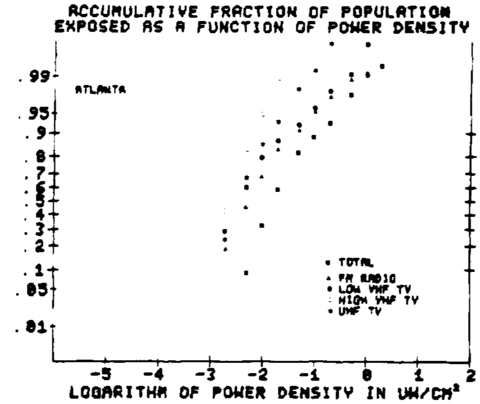

Fig. 3. Accumulative fraction of population in Atlanta exposed ≤log S (μW/cm^2).

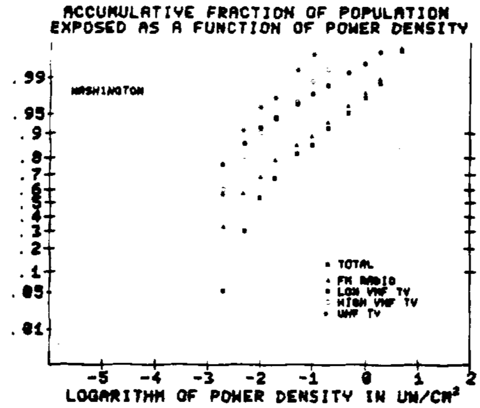

Fig. 4. Accumulative fraction of population in Washington exposed ≤log S (μW/cm^2).

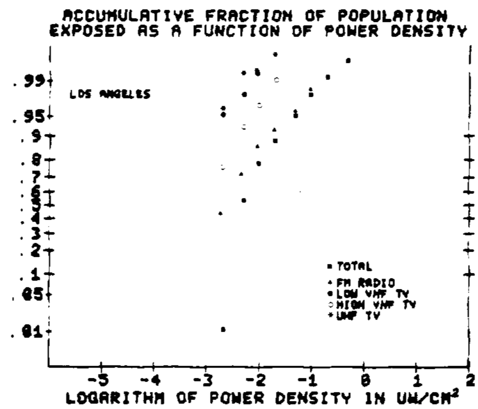

Fig. 5. Accumulative fraction of population in Los Angeles exposed ≤log S (μW/cm^2).

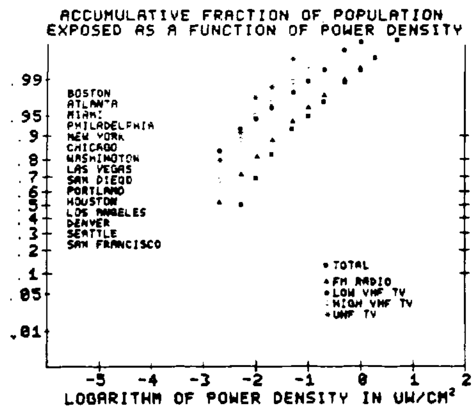

Fig. 6. Accumulative fraction of population in 15 cities exposed ≤log S (μW/cm^2).

TABLE III
POPULATION EXPOSURE RESULTS IN 15 CITIES

City	Median Exposure (μW/cm^2)	Percent of Population Exposed ≤1μW/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	0.0020	97.66
ALL CITIES	0.0048	99.44

TABLE IV
SUMMARY OF EXPOSURE TEST PROGRAM RESULTS

City	No. Sites	Mean Field Error (dB)	Mean Power Density Error (dB)
Boston	9	11.9	16.8
Atlanta	16	5.8	4.4
Miami	16	6.5	7.6
Philadelphia	31	7.3	6.9
New York	36	7.2	6.2
Chicago	39	6.9	7.6
Washington	37	6.1	5.5
Las Vegas	42	7.2	5.2
San Diego	38	8.4	10.5
Portland	38	9.7	5.2
Houston	33	7.3	5.6
Los Angeles	38	5.8	6.6
Denver	43	7.3	5.0
Seattle	35	9.0	6.9
San Francisco	35	9.8	6.3

data refer to the average of all individual field strength deviations and power density deviations at all measurement sites within each city. The observed high deviation in power density calculations in Boston undoubtedly reflects the few measurement sites used in that study.

In order to assess the uncertainty in our overall estimates of population exposure for all cities studied to date, Fig 8 was prepared which provides the frequency of occurrence of deviations between measured and calculated values of exposure at all 486 sites visited. Fig. 8 shows that the distribution of these uncertainties is approximately chi-squared in nature suggesting that the population of power densities from which these determinations were obtained is normally distributed, this being in consort with the general appearance of Fig. 6. The most significant point of Fig. 8 is that the most likely uncertainty appears to be about 2 dB while 70 percent of all our exposure calculations are within 8 dB.

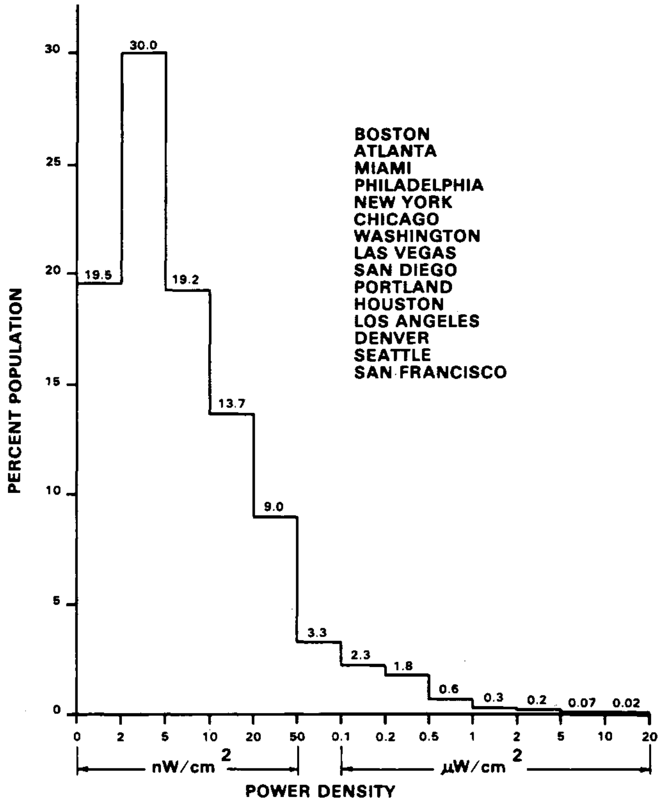

Fig. 7. Differential fraction of population in 15 cities exposed ≤log S (μW/cm^2).

DIRECT ESTIMATION METHOD

Our choice of the population weighted random method for selection of CED's as measurement sites was prompted by a desire to establish a consistent approach from city to city. In the beginning phases of the metropolitan area studies, measurement sites were not chosen on this basis but were decided upon by common sense and the apparent distribution of population as inferred from city maps. An interesting observation from application of the computer selection method, however, is that if measurements are conducted at locations which are truly random in the population space, then a simple inspection of the measurement data according to sites should provide a direct assessment of population exposure in the general area. To illustrate this process, measurement sites corresponding to CED's (most do) are sorted according to increasing power density and the accumulative fraction of sites are plotted against the logarithm of power densities on probability paper. Fig. 9 provides an example of this method applied to data obtained in Los Angeles. From the data, which is seen to be almost perfectly log normally distributed, one obtains a median exposure value of about 0.006 μW/cm^2 which compares favorably with the most comprehensive method which necessitates many calculations at all CED's in the area. Note that this method, after the initial site selection is completed, requires no further information on population. We have observed a generally good agreement between the two approaches in determining population exposure, particularly near the

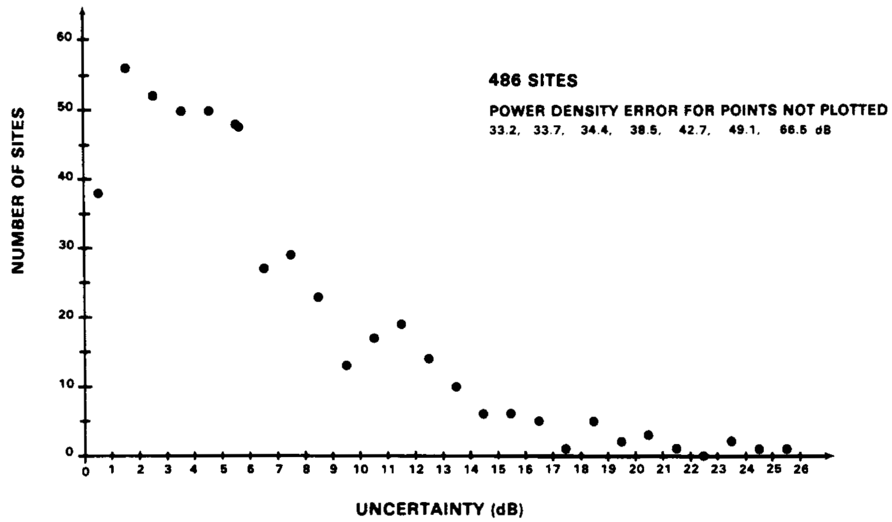

Fig. 8. Distribution of uncertainties in exposure calculations.

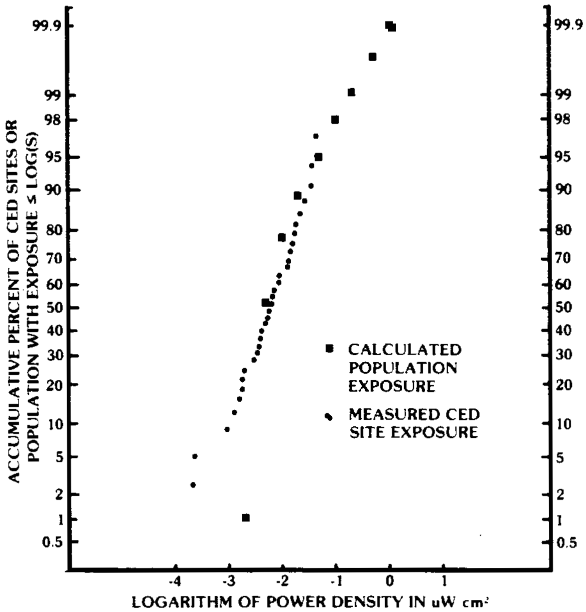

Fig. 9. Site exposure and population exposure in Los Angeles.

median exposure values, and often utilize the direct method, in favor of its simplicity, to obtain preliminary estimates of results.

Conclusions

Results of the methods outlined here suggest that, of the population group studied representing 20 percent of the total U.S. population, a median exposure value of about 0.005 μW/cm^2 time averaged power density exists and perhaps, more interestingly, less than 1 percent of the population are potentially exposed at levels above 1 μW/cm^2. It is observed that the FM radio broadcast service is responsible for most of the continuous illumination of the general population. Indeed, that fraction of the population exposed beyond 1 μW/cm^2 needs more careful definition and the absolute maximum intensities observed demand precise determination, but it is interesting to note from our results that, even at this time, at least 99 percent of the population studied are not exposed to levels above the suggested level of safety established in the USSR of 1 μW/cm^2 (Shandala [11]). Additional data obtained by the USEPA, in special areas wherein main beam illumination of tall buildings occur nearby various high power broadcast installations, has shown that it is difficult to find areas where intensities exceed 100 μW/cm^2 (Tell and Hankin [8]).

These data must be viewed from the standpoint of long term exposure and certainly, it is true that, on occasion, localized exposures may greatly exceed 1 μW/cm^2. The authors recognize the case of limited time exposure of some individuals to microwave oven leakage, portable or mobile communication equipments, and various other sources of RF and microwave exposure including pulsed sources; however, we feel that at this time, there do not exist adequate quantitative techniques for evaluating these more extreme exposure regimes in terms of their impact on our population exposure estimates provided in this paper. It is our observation that these higher intensity situations must be addressed on the basis of the length of time spent in the field and will require an accentuated emphasis upon field measurements conducted from the viewpoint of determining absolute maximum exposure values that may be encountered such as inside building measurements.

Future Work

The evidence provided by the rather extensive environmental measurements program conducted by the USEPA within the U.S. seems to overwhelmingly support the contention that most of the general population is not chronically exposed to high intensity (i.e., >100 μW/cm^2) RF and microwave radiation. Accordingly, future field measurement efforts will include to a greater extent examination of those unique kinds of exposure circumstances wherein relatively high intensity exposures are possible or expected. A more detailed investigation of environmental levels of pulsed RF and microwave fields is currently being developed. Additionally, we are examining our data from the viewpoint of developing deterministic propagation models, provided transmitter effective radiated power and antenna height, for different classes of transmitting stations. Our particular interest is in being able to more accurately model close-in exposure conditions, and in this connection we will be comparing our data and resulting propagation models with other existing models.

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Occupational Exposure to Radio-Frequency Electromagnetic Fields

KJELL HANSSON MILD

Abstract—Occupational exposure to radio-frequency (RF) electromagnetic (EM) fields occurs in various industrial processes. The exposure usually takes place in the near field, i.e., within one free space wavelength from the RF source. When a survey of a workplace is performed from a leakage radiation point of view, the near-field situation implies that the electric as well as the magnetic field strengths have to be monitored in order to assess the health hazard. This paper discusses the field strengths typically encountered in some of these occupational situations.

Thin sheets of plastic materials can be joined or sealed by application of RF energy. The plastic welding machine, using for this purpose, usually does not have shielded electrodes and this may lead to high levels of RF fields in the immediate vicinity of the machines. The ANSI standard is exceeded in several cases near the plastic welding machines.

In medicine, for instance, RF energy is used in shortwave therapy. Due to the construction of the apparatus (i.e. presence of electrodes and cables) the physiotherapist as well as the maintenance personnel may be exposed to very high levels of both E and H fields. The results of measurements of these fields in the vicinity of shortwave diathermy apparatus are discussed.

The maintenance personnel working in FM/TV broadcast towers are another group of workers subject to occupational exposure of intense RF fields, and some recent studies of the exposure are presented.

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Introduction

ELECTROMAGNETIC (EM) fields with frequencies from a few kilohertz to gigahertz are frequently employed in various industrial processes for heating purposes. In the lower frequency range we find the induction heaters which are used for melting, forging, annealing, surface hardening, and soldering operations. Dielectric heating equipment usually operates in the shortwave region. They are most commonly used to speed up gluing of wood, to facilitate the moulding of plastic, to remove moisture from materials or to join or seal thin plastic materials. High-frequency heating is also employed in medicine for shortwave therapy (diathermy). In all of these processes involving high-frequency EM fields, the risk of undesirable or harmful radiation at the workplaces cannot be overlooked. Occupational exposure to radio-frequency (RF) fields is not limited to the personnel operating the equipment but includes service and maintenance personnel, who in many cases work very close to the radiating parts with the equipment operating at full power.

In this paper we present the results of measurements of the electric as well as the magnetic field strengths in the immediate vicinity of some of the most common sources of RF emitting devices. The paper is based on results of measurements done by the Swedish National Board of Occupational Health and

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