Bioelectromagnetics 18:563–577 (1997)

Summary of Measured Radiofrequency Electric and Magnetic Fields (10 kHz to 30 GHz) in the General and Work Environment

Edwin D. Mantiply, Kenneth R. Pohl, Samuel W. Poppell, and Julia A. Murphy

National Air and Radiation Environmental Laboratory, U.S. Environmental Protection Agency, Montgomery, Alabama

We have plotted data from a number of studies on the range of radiofrequency (RF) field levels associated with a variety of environmental and occupational sources. Field intensity is shown in units of volts/meter (V/m) for electric field strength and amps/meter (A/m) for magnetic field strength. Duty factors, modulation frequencies, and modulation indices are also reported for some sources. This paper is organized into seven sections, each cataloging sources into appropriate RF frequency bands from very-low frequency (VLF) to super-high frequency (SHF), and covers frequencies from 10 kHz to 30 GHz. Sources included in this summary are the following: Coast Guard navigational transmitters, a Navy VLF transmitter, computer visual display terminals (VDTs), induction stoves or range tops, industrial induction and dielectric heaters, radio and television broadcast transmitters, amateur and citizens band (CB) transmitters, medical diathermy and electrosurgical units, mobile and handheld transmitters, cordless and cellular telephones, microwave ovens, microwave terrestrial relay and satellite uplinks, and police, air traffic, and aircraft onboard radars. For the sources included in this summary, the strongest fields are found near industrial induction and dielectric heaters, and close to the radiating elements or transmitter leads of high power antenna systems. Handheld transmitters can produce near fields of about 500 V/m at the antenna. Fields in the general urban environment are principally associated with radio and TV broadcast services and measure about 0.1 V/m root-mean-square (rms). Peak fields from air traffic radars sampled in one urban environment were about 10 V/m, 300 times greater than the rms value of 0.03 V/m when the duty factor associated with antenna rotation and pulsing are factored in. *Bioelectromagnetics 18:563-577, 1997.* © 1997 Wiley-Liss, Inc.†

Key words: radiofrequency; microwave; exposure; environmental; occupational

INTRODUCTION

Measurements have been reported over the past 20 years that quantify environmental and workplace radiofrequency (RF) fields from a variety of systems. These results have been reported in a scattered literature that includes government reports with limited circulation and excessive detail. We have collected the results of these studies and present them here in a graphical format using standard field strength units. In some cases, the field strength values reported here have been scaled to allow for standardized exposure distances or for changes in typical transmitter power levels. These scalings are detailed in the main text.

This paper is limited to summarizing field strengths and does not make comparisons with permissible exposure limits recommended in various standards and guidelines. Specific absorption rate (SAR), a measure of dose rate as opposed to exposure, is the primary parameter for comparison to safety standards regardless of external field strength. Knowledge of instantaneous SAR or internal field is more fundamental than an external field strength measurement. This is particularly important in the near field of small sources such as handheld transmitters, where electric and magnetic field strength maxima do not necessarily occur at the same point in space or produce high peak SARs.

In addition to field strength, the time variation

*Correspondence to: Edwin D. Mantiply, National Air and Radiation Environmental Laboratory, U.S. Environmental Protection Agency, 540 South Morris Avenue, Montgomery, AL 36115-2601. E-mail: mantiply.edwin@epamail.epa.gov

Received for review 15 May 1996; revision received 11 March 1997

TABLE 1. Frequency Bands and Sources Included in Summary

Descriptive band designation	Abbreviation	Frequency range	Sources included
Very-low frequency	VLF	3 to 30 kHz	Omega navigational transmitters, a Navy communication transmitter, visual display terminals, induction stoves
Low frequency	LF	30 to 300 kHz	Loran navigational transmitters
Medium frequency	MF	300 to 3000 kHz	AM broadcast, 160 meter amateur radio, induction heaters, electrosurgical units
High frequency	HF	3 to 30 MHz	International broadcast, amateur and citizens band radio, dielectric heaters, shortwave diathermy
Very-high frequency	VHF	30 to 300 MHz	FM broadcast, VHF television, mobile and handheld transmitters, cordless telephones
Ultra-high frequency	UHF	300 to 3000 MHz	UHF television, cellular telephones, microwave ovens, microwave diathermy, air traffic radars
Super-high frequency	SHF	3 to 30 GHz	Microwave relays, satellite uplinks, aircraft onboard radar, police radar

(or modulation) and spatial character of the fields are discussed. As an example of spatial character, data on three exposure scenarios are included for broadcast stations. We first describe a range of general environmental levels; second, the range of field values found near grade or at buildings in the immediate vicinity of the transmitting antenna; and third, possible exposure values for an individual climbing the antenna tower. The temporal character of pulse or amplitude modulated fields is also considered, especially when there are large differences between peak and root-mean-square (rms) values.

This work is intended as an overview and bibliography for typically encountered RF fields. Earlier reviews contain more descriptive information on how fields are measured, calculated, and shielded [Stuchly, 1977; Hankin, 1986; Stuchly and Mild, 1987; Joyner, 1988; Mild and Lovstrand, 1990]. This summary is organized into the seven RF bands and covers the sources shown in Table 1.

As an example graph, Figure 1 displays the range of electric and magnetic field strengths measured in the very-low frequency (VLF) band from 10 to 30 kHz. This format communicates information about frequency and wavelength, relative field strengths, and the ratio of electric to magnetic field strength (field impedance). Each graph uses the same scales for electric and magnetic field strength, which are aligned so that the values found on a horizontal line correspond to the idealized case of fields in a plane electromagnetic wave propagating in free space where the ratio of the electric to the magnetic field strength magnitude is 377 ohms. A single data set is shown as a rectangle; its boundaries give the frequency and wavelength range and either the electric or magnetic field strength range for the data set. The rectangle is filled with hatching down to the right if electric field strength values are represented or filled with hatching down to the left for magnetic field strength data. For example, the upper rectangle for the induction stove represents magnetic field strengths ranging from 0.7 to 1.6 A/m in a frequency range of 26 to 29 kHz and wavelength range of 10.3 to 11.5 km.

Overlapping electric and magnetic field strength data sets result in a cross-hatched region, indicating a range of field magnitudes with ratios similar to 377 ohms. It is important to understand that in the near field case, the overlap is coincidental; i.e., the fields may not be related by 377 ohms. The typical rectangle represents the extreme range of field strengths measured at some fixed distance from a specific type of field source in several studies. However, each data set is defined individually in an effort to summarize the essence of each study. For example, some rectangles represent variation with distance and should not be considered a statistical sample.

For the sample data sets, the underlying statistical distribution of field strengths is typically log-normal. Because the field scales are logarithmic, in some cases one can visualize a normal distribution in the third-dimension oriented perpendicular to the page with low probability extreme values at the top and bottom rectangle boundaries, and with most values clustered near the center.

For graphical clarity and separation of data sets, the frequency range plotted is often schematic—the text gives exact frequency values. Also, reported field strengths can be found in the text that are not shown in the graphs. Where data sets overlap, obscure other data, or do not add qualitatively to the graph, the data is included only in the text.

Electric and magnetic field strength units have been used for all bands. Plane-wave equivalent power density units are normally used at higher frequencies.

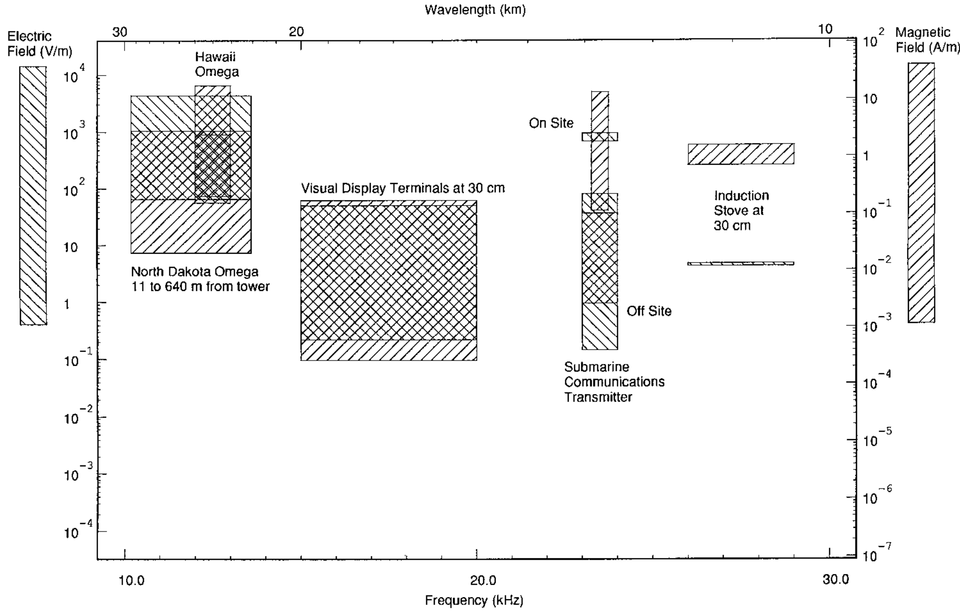

Fig. 1. Very-low frequency band.

This power density (S) in milliwatts per square centimeter (mW/cm^2) may be obtained from the electric field strength (E) using $S(mW/cm^2) = [E(V/m)]^2/3770$. Similarly, to convert the magnetic field strength (H) to power density use $S(mW/cm^2) = [H(A/m)]^2(37.7)$. Note that while power density may be scaled in direct proportion to power or duty cycle, rms field strength scales in direct proportion to the square root of power or duty cycle.

VERY-LOW FREQUENCY: 10 TO 30 kHz

The wavelengths for this frequency range vary from 30 km at 10 kHz to 10 km at 30 kHz. Antennas designed to transmit or radiate electromagnetic waves at these long wavelengths are large structures driven at high voltage. The typical antenna is similar to that for a standard AM radio broadcast station in which the entire tower is part of the antenna. However, in contrast to most AM antennas, many VLF antennas use extended wire structures connected to the top of a tower or transmitter lead (feed line) to increase the effective height of the antenna. In all cases, the radiating structure is insulated and driven at some high RF potential referenced to a buried radial ground wire system. Large VLF transmitting systems that have been studied include omega navigational systems and the VLF submarine communication system at Lualualei, Hawaii. Sources such as visual display terminals (VDTs) and induction heaters can be described as near-field sources because VLF electric and magnetic fields are generated in their immediate vicinities but are not radiated as electromagnetic waves. Also, electric and magnetic field strength maxima may not occur at the same location. Figure 1 displays the range of field strengths measured for some VLF sources.

Omega Navigational Transmitters

There are eight ''omega'' very-long-distance navigational transmitters in the world. Two are in the United States—one in North Dakota and one in Hawaii [Gailey, 1987]. Omega transmitters switch between frequencies ranging from 10.2 to 13.6 kHz in a repeating 10-s cycle. The transmission is a series of eight single-frequency sinusoidal carriers switched on for 0.9 to 1.2 s with a pause of 0.2 s between each carrier. The drive voltage on omega antennas is about 250 kV. The North Dakota antenna is a single top-loaded tower, whereas the Hawaii antenna is an array of horizontal wires stretched across a valley and connected to the transmitter by a vertical feed line. For the North Dakota station, the measured rms electric field strength varied with distance along one radial from 66 V/m at 640 m to 4400 V/m at 12 m from the tower base. Similarly, the rms magnetic field strength varied from 20 mA/m at 640 m to 2.9 A/m at 11 m from the tower. The Hawaii omega station antenna is more complex, and so are the field variations. For example, outside the station building, electric field strengths varied from 57 to 938 V/m and magnetic field strengths varied from

1.2 to 4.4 A/m. The maximum magnetic field strength at the Hawaii site was 18 A/m near the main feed line [Gailey, 1987]. Other investigators reported magnetic field strengths from 0.2 to 6.2 A/m in the transmitter building and near the feed line [Guy and Chou, 1982].

VLF Submarine Communications System

The U.S. Navy operates a 23.4 kHz VLF submarine communications system at Lualualei, Hawaii [Mantiply, 1992]. The signal is frequency modulated with a small deviation relative to the carrier frequency so that it appears to be a constant sinusoidal carrier for field measurement purposes. Outside the station boundary the measured electric field strength varied from 0.15 to 82 V/m and the magnetic field strength varied from 2.5 to 99 mA/m. These measurements were made at distances between approximately 0.8 and 7 km from the transmitting antennas. On-site measurements [Guy and Chou, 1982] showed that the electric field strength varied from 972 to 700 V/m between about 80 and 150 m from the antenna. Measured magnetic field strength in the transmitter building and near the feed line varied from 0.11 to 14 A/m.

Visual Display Terminals

The common VDT employs a vertically oriented sawtooth-waveform VLF magnetic field that rapidly sweeps the electron beam horizontally across the screen. Horizontal extremely low-frequency (ELF) magnetic fields slowly sweep the electron beam vertically, but these ELF fields are outside the scope of this paper. VLF electric fields are also generated by the flyback transformer in the high-voltage power supply. The fundamental frequency of the VLF field is between 15 and 35 kHz (some high resolution terminals operate at higher frequencies) and harmonics exist up to several hundred kilohertz. Many studies and reviews have been made of fields near VDTs [Stuchly et al., 1983; Marha et al., 1983; Guy, 1987; Charron, 1988; Jokela et al., 1989; Tell, 1990; Tofani and D'Amore, 1991; Walsh et al., 1991; Schnorr et al., 1991; Kavet and Tell, 1991; Mild and Sandstrom, 1992]. Reported VLF electric field strengths 30 cm (1 foot) in front of the screen center, range from 0.22 to 52 V/m, and mean values reported by different investigators vary from 0.83 to 12.5 V/m. Reported VLF magnetic field strengths measured at 30 cm range from 0.26 to 170 mA/m, and mean values reported vary from 20 to 85 mA/m. These means are rms field strength summary values reported in some of the studies.

Induction Heating Stoves

Induction heating stoves used in the home generate VLF magnetic fields with fundamental frequencies of about 22 to 34 kHz. These range tops heat food by inducing eddy currents in cooking utensils. Electric and magnetic field strengths have been measured near two stoves heating a variety of utensils [Stuchly and Lecuyer, 1987]. At 30 cm from the stove, electric field strengths averaged 4.3 to 4.9 V/m and magnetic field strengths varied from 0.7 to 1.6 A/m.

LOW FREQUENCY: 30 TO 300 kHz

Loran Navigational Transmitters

Loran navigational transmitters emit a pulsed signal centered at 100 kHz. Each transmitter generates a unique pulse train repeating at 10 Hz. Depending on the pulse train, instantaneous peak fields vary from 11 to 18 times greater than the rms fields reported here. Electric and magnetic field strengths were measured at nine different loran stations. Electric field strength varied from 28 to 350 V/m and magnetic field strength varied from 0.6 to 2.9 A/m at distances of 3 to 4 m from the antenna base or feed point. At a distance of 300 m the electric field strength varied from 3 to 9 V/m, and the magnetic field strength varied from 6 to 41 mA/m [Gailey, 1987]. These field values are shown in Figure 2.

The strongest fields are found in close proximity to the antenna insulator (electric field) or tuning coils (magnetic field). For example, at eight stations, the maximum electric field strength varied from 463 to 2830 V/m, and the maximum magnetic field strength varied from 3.8 to greater than 10 A/m [Gailey, 1987]. The electric and magnetic field maxima are not found at the same point in space. In another study, magnetic field strengths up to 52 A/m near loran feeds were reported [Guy and Chou, 1982].

MEDIUM FREQUENCY: 300 kHz TO 3 MHz

The medium frequency range from 300 kHz to 3 MHz has corresponding wavelengths of 1000 to 100 m. Sources that operate in this frequency range include AM standard broadcast transmitters operating at frequencies between 535 to 1705 kHz with wavelengths of 560 to 176 m, amateur radio transmitters at 1.8 to 2.0 MHz in the 160-m wavelength band, and industrial and medical devices such as induction heaters and electrosurgical units. Figure 3 summarizes fields in the medium frequency band.

AM Standard Broadcast

Studies of general population exposure in the United States showed that approximately 3% of the urban population were exposed to electric field strengths greater than 1 V/m from AM broadcast ser-

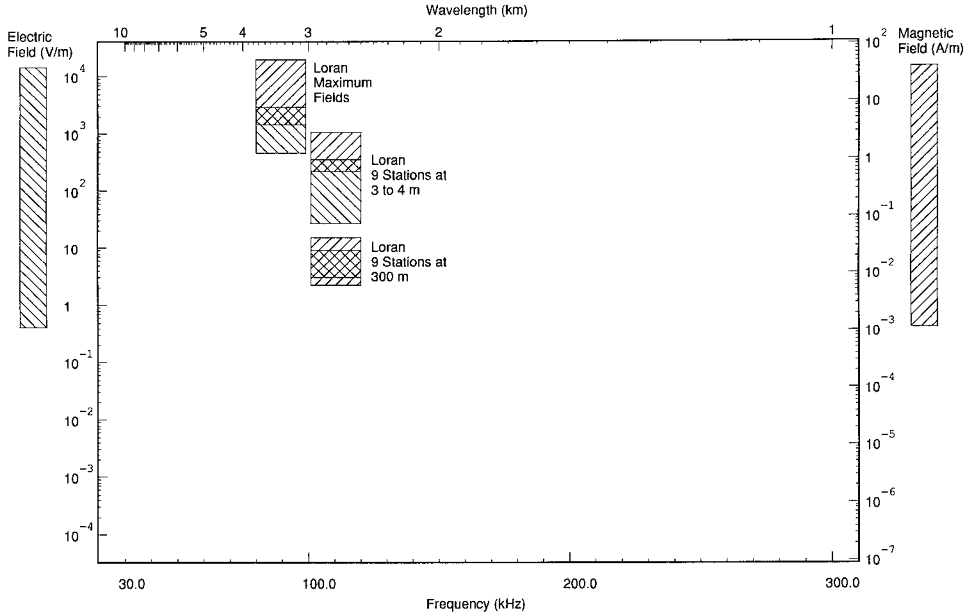

Fig. 2. Low frequency band.

vices. Ninety-eight percent of the population were exposed to greater than 70 mV/m, and the median exposure was about 280 mV/m [Hankin, 1986].

Electric and magnetic field strengths were measured near eight typical AM broadcast stations [Mantiply and Cleveland, 1991]. The fields were measured from 1 to 100 m from the center of each tower base. One station operated at the maximum power of 50 kilowatts (kW); three stations operated at approximately 5 kW; and the remaining four stations operated at 1 kW. Fields were measured along three radials at most stations. In the near field, at distances of 1 or 2 m, electric field strengths varied from 95 to 720 V/m and magnetic field strengths varied from 0.1 to

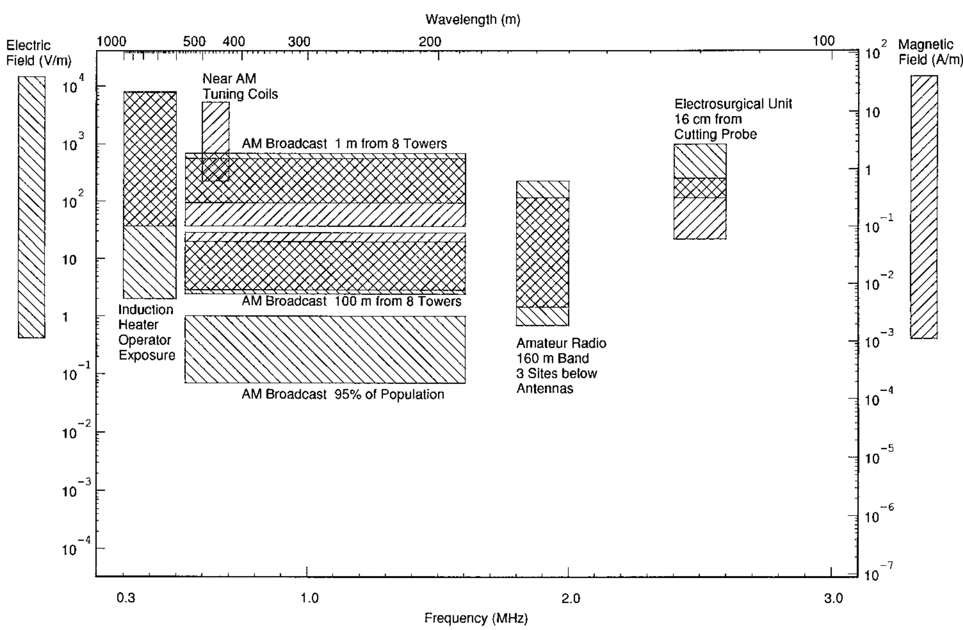

Fig. 3. Medium frequency band.

1.5 A/m. At 100 m from the tower, electric field strengths varied from 2.5 to 20 V/m; magnetic field strengths varied from 7.7 to 76 mA/m.

Fields were measured close to five AM towers operated at up to 30 kW in the Honolulu, Hawaii area [U.S. EPA, 1985]. Accessible regions near the tower base or tuning network were probed for maximum electric and magnetic field strength. The maximum electric field strength at the five towers varied from 100 to 300 V/m and the maximum magnetic field strength varied from 0.61 to 9.3 A/m. Wang and Linthicum [1976] measured magnetic field strengths up to 14.4 A/m at about 60 cm from an antenna tuning coil at the base of a 50 kW AM tower.

Studies of field strengths at residences and at a school near AM radio stations have been made in Spokane, Washington, and Honolulu, Hawaii [Tell et al., 1988; U.S. EPA, 1985]. In Honolulu, measurements were made at high rise condominiums adjacent to a 30 kW AM broadcast tower. Electric field strengths at an outdoor recreational area on the roof of one building were typically 100 to 200 V/m, and the magnetic field strength was 120 mA/m. Indoors in a 30th floor apartment, the electric field strength was 2 to 3 V/m, and the magnetic field strength was 240 mA/m. Electric and magnetic field strengths were also measured inside and outside a single family house in Spokane near a 50 kW AM station. At locations outside on the family property where the fields did not appear to be perturbed, the electric field strength varied from 9 to 19 V/m. Perturbed electric field strength inside the house varied from 1 to 55 V/m. The magnetic field strength outside varied from 30 to 40 mA/m and inside varied from 31 to 49 mA/m. Electric and magnetic field strengths were also measured inside an elementary school in Spokane approximately 100 m from the same AM station. The electric field strength in the school varied from 1 to 28 V/m and the magnetic field strength varied from 22 to 470 mA/m. Unperturbed electric and magnetic field strengths at the school were estimated to be 15 V/m and 40 mA/m. Clearly, both electric and magnetic field strengths due to medium frequency AM broadcast can be either increased or decreased in the indoor environment relative to the unperturbed values found outdoors. Any vertically extended conductor in a building, especially when grounded, strongly perturbs the RF electric field. RF currents induced on these conductors can generate relatively strong localized magnetic fields.

Standard AM broadcast uses conventional double sideband amplitude modulation at audio frequencies. Amplitude modulation is measured in percent: if the root-mean-square field goes to zero, the signal is 100% modulated. Modulation index is the ratio of maximum modulating signed amplitude to the carrier amplitude. Measurement of nine different AM signals in Las Vegas, Nevada, showed ELF modulation indices from 4 to 30% in the modulation frequency range of 3 to 100 Hz [unpublished data].

Amateur Radio (160 Meter Band)

Amateur radio operators may transmit up to 1.5 kW (peak envelope power) in the 160-m wavelength band (1.8 to 2.0 MHz). Electric and magnetic field strengths in this band were measured at three amateur radio installations [Cleveland and Mantiply, 1996]. These measurements were made outdoors at 1 or 2 m above ground beneath active antenna wires. The operator set the transmitter for a constant carrier at 1.95 MHz. Beneath an open line ''modified T'' antenna feed operating at 500 watts, electric field strengths varied from 52 to 240 V/m and magnetic field strengths varied from 37 to 310 mA/m. Beneath an ''inverted V'' dipole operating at 100 watts the electric field strength varied from 0.7 to 5.4 V/m, and the magnetic field strength varied from 4 to 100 mA/m. Beneath another 160-m dipole antenna operating at 80 watts, the electric field strength varied from 5 to 22 V/m, and the magnetic field strength varied from 13 to 78 mA/m.

Induction Heaters

Industrial induction (eddy current) heaters are used to heat metals or semiconductors by generating a strong alternating magnetic field inside a coil. Frequencies range from 50 Hz to 27 MHz. Lower frequency units produce stronger magnetic fields that also penetrate and heat the material more deeply. Higher frequencies are used for surface heating or heating small volumes. The strongest magnetic field strengths measured have been for heaters operating at frequencies below 10 kHz that are outside the scope of this summary [Stuchly and Lecuyer, 1985; Mild and Lovstrand, 1990]. In five studies [Aniolczyk, 1981; Centaur, 1982; Stuchly and Lecuyer, 1985; Conover et al., 1986; Andreuccetti et al., 1988] measurements were made near medium frequency induction heaters operating from 250 to 790 kHz. These near fields vary greatly over small distances and with the type of unit and process. Typically, the electric field strength decreases from 1000 to 100 V/m and the magnetic field strength decreases from 20 to 0.5 A/m as distance from the coil is increased from 20 to 100 cm. Reported electric and magnetic field strengths (unperturbed) at the operator position vary from 2 V/m to 8.2 kV/m and 0.1 to 21 A/m, respectively. These field values are not corrected for duty cycle, which is typically 50%. It is likely that RF induction heater fields are amplitude modulated at multiples of the power frequency. Generally, 60 or 50 Hz ripple in the power supply is not controlled for sources used solely for heating.

Electrosurgical Units

Medical electrosurgical units operate from 0.5 to 2.4 MHz with significant harmonics and spurious frequencies up to 100 MHz. Electric and magnetic near fields measured under typical conditions varied from about 200 V/m and 0.1 A/m at 40 cm to about 1000 V/m and 0.35 A/m at 10 cm from the cutting probe lead. The fields also vary greatly depending on operating mode. At 16 cm, fields varied from 120 to 1000 V/m and 0.06 to 0.71 A/m depending on the mode of operation. The unit may operate with amplitude modulation at frequencies of approximately 10 to 30 kHz [Ruggera, 1977].

HIGH FREQUENCY: 3 TO 30 MHz

A major use of the HF band or shortwave range of frequencies (from 3 to 30 MHz with corresponding wavelengths of 100 to 10 m) is long-range communication by ionospheric reflection. Because of this propagation characteristic, there is always an HF background of fields from distant sources. For example, one set of measurements showed about 50 signals between 0.1 and 1 mV/m from 3 to 30 MHz [Mantiply and Hankin, 1989]. HF is used in long-range radio communications for international broadcast by governments and private organizations, amateur radio operators, commercial communication with aircraft and ships at sea, and military communications. Typical transmitter powers for amateurs are 100 or 1000 watts; other classes of operators typically use 2 to 30 kilowatts (kW); and broadcasters normally operate at 50 to 500 kW. HF sources are also used in industry and medicine for plastic welding and diathermy. Figure 4 summarizes the range of fields measured for several types of HF sources.

Amateur Radio

Electric and magnetic field strengths were measured at nine amateur radio transmitting sites. Fields were measured beneath antennas at a height of 1 to 2 m for various antenna configurations and frequency bands [Cleveland and Mantiply, 1996]. The average transmitter power varied from 100 to 1400 watts for these measurements. The transmitters were set to transmit a constant carrier (no duty cycle correction). The range of measured field strengths for each of five frequency bands (80, 40, 20, 15, and 10 m) are shown in Figure 4. For all five bands, electric field strengths varied from 1 to 200 V/m and magnetic field strengths varied from 2 to 1400 mA/m. These are ‘‘example’’ values. Fields greater than these values were measured in some bands very close to antennas or feed points. Amateur keyed carrier and single-sideband voice transmissions are amplitude modulated at frequencies below 100 Hz. For example, one measurement of an amateur keyed carrier signal resulted in 90% modulation from 3 to 100 Hz [unpublished data].

Citizens Band Radio

The citizens band (CB) 40 channel frequency band extends from 26.965 to 27.405 MHz. Most transmission is AM, but single sideband can be used. Electric and magnetic fields near several CB antennas have been investigated in some detail [Ruggera, 1979]. Tests were performed with the antennas operating at 27.12 MHz and 4 watts. Near fields were measured as a function of height at a horizontal distance of 5, 12, and 60 cm from the antennas. The maximum electric and magnetic field strengths measured at 5 cm varied from 230 to 1400 V/m and 0.1 to 1.3 A/m; at 12 cm, from 90 to 610 V/m and 0.05 to 0.8 A/m. At 60 cm, maximum electric field strengths varied from 18 to 60 V/m, and maximum magnetic field strengths were less than the instrument sensitivity of 0.04 A/m. Maximum electric field strengths were found near the top of the antenna, and maximum magnetic field strengths were observed near the base.

International Broadcast

High-power HF transmitters are used for international broadcasts by governments and private organizations. Measurements at two Voice of America (VOA) sites are included here. Typically, VOA uses 250 kW transmitters (standard amplitude modulation) and large rhombic or curtain type antennas. Also, 50 kW dual independent sideband transmitters are used for relay. At the Bethany, Ohio, VOA station electric field strengths of 2.5 to 100 V/m were measured beneath RF transmission lines and rhombic antennas [unpublished data]. A study near the VOA transmitter site at Delano, California, emphasized measurements of potential exposures in a community 10 km from the VOA transmitter [Mantiply and Hankin, 1989]. High frequency electric and magnetic field strengths in the community due to the VOA antenna were measured at six sites and four frequencies: 6.155, 9.765, 9.815, and 11.74 MHz. For any one frequency, electric field strength varied from 1.5 to 64 mV/m, and magnetic field strength varied from 0.0055 to 0.16 mA/m. The maximum HF electric and magnetic field strengths measured just outside the Delano VOA boundary were 8.6 V/m and 29 mA/m.

Electric and magnetic field strengths were also measured on the VOA Delano site [unpublished data] along traverses 1 m above ground and perpendicular

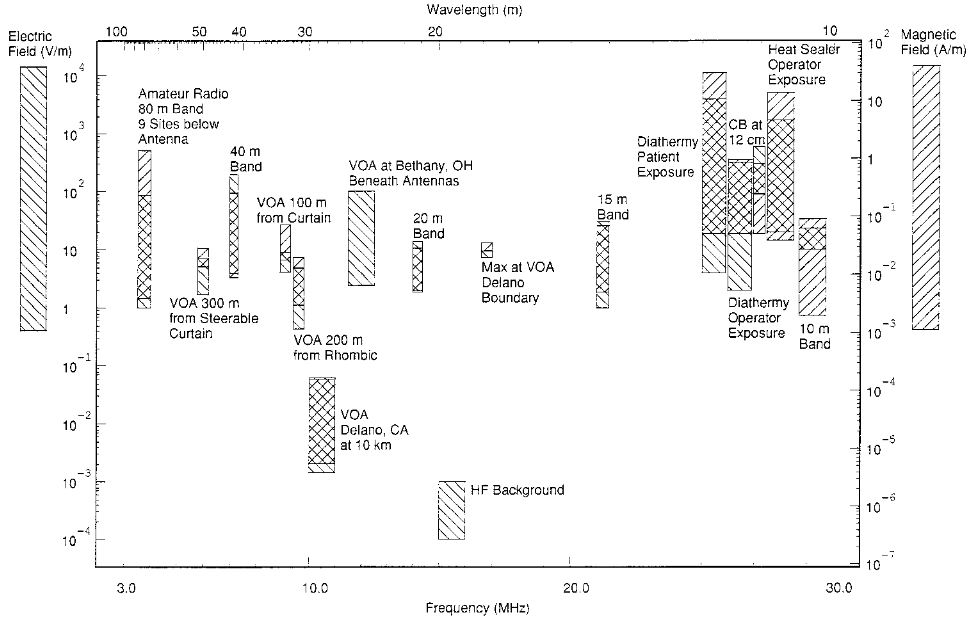

Fig. 4. High frequency band.

to the direction of propagation in front of a rhombic antenna and a conventional curtain antenna. Fields in front of a steerable curtain antenna were investigated by varying its operating direction. All three antennas were operated at 100 kW of input power. At a distance of 200 m in front of the rhombic antenna operating at 9.57 MHz, the electric and magnetic field strengths varied from 0.45 to 5.0 V/m and 3.0 to 20 mA/m, respectively, along the traverse. At a distance of 100 m in front of the conventional curtain antenna operating at 9.57 MHz the electric and magnetic field strength varied from 4.2 to 9.2 V/m and 18 to 72 mA/m along the traverse. At a distance of 300 m in front of the steerable curtain antenna operating at 5.96 MHz, the electric and magnetic field strength varied from 1.7 to 6.9 V/m and 14 to 29 mA/m as the antenna was electrically steered to angles of ± 25°.

Dielectric Heaters

Dielectric heaters (heat sealers) are used in industry to heat or weld nonconductors such as plastics by applying a strong alternating electric field between metal plates. Operating frequencies range from a few megahertz to greater than 120 MHz. The most common frequency is 27.12 MHz. Near fields measured at the operator's position are nonuniform and are not well correlated with system power and the electric and magnetic field strength maxima are not collocated. In 12 studies [Conover et al., 1975; Ruggera, 1977; Hietanen et al., 1979; Conover et al., 1980; Mild, 1980; Stuchly et al., 1980; Aniolczyk, 1981; Cox et al., 1982; Stuchly and Lecuyer, 1985; Joyner and Bangay, 1986; Bini et al., 1986; Conover et al., 1992], field measurements were made at various locations at the operator's body (head, chest, waist) for dielectric heaters operating from 6.5 to 65 MHz. In some of the earlier studies, measurements were made by simply positioning the field probe at the operator's body. More recent measurements have been made by positioning the probe at the operator's body as above, but then having the operator move away and reading the instrument with the operator absent. This procedure is an effort to prevent perturbation of the fields by the operator.

Measured electric and magnetic field strength in the 12 studies varied from about 20 to 1700 V/m and 0.04 to 14 A/m. Typical values are 250 V/m and 0.75 A/m. These values are not corrected for duty cycle and do not include values reported as greater or less than the range of a measuring instrument. Reported duty cycles varied from 2.5% to greater than 50%. Dielectric heaters typically operate 10% of the time.

Shortwave Diathermy

Shortwave diathermy is a medical treatment using continuous or pulsed 27 MHz RF fields to heat tissue within the body. RF power is coupled into the body using either insulated plates or a loop as an applicator. The applicator is connected to an RF power generator using two separate insulated leads. After the applicator is in place the generator is adjusted to optimize the transfer of RF energy into a specific part of the body. Plate applicators generate relatively high electric fields to capacitively couple power into the tissue, whereas loop applicators generate relatively high magnetic fields to inductively couple power. Exposure of the patient is in the near field. Fields are produced along the leads from the generator as well as at the applicator.

The dominant source of fields at the operator's position may be the leads. Typical field strengths near the leads decrease from 2000 to 200 V/m and from 3 to 0.2 A/m as the distance from the cables increases from 5 to 35 cm. Two major studies found similar values for the fields at the operators' eyes and waists [Ruggera, 1980; Stuchly et al., 1982]. The range of values for the operator was 2 to 315 V/m for the electric field strength and 0.05 to 0.95 A/m for the magnetic field strength.

In one study [Kalliomaki et al., 1982] electric and magnetic field strengths were measured near the patient's body for various types of applicators or electrodes. As expected, patients are exposed to higher levels than operators. At the area of treatment, electric and magnetic field strengths varied from 400 to 4000 V/m and 3 to 30 A/m. At areas of the body not prescribed for treatment, field strengths varied from 20 to 4000 V/m and 0.2 to 14 A/m. Another investigator [Stuchly et al., 1982] found that electric and magnetic field strengths at untreated areas of the patient ranged from 4 to 2650 V/m and 0.05 to 1.6 A/m.

VERY HIGH FREQUENCY: 30 TO 300 MHz

The VHF frequency range is from 30 to 300 MHz with corresponding wavelengths of 10 to 1 m. Common sources include FM radio and VHF television broadcast stations. This frequency range is also popular for two-way voice communications. Note that at VHF and higher frequencies, transmitter towers are only support structures for antennas and not an active part of the antenna. Figure 5 shows the range of fields and population exposure for some VHF sources.

FM Radio Broadcast

The median electric field strength reported in urban areas in the United States from FM broadcast services (88 to 108 MHz) is about 0.1 V/m with 0.5% of the population exposed to field strengths above 2 V/m [Tell and Mantiply, 1980; Hankin, 1986]. The maximum electric field strengths at ground level beneath FM towers in the United States vary from about 2 to 200 V/m [Gailey and Tell, 1985; U.S. EPA, 1987]. One measurement, made on a rooftop directly below an antenna mounted 2 m above the roof, yielded an electric field strength of 800 V/m [unpublished data]. Measured fields on the transmitter tower varied from 60 to 900 V/m [Tell, 1976; Mild, 1981]; even higher electric field strengths exist within 30 cm of an antenna element. Magnetic field strengths up to 4.6 A/m have been reported near an element radiating about 300 watts in Sweden [Mild, 1981]. The power radiated from single antenna elements on U.S. towers is typically 5 kilowatts.

Fields from FM broadcast antennas are not intentionally amplitude modulated, but transmitter power supply imperfections can cause amplitude modulation (AM). In one case, significant 120 Hz AM was detected on an FM signal. Measurements on 10 FM radio stations showed amplitude modulation from 1 to 5% for frequencies between 3 and 100 Hz [unpublished data].

VHF Television Transmitters

The VHF television channels are separated into low band VHF-TV (channels 2 through 6) at 54 to 88 MHz and high band VHF-TV (channels 7 to 13) at 174 to 216 MHz. Calculations based on measurements in the late 1970s [Tell and Mantiply, 1980] showed that about 16% of the population were exposed to fields above 0.1 V/m and 0.1% were exposed to fields above 2 V/m due to low band VHF-TV. For high band VHF-TV, 32% of the population were exposed to electric field strengths above 0.1 V/m and about 0.005% were exposed to fields above 2 V/m. The maximum fields at ground level beneath VHF-TV towers are estimated to be between 1 and 30 V/m [Gailey and Tell, 1985]. Measured electric and magnetic field strengths on a transmitter tower adjacent (less than 30 cm) to a VHF-TV antenna radiating 4 kW were usually about 430 V/m and 2 A/m. Electric field strengths up to 900 V/m were seen in some cases [Mild, 1981].

The television signal consists of an amplitude-modulated video signal and a frequency-modulated audio signal. Amplitude modulation of 4 to 12% was measured for nine TV video signals at 59.94 Hz (the vertical retrace rate) [unpublished data].

Mobile Transmitters

Studies have been made of electric fields associated with VHF mobile transmitters in various motor vehicles with different antenna configurations [Lambdin, 1979; Adams et al., 1979]. Tests made with a 60 W, 164 MHz frequency-modulated radio resulted in electric field strengths ranging from 3.4 to 30 V/m, whereas tests made with a 100 watt, 41 MHz radio resulted in electric field strengths from 3.4 to 120 V/m near an occupant. Tests using 100 watt FM radios at 25, 35, 39, 51, and 145 MHz in a mid-size automobile resulted in fields from 50 to 150 V/m [Muccioli and Awad, 1987]. These fields were measured with the transmitter keyed and no correction for duty

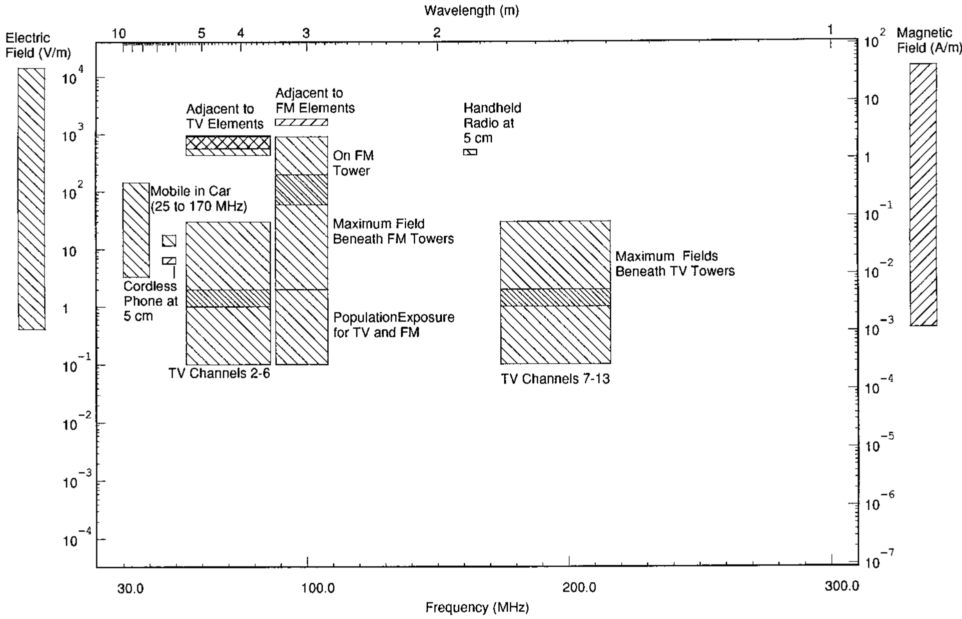

Fig. 5. Very-high frequency band.

cycle. The highest electric field strengths are normally seen near the occupant's head or the driver's hands. Magnetic field strengths were not reported. The replacement of metal with plastic and fiberglass in the bodies of newer vehicles can reduce shielding from an external antenna and increase occupant exposure.

Portable Transmitters

Electric and magnetic field strengths near handheld transmitters were measured by searching for the maximum unperturbed field 5 cm from any surface of the unit [unpublished data]. The largest electric and magnetic field strengths were typically found near the base of the antenna. The maximum electric and magnetic field strengths found near a 10 μW cordless telephone handset operating at 50 MHz were 15 V/m and 18 mA/m. Maximum fields near a 2 W handheld radio operating at 164 MHz were 470 V/m and greater than 0.73 A/m. As discussed in the introduction, these devices produce highly localized near-fields that may not couple well to the user and any comparison with safety standards requires dosimetric evaluation of SAR. That is, it is inappropriate to compare these fields with the corresponding field limits found in safety criteria.

ULTRA-HIGH FREQUENCY: 300 MHz TO 3 GHz

Use of the UHF frequency range of 300 MHz to 3 GHz (100 to 10 cm wavelength) includes UHF television, cellular telephone, microwave ovens, microwave diathermy, and air traffic control radar. Figure 6 shows the range of fields measured for several common UHF sources.

UHF Television Transmitters

The UHF-TV channels 14 to 67 operate in the frequency range of 470 to 806 MHz. Typical transmitter powers are on the order of 30 kW, with effective radiated powers (power into the antenna times the antenna gain over a dipole) of up to 5 MW. General-population exposure calculations showed that about 20% of the population was exposed to fields above 0.1 V/m and about 0.01% was exposed above 1 V/m [Tell and Mantiply, 1980]. Maximum electric fields at about a quarter wavelength above grade beneath UHF-TV towers were estimated to be between 1 and 20 V/m [Gailey and Tell, 1985; Hankin, 1986]. The maximum measured electric field strength near an antenna element was 620 V/m [Mild, 1981]. The modulation for UHF-TV is the same as for VHF-TV.

Cellular Telephones

Cellular base station transmitters in the United Staes operate in the frequency band of 869 to 894 MHz. Electric field strengths have been measured at about a meter above grade beneath base station antenna towers ranging in height from 46 to 82 m [Petersen and Testagrossa, 1992]. For simultaneous operation of up to 16 channels, the maximum electric field strength was found to be between 0.1 to 0.8 V/m. Portable and

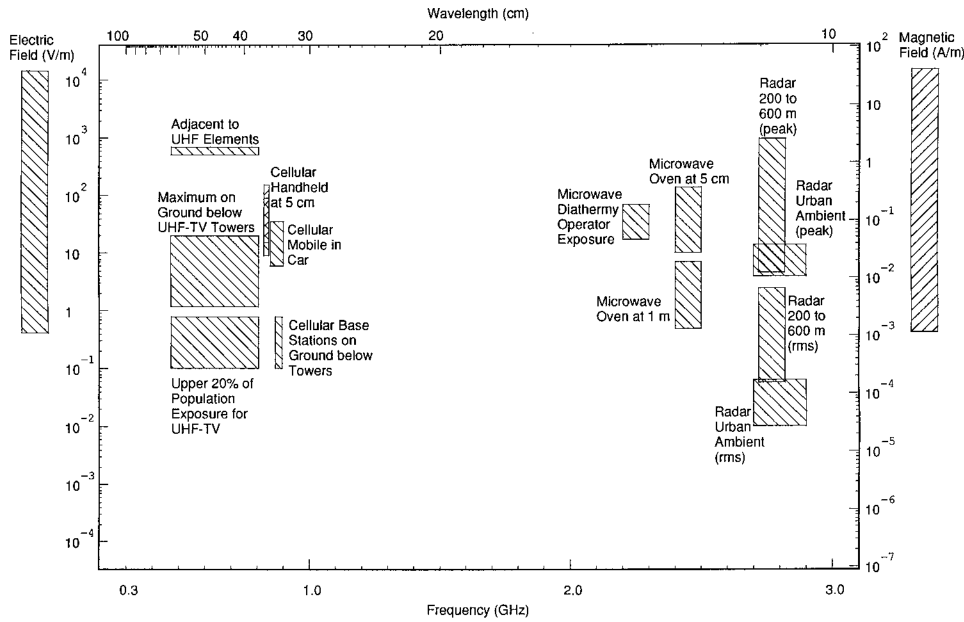

Fig. 6. Ultra-high frequency band.

mobile cellular telephones transmit in the frequency band of 824 to 849 MHz. The fields measured inside a car using an external antenna and 3 W transmitter were between 6 and 36 V/m [Balzano et al., 1986]. For handheld cellular phones, maximum fields of 9.4 to 94 V/m and 41 to 410 mA/m were calculated at a distance of 5 cm from the antenna for a variable power of 6-600 mW (current practice). This calculation is a simple scaling from measurements for an 800 mW fixed power phone [Balzano, 1984]. In that measurement, the maxima in both the electric and magnetic field strengths were found at the antenna base. As noted previously, these devices produce highly localized near-fields, and comparison with safety standards requires dosimetric evaluation of SAR.

These cellular telephone studies were made on systems using conventional frequency modulation, not the newer digital modulated systems. Note that the highest-frequency device for which the magnetic-field value is given in this paper is the handheld cellular phone. For sources operating at higher frequencies (and at many lower frequencies) only the electric field strength was measured. Also, as specified in the introduction, electric field strength may be converted to equivalent power density.

Microwave Ovens

Most household microwave ovens operate at 2.45 GHz and an RF power of about 600 W. Essentially all field measurements have been made at a distance of 5 cm from the oven and range from about 10 to 140 V/m [Mild and Lovstrand, 1990].

The electric field strengths 1 m in front of a microwave oven are estimated to range from 0.5 to 7 V/m, with typical values of 1 to 2 V/m when the oven is in use (with a typical load). The 1 m estimates are based on the 5 cm measurements, with the field decreasing by 1/r (where r is the distance from the front of the oven), which may be inaccurate if the physical size of the leaking area is large. However, this ''point source'' approximation has been previously justified [Osepchuck, 1979; Reynolds, 1989]. Microwave-oven fields vary in time in several ways. The field is amplitude modulated at 60 Hz because of the power supply. Operation of the field stirrer, changes in the load, such as boiling, and cycled low-power operation also amplitude modulate microwave oven fields.

Microwave Diathermy

Electric field strengths measured at the operator's location for a 2.45 GHz microwave diathermy system were between 17 and 70 V/m [Ruggera, 1980]. These values are lower than those reported for HF diathermy (2-315 V/m) because the shorter-wavelength fields are easier to control.

Pulsed Radar

Conventional pulsed radar emits a microwave pulse that is reflected from a target and returns before the radar antenna rotates significantly. The distance and bearing to the target are determined from the time delay and antenna azimuth respectively. The pulsing and antenna rotation cause a large difference between peak and rms field strengths. For a typical air traffic radar, a 1-μs pulse is transmitted every 1000 μs, resulting in a pulse duty factor of 0.001. Also, the antenna rotates every 5 or 12 s and the horizontal width of the beam is about 3°, resulting in a 3°/360° duty factor for a full rotation. The total duty factor, which is the product of the rotation and pulse duty factors, is about 8 x 10^{-6}; therefore, the peak power density is 1.2×10^5 times higher than the average power density. Because the field strength is proportional to the square root of the power density, the peak field during the pulse while the narrow radar beam is directed at a measurement point is about 350 times higher than the rms field when pulsing and rotational factors are taken into account.

The peak-to-rms ratio is less in the near field or below the radar, where the radar beam is not well defined. Air traffic radars generally operate at about 1.3 or 2.8 GHz. The electric field strength measured at several locations at distances of 200 to 600 m from air traffic radars [Tell and Nelson, 1974a] were from 57 mV/m rms or 4.7 V/m peak to 2.5 V/m rms or 960 V/m peak. The results of measurements of all detectable radars operating from 1.3 to 9.5 GHz at three randomly chosen sites in the San Francisco area [Tell, 1977] were rms electric field strengths ranging from 10 to 64 mV/m and peak electric field strengths for any one radar of 4 to 14 V/m.

SUPER-HIGH FREQUENCY: 3 TO 30 GHz

The microwave SHF band from 3 to 30 GHz (wavelength of 10 to 1 cm) includes such sources as terrestrial microwave relays, satellite relay uplinks, onboard aircraft radars, and police traffic radars. Figure 7 shows measured fields for some of these sources.

Microwave Relay

Terrestrial point-to-point microwave radio is typically used to relay telephone traffic and data using frequency modulation with transmitter powers of about 1 W. The operating frequency varies for long-haul service from 2 to 13 GHz in several bands. Electric field strengths at ground level beneath microwave relay towers are in the range of 20 mV/m to 0.6 V/m [Petersen, 1980; Hankin, 1986].

Satellite Communications Uplinks

RF fields generated by a number of satellite uplink transmitters were measured in the community of Vernon, New Jersey [U.S. EPA, 1986]. Typical uplink transmitter powers are about 1 kW. In the 6 GHz band, fields varied from 70 V/m to 15 mV/m; in the 14 GHz band, from 0.2 to 33 mV/m. On a hill in front of one dish operating at a low elevation angle at 6 GHz, the electric field strength varied from 2.4 to 15 V/m. Calculations have shown that the maximum on-axis electric field strengths for individual satcom uplinks can range from 22 to 610 V/m [Hankin, 1986].

Aircraft Onboard Weather Radars

Measurements made in front of several aircraft onboard weather radars at 9.375 GHz typically showed rms fields ranging from 20 V/m at 10 m to 200 V/m at 10 cm. The calculated peak electric field strength in front of these radars was 19 kV/m [Tell and Nelson, 1974b; Tell et al., 1976]. Individuals could be exposed to these field strengths if the radar is operated while the aircraft is on the ground.

Police Traffic Radar

The maximum field in the transmitting aperture of police traffic radar units has been measured for some 5000 devices [Fisher, 1993]. For handheld 10.5 GHz units, the aperture field varied from 33 to 120 V/m; for 24 GHz units the aperture field varied from 27 to 125 V/m. Operator exposure was estimated to be from 1 to 15 V/m if the unit was pointed away from the operator. Fields at a distance of 30 to 300 m in front of these radars varied from about 1 to 0.1 V/m [Hankin, 1976]. Police radar units can be operated continuously and are not modulated.

DISCUSSION

Figure 8 is a compression of the data previously shown for each band. The major peaks represent the following measurement results: adjacent to omega and loran antenna feeds at about 10^{-2} and 10^{-1} MHz; for operators of industrial induction heaters and heat sealers at about 0.3 and 30 MHz; at the radiating elements of TV and FM antenna systems shown at about 70 and 100 MHz; for near fields at the antennas of handheld transmitters for CB, commercial use, and cellular telephone at about 30, 200, and 800 MHz; at the surface of some microwave ovens at about 2450 MHz, and for patients and operators of medical electrosurgical and diathermy equipment at about 2.4, 27, and 2450 MHz. These maxima represent real or potential exposures that are either occupational or voluntary.

In the occupational setting, there has been more characterization of exposure for industrial equipment operators than for workers at transmitter sites such as tower climbers and radar maintainers. However, transmitting antennas, which are engineered to intentionally generate fields, are relatively easy to characterize. Inci-

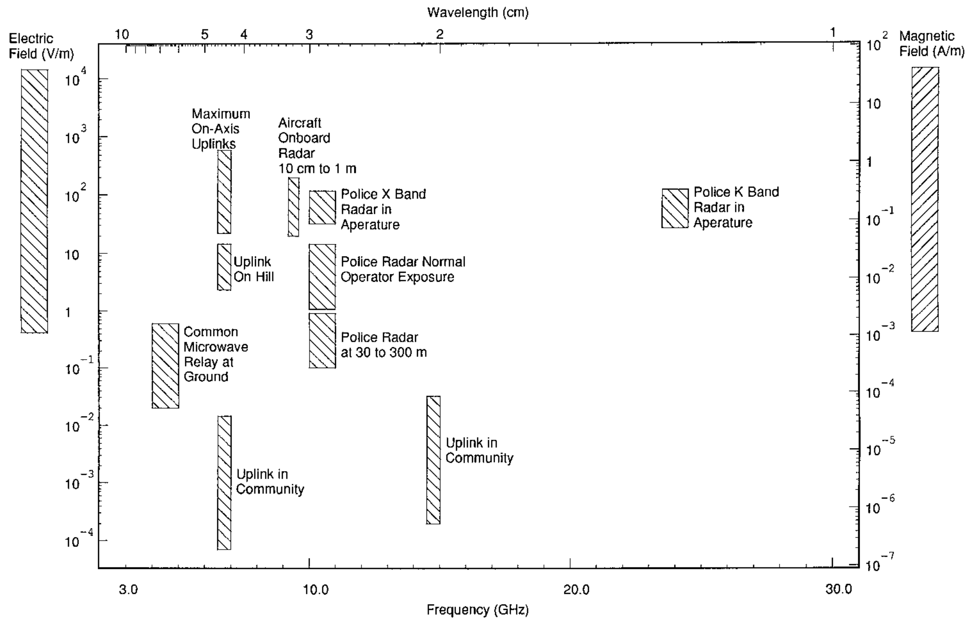

Fig. 7. Super-high frequency band.

dental sources such as video displays, microwave ovens, or industrial heaters require significant testing and statistical evaluation to determine exposure. Also, incidental and heating sources have no requirement for modulation control, so modulation (if of interest) must also be tested more extensively.

In the public environment, relatively high fields are reported at the base of some high-power AM and FM radio towers (shown at about 1 and 100 MHz). In the FM case, fields are more variable from one installation to the next because of differences in the height and radiation pattern of the antenna mounted on the tower. In the AM case, the tower is the antenna, so approaching the tower base results in a rapid climb in

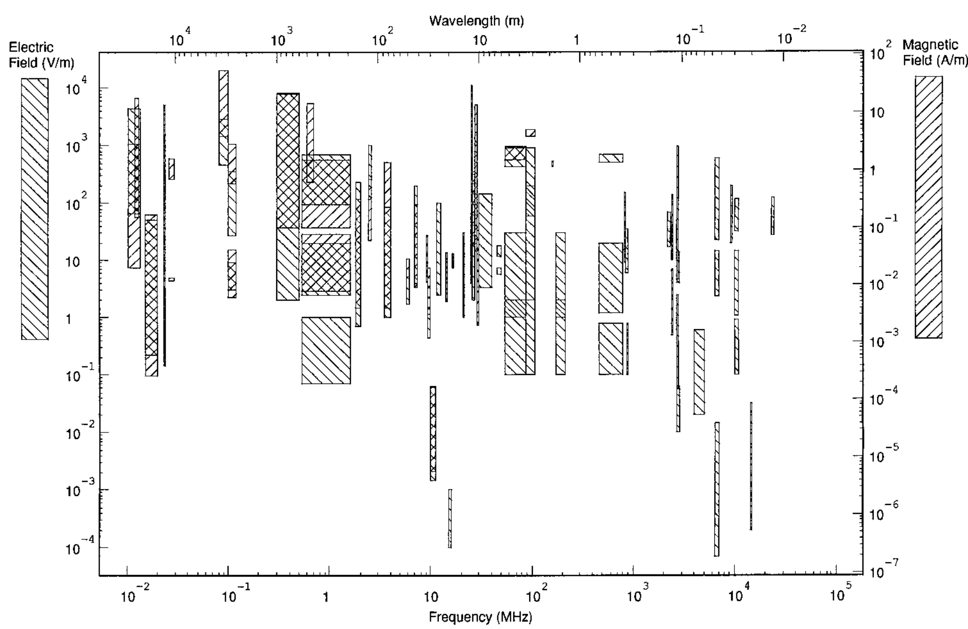

Fig. 8. Summary for all bands.

field strength that depends on transmitter power and tower impedance. TV transmitter antennas tend to be mounted higher on the tower and have more controlled patterns to illuminate the horizon, so that fields at the tower base are less than might be expected, especially for UHF-TV stations. If time-domain peak fields are considered, air traffic radars may generate relatively high field strengths out to several hundred meters (shown at about 3 GHz).

In the low-exposure general urban environment, peak fields due to air traffic radars may be significantly higher than peak (or rms) fields due to broadcast radio or TV. Some sources that generate only very weak fields in the public environment, such as cellular phone base stations, terrestrial microwave relay, and fixed satellite uplinks seem to have received an inordinate amount of attention and study.

ACKNOWLEDGMENTS

We thank J.A. Elder, N.N. Hankin, and C.M. Petko for suggestions and encouragement on this project. Robert Trefethen had the right combination of editorial, clerical, and computer skills to bring this task to closure.

REFERENCES

Adams JW, Taggart HE, Kanda M, Shafer J (1979): ''Electromagnetic Interference (EMI) Radiative Measurements for Automotive Applications.'' Boulder, Colorado: U.S. Department of Commerce, National Bureau of Standards.

Andreuccetti D, Bini M, Ignesti A, Olmi R, Rubino N, Vanni R (1988): Analysis of electric and magnetic fields leaking from induction heaters. Bioelectromagnetics 9:373–379.

Aniolczyk H (1981): Measurements and hygienic evaluation of electromagnetic fields in the environment of diathermy, welders, and induction heaters. Med Pr 32:119–128.

Balzano Q (1984): ''Dyna TAC Exposure Measurements.'' Plantation, Florida: Motorola Inc., Portable Products Division.

Balzano Q, Garay O, Manning T (1986): RF energy in cars from window-mounted antennas. Conference Record of the 36th Annual Conference, IEEE Vehicular Technology Group, Dallas, Texas, pp 32–40.

Bini M, Checcucci A, Ignesti A, Millanta L, Olmi R, Rubino N, Vanni R (1986): Exposure of workers to intense RF electric fields that leak from plastic sealers. J Microw Power 21:33–40.

Centaur Associates, Inc. (1982): Study of Radiofrequency and Microwave Radiation - Phase I. Washington, DC: National Technical Information Service Document No. PB83-191130.

Charron D (1988): ''Health Hazards of Radiation from Video Display Terminals: Questions and Answers.'' Hamilton, Ontario: Canadian Center for Occupational Health and Safety.

Cleveland RF, Mantiply ED (1996): ''Measurements of Environmental Electromagnetic Fields at Amateur Radio Stations.'' Washington, DC: Federal Communications Commission No. FCC/OET ASD-9601.

Conover DL, Parr WH, Sensintaffar EL, Murray WE (1975): Measurement of electric and magnetic field strengths from industrial radiofrequency (15–40.68 MHz) power sources. In Johnson CC, Shore ML (eds): ''Biological Effects of Electromagnetic Waves.'' Rockville, Maryland: HEW Publication (FDA).

Conover DL, Murray WE, Foley ED, Lary JM, Parr WH (1980): Measurement of electric- and magnetic-field strengths from industrial radio-frequency (6-38 MHz) plastic sealers. Proc IEEE 68:17–20.

Conover DL, Murray WE, Lary JM, Johnson PH (1986): Magnetic field measurements near RF induction heaters. Bioelectromagnetics 7:83-90.

Conover DL, Moss CE, Murray WE, Edwards RM, Cox C, Grajewski B, Werren DM, Smith JM (1992): Foot currents and ankle SARs induced by dielectric heaters. Bioelectromagnetics 12:103–110.

Cox C, Murray WE, Foley EP (1982): Occupational exposures to radiofrequency radiation (18-31 MHz) from RF dielectric heat sealers. Am Ind Hyg Assoc J 43:149–153.

Fisher PD (1993): Microwave exposure levels encountered by police traffic radar operators. IEEE Trans Electromag Compatibility 35:36–45.

Gailey PC (1987): ''Modeling and Measurement of Electromagnetic Fields Near Loran-C and Omega Stations.'' Oak Ridge, Tennessee: The EC Corporation.

Gailey PC, Tell RA (1985): ''An Engineering Assessment of the Potential Impact of Federal Radiation Protection Guidance on the AM, FM, and TV Broadcast Services.'' Las Vegas, Nevada: U.S. Environmental Protection Agency EPA 520/6-85-011.

Guy AW (1987): ''Measurement and Analysis of Electromagnetic Field Emissions from 24 Video Display Terminals in American Telephone and Telegraph Office.'' Washington, D.C., Cincinnati, Ohio: National Institute of Occupational Safety and Health.

Guy AW, Chou CK (1982): Hazard Analysis: ''Low Frequency Through Medium Frequency Range.'' Brooks Air Force Base, TX: U.S. Air Force School of Aerospace Medicine.

Hankin NN (1976): ''Radiation Characteristics of Traffic Radar Systems.'' Silver Spring, Maryland: U.S. Environmental Protection Agency ORP/EAD-76-1.

Hankin NN (1986): ''The Radiofrequency Radiation Environment: Environmental Exposure Levels and RF Radiation Emitting Sources.'' Washington, DC: U.S. Environmental Protection Agency EPA 520/1-85-014.

Hietanen M, Kalliomaki K, Kalliomaki P-L, Lindfors P (1979): Measurements of strengths of electric and magnetic fields near industrial radio-frequency heaters. Radio Sci 14:31S–33S.

Jokela K, Aaltonen J, Lukkarinen A (1989): Measurements of electromagnetic emissions from video display terminals at the frequency range from 30 Hz to l MHz. Health Phys 57:79–88.

Joyner KH (1988): Measurement of electromagnetic radiation below 100 GHz. In Repacholi MH (ed): ''Non-ionizing Radiations: Physical Characteristics, Biological Effects and Health Hazard Assessment.'' Proceedings of the International Non-ionizing Radiation Workshop. London: International Radiation Protection Association Publications, pp 373–393.

Joyner KH, Bangay MJ (1986): Exposure survey of operators of radiofrequency dielectric heaters in Australia. Health Phys 50:333–344.

Kalliomaki PL, Hietanen M, Kalliomaki K, Koistinen O, Valtonen E (1982): Measurements of electric and magnetic stray fields produced by various electrodes of 27-MHz diathermy equipment. Radio Sci 17:29S–34S.

Kavet R, Tell RA (1991): VDTs: Field levels, epidemiology, and laboratory studies. Health Phys 61:47–57.

Lambdin DL (1979): ''An Investigation of Energy Densities in the Vicinity of Vehicles with Mobile Communications Equipment and Near a Handheld Walkie Talkie.'' Las Vegas, Nevada: U.S. Environmental Protection Agency ORP/EAD 79-2.

Mantiply ED (1992): ''Measurements of Electric and Magnetic Fields in the Waianae, Hawaii Area.'' Montgomery, Alabama: U.S. Environmental Protection Agency 400R-92-009.

Mantiply ED, Cleveland RF (1991): ''Electric and Magnetic Fields Near AM Broadcast Towers.'' Las Vegas, Nevada: U.S. Environmental Protection Agency EPA/520/6-91/020.

Mantiply ED, Hankin NN (1989): ''Radiofrequency Radiation Survey in the McFarland, California Area.'' Las Vegas, Nevada: U.S. Environmental Protection Agency EPA/520/6-89/022.

Marha K, Spinner B, Purdham J (1983): ''The Case for Concern About Very Low Frequency Fields from Visual Display Terminals: The Need for Further Research and Shielding of VDTs.'' Hamilton, Ontario: Canadian Center for Occupational Health and Safety.

Mild KH (1980): Occupational exposure to radio-frequency electromagnetic fields. Proc IEEE 68:12–17.

Mild KH (1981): Radiofrequency electromagnetic fields in Swedish radio stations and tall FM/TV towers. Bioelectromagnetics 2:61–69.

Mild KH, Lovstrand KG (1990): Environmental and professionally encountered electromagnetic fields. In Gandhi OP (ed): ''Biological Effects and Medical Applications of Electromagnetic Energy.'' Englewood Cliffs, New Jersey: Prentice Hall, pp 48–74.

Mild KH, Sandstrom M (1992): From VDT to radar/EM fields in our environment. First World Congress for Electricity and Magnetism in Biology and Medicine. Frederick, Maryland: W/L Associates.

Muccioli JP, Awad SS (1987): The electromagnetic environment of an automobile electronic system. IEEE Trans Electromag Compatibility 29:245–251.

Osepchuk JM (1979): A review of microwave oven safety. Microw J 22:25–37.

Petersen RC (1980): Electromagnetic radiation from selected telecommunications systems. Proc IEEE 68:21–24.

Peterson RC, Testagrossa PA (1992): Radio-frequency electromagnetic fields associated with cellular-radio cell-site antennas. Bioelectromagnetics 13:527–542.

Reynolds LR (1989): The history of the microwave oven. Microwave World 10:7–11.

Ruggera PS (1977): Near-field measurements of RF fields. In Hazzard DG (ed): ''Symposium on Biological Effects and Measurements of Radio Frequency/Microwaves.'' Rockville, Maryland: HEW publication (FDA).

Ruggera PS (1979): ''Measurements of Electromagnetic Fields in the Close Proximity of CB Antennas.'' Rockville, Maryland: U.S. Department of Health and Human Services, Bureau of Radiological Health.

Ruggera PS (1980): ''Measurements of Emission Levels During Microwave and Shortwave Diathermy Treatments.'' Rockville, Maryland: U.S. Department of Health and Human Services, Bureau of Radiological Health.

Schnorr TM, Grajewski BA, Hornung RW, Thun MJ, Egeland GM, Murray WE, Conover DL, Halperin WE (1991): Video display terminals and the risk of spontaneous abortion. N Engl J Med 324:727–733.

Stuchly MA (1977): Potentially hazardous microwave radiation sources: A review. J Microw Power 12:369–381.

Stuchly MA, Lecuyer DW (1985): Induction heating and operator exposure to electromagnetic fields. Health Phys 49:693–700.

Stuchly MA, Lecuyer DW (1987): Electromagnetic fields around induction heating stoves. J Microw Power 22:63–69.

Stuchly MA, Mild KH (1987): Environmental and occupational exposure to electromagnetic fields. IEEE Eng Med Biol 6:15–17.

Stuchly MA, Repacholi MH, Lecuryer DW, Mann RD (1980): Radiation survey of dielectric (RF) heaters in Canada. J Microw Power 15:113–121.

Stuchly MA, Repacholi MH, Lecuyer DW, Mann RD (1982): Exposure to the operator and patient during short wave diathermy treatments. Health Phys 42:341–366.

Stuchly MA, Repacholi MH, Lecuyer DW, Mann RD (1983): Radiofrequency emissions from video display terminals. Health Phys 45:772–775.

Tell RA (1976): ''A Measurement of RF Field Intensities in the Immediate Vicinity of an FM Broadcast Station Antenna.'' Washington, DC: U.S. Environmental Protection Agency ORP/EAD-76-2.

Tell RA (1977): ''An Analysis of Radar Exposure in the San Francisco Area.'' Las Vegas, Nevada: U.S. Environmental Protection Agency ORP/EAD-77-3.

Tell RA (1990): ''An Investigation of Electric and Magnetic Fields and Operator Exposure Produced by VDTs: NIOSH VDT Epidemiology Study.'' Cincinnati, Ohio: National Institute of Occupational Safety and Health PB91-130500.

Tell RA, Mantiply ED (1980): Population exposure to VHF and UHF broadcast radiation in the United States. Proc IEEE 68:6–12.

Tell RA, Nelson JC (1974a): ''RF Pulse Spectral Measurements in the Vicinity of Several Air Traffic Control Radars.'' Silver Spring, Maryland: U.S. Environmental Protection Agency EPA-520/1-74-005.

Tell RA, Nelson JC (1974b): Microwave hazard measurements near various aircraft radars. Radiat Data Rep 15:161–179.

Tell RA, Hankin NN, Janes DE (1976): Aircraft radar measurements in the near field. Proceedings of the Ninth Midyear Topical Symposium of the Health Physics Society, Operational Health Physics.

Tell RA, Mantiply ED, Wagner P, Cleveland RF (1988): ''Radiofrequency Electromagnetic Fields and Induced Currents in the Spokane, Washington Area.'' Las Vegas, Nevada: U.S. Environmental Protection Agency EPA/520/6-88/008.

Tofani S, D'Amore G (1991): Extremely-low-frequency and very-low-frequency magnetic fields emitted by video display units. Bioelectromagnetics 12:35–45.

U.S. Environmental Protection Agency (1985): Radiofrequency Radiation Measurement Survey, Honolulu, Hawaii May 14-25, 1984. Las Vegas, Nevada: U.S. Environmental Protection Agency.

U.S. Environmental Protection Agency (1986): An Investigation of Microwave and Radiofrequency Radiation Levels in Vernon Township, New Jersey. Las Vegas, Nevada: U.S. Environmental Protection Agency .

U.S. Environmental Protection Agency (1987): An Investigation of Radiofrequency Radiation Levels on Lookout Mountain, Jefferson County, Colorado. Las Vegas, Nevada: U.S. Environmental Protection Agency.

Walsh ML, Harvey SM, Facey RA, Mallette RR (1991): Hazard assessment of video display units. Am Ind Hyg Assoc J 52:324–331.

Wang JC, Linthicum JM (1976): ''RF Field Intensity Measurements in Selected Broadcast Facilities.'' Washington, DC: Federal Communications Commission, Research and Standards Division.