IEEE Guide for the Measurement of Quasi-Static Magnetic and Electric Fields

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Abstract: A listing of possible measurement goals related to characterizing quasi-static magnetic and electric fields and possible methods for their accomplishment is provided.
Keywords: measurement protocols, power frequency, power frequency harmonic fields, quasi-static magnetic and electric fields

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Introduction

(This introduction is not part of IEEE Std 1460-1996, IEEE Guide for the Measurement of Quasi-Static Magnetic and Electric Fields.)

As an aid for groups and individuals interested in developing magnetic and/or electric field measurement protocols, this guide describes different magnetic and electric field measurement methods that can accomplish specific measurement goals. A single measurement approach is not given because the measurement strategies and instrumentation requirements will differ depending on the measurement environment of interest and the goals of a measurement program. For example, the measurement protocols and instrumentation for characterizing electric and magnetic fields from power lines will differ significantly from those for characterizing fields from video display terminals.

Frequent reference is made to a companion document for this guide: IEEE Std 1308-1994, IEEE Recommended Practice for Instrumentation: Specifications for Magnetic Flux Density and Electric Field Strength Meters—10 Hz to 3 kHz. IEEE Std 1308-1994 describes the types of available instrumentation used for measuring quasi-static magnetic and electric fields, their principles of operation, definitions of terminology, calibration procedures, and sources of measurement uncertainty.

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IEEE Guide for the Measurement of Quasi-Static Magnetic and Electric Fields

1. Overview

This guide is divided into six clauses. Clause 1 provides the overview, Clause 2 lists other standards that are useful in applying this guide, and Clause 3 describes the characteristics of quasi-static magnetic and electric fields that are candidates for measurements. The text for Clause 3 is taken from IEEE Std 1308-1994.[1] Clause 4 briefly describes the types of available quasi-static magnetic and electric field measuring instrumentation. Clauses 5 and 6 describe specific measurement goals related to characterizing quasi-static magnetic and electric fields, respectively, and possible measurement methods for their accomplishment. Throughout this guide, the terms "magnetic field" and "magnetic flux density" will be considered synonymous. Annex A provides a listing of bibliographical references cited.

This guide provides a listing of possible measurement goals related to characterizing quasi-static magnetic and electric fields and possible methods for their accomplishment. The fields of interest are typically produced by devices that operate at power frequency and that produce power frequency and power frequency harmonic fields, as well as devices that produce fields that are independent of the power frequency. The listings of possible goals and methods should not he considered as complete because there are many possible goals and methods for their accomplishment. The approach taken in this guide parallels a method described in [B3].[2]

Descriptions of instrumentation, their principles of operation, definitions of terminology, calibration procedures, and a listing of sources of measurement error are given in IEEE Std 1308-1994 and should be used with this guide. Protocols for measuring magnetic and electric fields near power lines and video display terminals are given in IEEE Std 644-1994 and IEEE Std 1140-1994.

[1]Information on references can be found in clause 2.
[2]The numbers in brackets preceded by the letter B correspond to those of the bibliography in Annex A.

2. References

This guide shall be used in conjunction with the following publications:

IEEE Std 539-1990, IEEE Standard Definitions of Terms Relating to Corona and Field Effects of Overhead Power Lines (ANSI).[3]

IEEE Std 644-1994, IEEE Standard Procedure for Measurements of Power Frequency Electric and Magnetic Fields from AC Power Lines (ANSI).

IEEE Std 1140-1994, IEEE Standard Procedures for the Measurement of Electric and Magnetic Fields from Video Display Terminals (VDTs) from 5 Hz to 400 kHz (ANSI).

IEEE Std 1308-1994, IEEE Recommended Practice for Instrumentation: Specifications for Magnetic Flux Density and Electric Field Strength Meters—10 Hz to 3 kHz (ANSI).

3. General characteristics of quasi-static magnetic and electric fields

Magnetic and electric fields produced by power lines, appliances, and other electrical equipment may be characterized according to magnitude, frequency, waveform (harmonic content), degree of polarization, spatial variation, and temporal variation.[4] These characteristics are described briefly because one or more of them may be selected for measurement, and because of their importance in specifying requirements for instrumentation used to measure the fields.

Several of the field parameters may be introduced by considering magnetic fields produced by currents in three-phase power lines. Some of the same parameters are also used to characterize electric fields. In general, the magnetic field at a point in space may be represented as a rotating vector that traces an ellipse for every cycle of the currents in the conductors, as shown schematically in Figure 1 (a) [B10]. The root-mean-square (rms) magnitude and direction of the semi-major axis, given by M in Figure 1 (a), indicates the magnitude and direction of the maximum magnetic field. Similarly, the rms magnitude and direction of the semiminor axis, given by m in Figure 1 (a), describes the minimum magnetic field. Such fields are said to be elliptically polarized.

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[3]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[4]This guide does not consider transient temporal variations, i.e., events that are fast compared to the periods of quasi-static magnetic and electric fields under consideration.

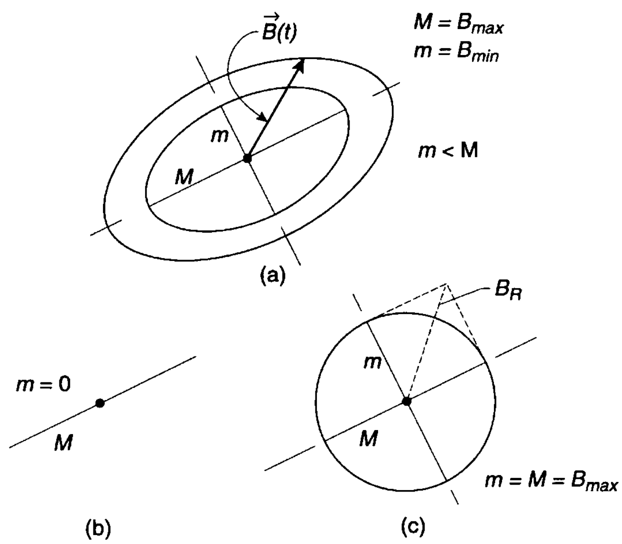


Figure 1— Oscillating and rotating magnetic field quantities for the cases of (a) elliptical *m<M*, (b) linear m=0, and (c) circular polarization *m =M*.

NOTE — The resultant, B_R, and the maximum magnetic field, *M*, are equal only for the case of linear polarization. The largest difference between the resultant and maximum magnetic field occurs for circular polarization, i.e., B_R exceeds *M* by 41%.

An often-measured field quantity is the resultant magnetic field. B_R, given by

$$B_R = \sqrt{B_x^2 + B_y^2 + B_z^2} \qquad (1)$$

where B_x, B_y, and B_z are the rms values of the three orthogonal field components. The differences between B_R and the maximum magnetic field, *M*, for different field polarizations are discussed in IEEE Std 1308-1994 and [B20] (see also Figure 1 of this guide).

Because magnetic fields in environments away from power lines also can be produced by multiple current sources that are not necessarily in phase, elliptically polarized magnetic fields can occur in many settings (e.g., homes and work places). Depending on the geometry and currents in the conductors, the degree of magnetic field polarization at a point can vary from linear ($m = 0$) to circular ($m = M$), as shown in Figure 1 (b) and (c). Linearly polarized fields are also referred to as single-phase alternating fields. This discussion of polyphase fields assumes that there are no harmonics in the field. The polarization state of fields with significant harmonic content is more complicated [B24, B32].

Near ground level, the magnitude of the magnetic field from a three-phase transmission line changes slowly as a function of the height of the measurement point above ground. For example, for a typical 500 kV line, the change in the magnetic field magnitude at a height of 1 m above ground level is less than 2% for a 10% change in the measurement height for locations underneath the line. The uniformity increases at more distant points. For locations far from the line, the magnitude of the magnetic field from a single circuit three-phase line, with balanced or nearly balanced currents, decreases approximately as $1/r^2$, where *r* is the lateral distance from the line (*r* is assumed to be much greater than the conductor spacing) [B29]. As the net current increases, the decrease in magnetic field magnitude changes from a $1/r^2$ to a $1/r$ dependence [B29, B38].[5] The magnetic field from balanced double-circuit, three-phase lines with low reactance phasing (i.e., for identical or nearly identical load currents for both circuits) decreases nearly as $1/r^3$ where *r* is again much larger than conductor spacing. The temporal variations of the magnetic field is a function

[5]The net current is given by the summation over *N* conductors, Σi_n where i_n is the current in the nth conductor and is characterized by its phase with respect to current in the other conductors, and its magnitude.

of load current variations, e.g., during heavy usage of electrical energy, the load currents increase and produce greater magnetic fields (the concurrent sagging of the conductors also can contribute to greater field levels at ground level).

Other commonly encountered sources of magnetic fields are straight conductors (e.g., connections to grounding systems/electrodes) and approximately circular turns of wire (e.g., found in transformers, motors, video display terminals, etc.) with single-phase currents. The magnetic field lines and vectors at representative points from such sources are shown schematically in (a) and (b) of Figure 2. The magnetic fields are typically linearly polarized and the time-dependence of the oscillating vectors depends on the waveform of the currents. Sinusoidal currents produce sinusoidal magnetic fields free of harmonics; nonsinusoidal currents (e.g., the sawtooth waveforms from television deflection coils) produce non-sinusoidal magnetic fields that can be rich in harmonics [B19]. The magnitudes of magnetic fields produced by currents in an infinitely long straight wire and a circular loop of wire decrease as $1/r$ [B16] and $1/r^3$ [B34], respectively, where r is the distance from the field source (in the latter case it is assumed that r is much greater than the radius of the circular loop of wire).

As noted above, some of the field parameters for magnetic fields also are used to describe quasi-static electric fields. For example, electric fields from three-phase transmission lines are, in general, elliptically polarized at points in space as shown in Figure 3. Because normally the sum of the charges on the conductors is zero, the electric field decreases as $1/r^2$ at distances that are large compared to the conductor spacing. As for the magnetic field from a straight conductor, the electric field from an energized straight conductor also decreases as $1/r$.

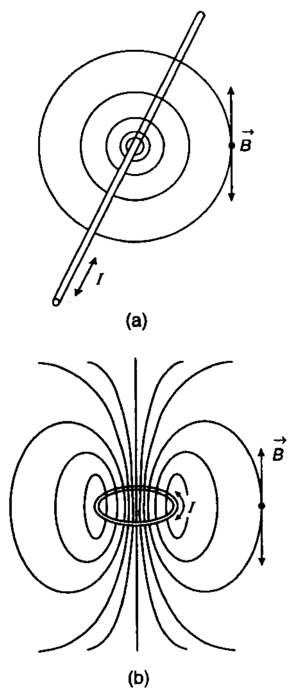


Figure 2— Magnetic field from current in (a) straight and (b) circular conductors

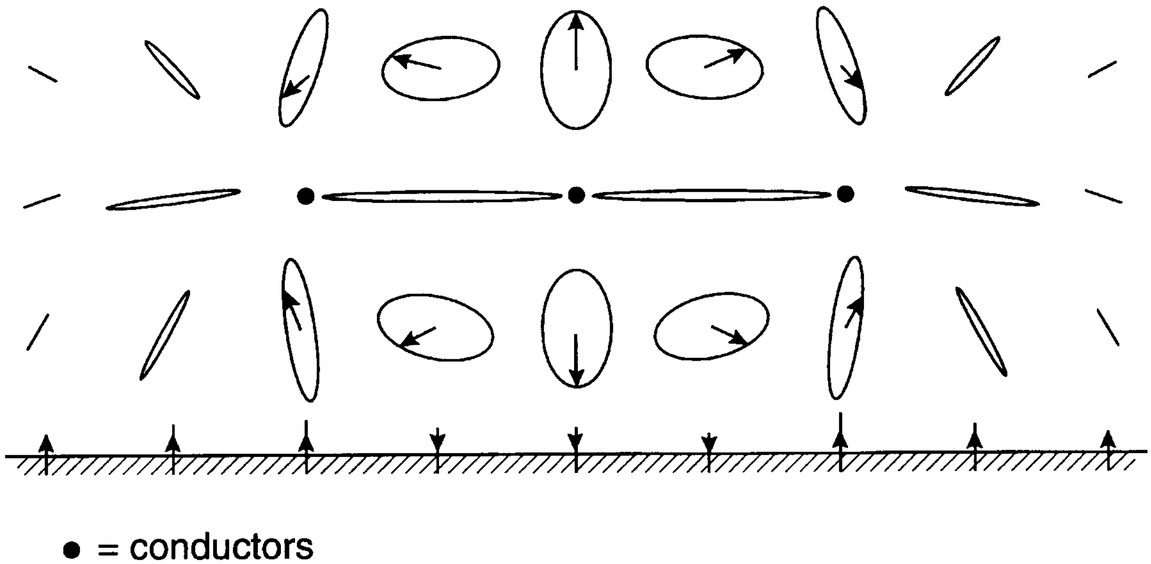


Figure 3— Electric field ellipses at representative points in vicinity of 3-phase transmission line (after [B9]) with conductors oriented perpendicular to page

4. Types of instrumentation

A range of instrumentation exists for characterizing quasi-static magnetic and electric fields. Only a brief listing is presented here. IEEE Std 1308-1994 should be consulted for further details regarding their use and principles of operation.

4.1 Magnetic field meters

The rms values of magnetic fields may be characterized with survey meters with different pass bands and dynamic range. Magnetic field meters are available with single- and three-axis coil probes or sensors. Single- and three-axis fluxgate magnetometers are also available and are able to measure alternating and static fields. Miniature three-axis field meters with on-board memory for periodically recording field levels have been developed for determining human exposure and also have been used as survey meters. Similarly, miniature three-axis meters have been developed to record the time integral of the magnetic field for human exposure purposes [B22]. Three-axis wave capturing systems are available that simultaneously record the field waveform in three orthogonal directions and provide rms (or peak, average, etc.) field values, polarization information, and frequency content [B32]. The probes of magnetic field meters may be held by hand without proximity effects of the observer under normal conditions. A simple example of a single-axis survey meter consisting of an electrically shielded coil probe and voltmeter detector is shown in Figure 4. Historically, single-axis magnetic field meters have been used to measure the maximum magnetic field at a point by rotating the probe until a maximum reading is observed. For temporally-stable magnetic fields (i.e., stable rms values), the single-axis magnetic field meter can also be used to measure the resultant magnetic field.

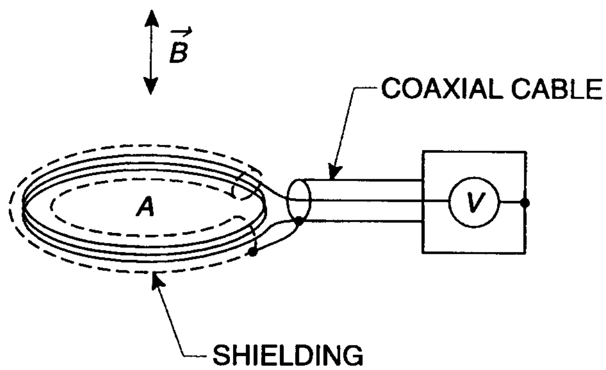


Figure 4— Schematic view of simple magnetic field meter with coil-type probe

4.2 Electric field meters

Electric field meters are of three types: free-body meters, ground reference meters, and electro-optic meters. Electric field meters used to measure quasi-static fields are typically single-axis devices, although three-axis meters are becoming available. Free-body meters are normally battery-operated, electrically isolated from ground potential, supported in the field at the end of an insulating rod, and may be used to measure fields at most locations above the ground plane. Geometries of commercial single-axis, free-body electric field meters are shown in Figure 5.

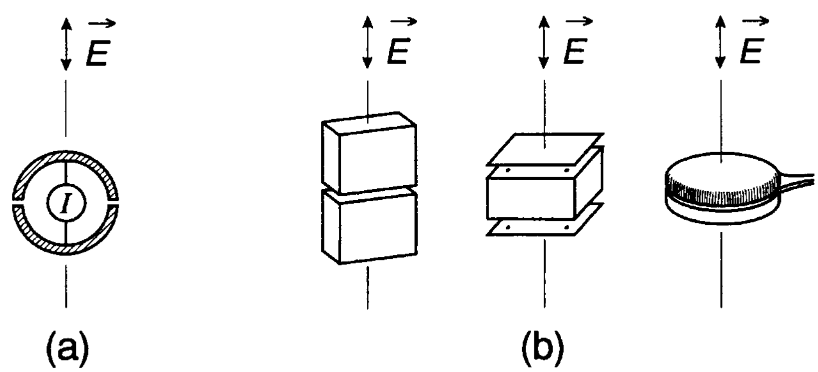


Figure 5— (a) Spherical free-body electric field meter;
(b) geometries of commercial U.S. electric field meters

Ground-referenced electric field meters are normally used to measure the electric field strength on grounded conducting surfaces (including the surface of the earth). One notable exception is the use of ground-referenced electric field meters to measure perturbed electric fields near video display terminals (VDTs), as described in IEEE Std 1140-1994 and [B28].

Although the principle of operation of electro-optic field meters differs from free-body meters, it is used in a similar fashion to measure the field at most locations above the ground plane. All of the noted electric field meters are susceptible to proximity effects. The observer is a major source of proximity error as discussed in IEEE Std 1308-1994. The proximity of other objects can also affect the field meter reading.

5. Magnetic field measurements

5.1 Goals and methods

As noted in Clause 3, magnetic (and electric) fields can be characterized according to a number of parameters, i.e., magnitude, frequency, polarization, etc. Characterization of one or more of these parameters and how they might relate to human exposure may serve as possible goals of a measurement program. This clause provides a listing of such possible measurement goals and possible methods for their accomplishment. The listing should not be considered as complete since there can be a wide variety of goals and methods. While outside the scope of field parameters considered in this guide, characterization of static magnetic fields may also be of interest.

It is extremely important that the goals of a measurement program such as those considered below be clearly defined at the outset. A clear definition of goals is required for determination of instrumentation and calibration requirements, e.g., instrumentation pass band, dynamic range, frequency calibration points, etc. Once the goals have been identified and appropriate instrumentation has been acquired, a pilot study in the measurement environment of interest is often desirable before decisions on final measurement methods and associated protocols are made. The protocol will describe the step-by-step procedure that should be followed, using the possible methods indicated, to accomplish the measurement goals. The protocol may explicitly indicate such things as instrument requirements, (e.g., pass band, probe size, magnitude range), location of measurements and duration of measurements. It should be possible, using the same protocol, to compare with confidence measurement results obtained in similar electrical environments, for example, two substations.

This guide is not detailed in its descriptions of measurement methods and protocols because of their dependence on the goals and because of significant differences that will be encountered in various measurement environments. When developing a protocol, the following sources of magnetic fields and items should be considered, when applicable:

— Electrical sources serving the facility
— Types and locations of transformers
— Locations of main cables and breakers
— Magnitude of supply voltages, periods of peak power use
— Frequencies (including dc) of power supplies and electrical devices
— Location of people relative to known field sources
— Presence of any motors and generators
— Presence of small heaters
— Any electrical device with coils of wire
— Grounding systems and connections

Decisions should be made regarding permissible uncertainty during calibration of the instrumentation, and total uncertainty during measurements. IEEE Std 1308-1994 describes uncertainties associated with the calibration process and uncertainties during measurements. Sketches of areas and locations where measurements will be made are often very useful. Electrical diagrams of buildings may be helpful in identifying sources of fields in office and similar buildings, although excessive reliance on such documentation should be avoided because of unrecorded changes in the building electrical system. While many sources of magnetic fields are visible, e.g., overhead lighting or electrical appliances, others are not, e.g., electrical equipment in adjacent rooms or on upper or lower floors. During pilot studies, decisions may be made regarding spacing between measurements, measurement locations, sample size, formats of data sheets, questionnaires for job/task classification, etc. If determining human exposure is the goal of the measurements, examination of measurement procedures as described in the epidemiological studies cited below, is strongly recommended as part of the process for developing a final measurement protocol.

While providing guidance for determining human exposure or estimates of human exposure to one or more magnetic field parameters is a major goal of this guide, other measurements goals with related applications exist. For example, "before" and "after" spatial distribution measurements of magnetic fields to check the effectiveness of power line field mitigation techniques, and spatial distributions of fields from electrical appliances are possible applications. For each goal, the frequency pass band of the instrumentation is chosen for the frequency or frequencies of interest [see 5.1, g)].

Possible goals and methods are as follows:

a) *Goal: characterization of magnetic field levels.* Limits on permissible magnetic field levels as a function of frequency have been indicated in a number of documents [B1, B5, B21] necessitating the determination of field levels with the greatest magnitude in specified areas.

   Method: Single-axis and three-axis meters may be used to make spot measurements of the maximum and resultant magnetic fields, respectively. The difference between the resultant and maximum magnetic field values is discussed in IEEE Std 1308-1994 and can be as much as 41% (see Figure 1). Guidance exists for measurements near power lines (IEEE Std 644-1994) and VDTs (IEEE Std 1140-1994, [B28]). Spot measurements near power lines may be correlated with load currents and estimates of magnetic fields for different load currents may be made. Load currents for appliances are constant, or else typically cycle through a fixed range in a relatively short time, permitting the determination of the largest maximum or resultant magnetic field with relatively few spot measurements.

   In environments away from power lines and appliances where correlations with magnetic field source currents are not readily made, spot measurements represent only a coarse characterization of field levels because they fail to capture the temporal variations of the field [B19, B20]. If more definitive measurements of the magnetic field are required, magnetic field meters with recording capability may be used at locations of interest for times thought to be representative for producing the full range of field values. For example, in residences this might involve several 24-hour records repeated during each season of the year [see 5.1, c)].

b) *Goal: Characterization of spatial variations.* The spatial distribution of magnetic fields away from power lines or single identifiable sources is typically unknown. For example, Figure 6 shows scatter plots of center-of-room measurements (vertical magnetic field, chest high) versus measurements at other locations in living rooms and kitchens during a survey of 77 residences [B33]. While the field levels at different locations were not determined at the same instant, the data are indicative of possible variations in the same room of residences. Alternating magnetic fields in most environments will be nonuniform because of the spatial dependence of the fields from the source currents. It is noteworthy that static magnetic fields also show considerable spatial variability in residences [B35].

   Method: Spatial variation measurements require the recording of the magnetic field components as a function of coordinate position. Standards exist for carrying out such measurements near power lines (IEEE Std 644-1994) and VDTs [IEEE Std 1140-1994, B28]. While such measurement may be made with survey meters, instrumentation incorporating measurement wheels is available for characterizing spatial distributions of magnetic fields in environments where physical obstructions do not hinder movement of the wheel. As the wheel rotates, it periodically triggers a three-axis magnetic field meter to record the resultant magnetic field at a fixed height above the ground or floor. Software provided with such instrumentation permits the generation of plots of magnetic field profiles, equifield contours, statistical analyses of the field levels, etc. As is the case for a), such data will not capture the temporal variations of the field profiles without repeated measurements.

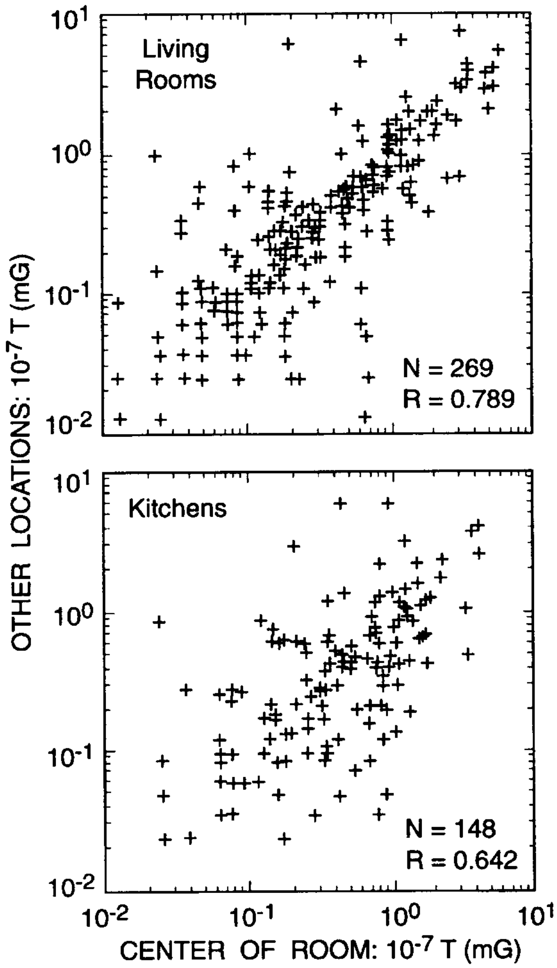


Figure 6— Scatter plots showing magnetic field at center of room versus other points in same room for living rooms and kitchens during survey of 77 homes [B32].

NOTE — One measurement is performed at the center of the room (abscissa) and the other measurement is performed elsewhere (ordinate) with the location unspecified.

c) *Goal: Characterization of temporal variation.* Because magnetic fields are produced by load currents and ground return currents that can vary greatly with time, the temporal variations of magnetic fields can easily exceed 100%. For example, Figure 7 shows 24-h histories of the background resultant magnetic field at the center of a living room in a metropolitan area on two days during which load currents varied significantly because of weather conditions and the associated use of air conditioning in residences and places of business [B20]. The data were recorded with an exposure meter every 15 s at a height of 1 m above the floor and the pass band was adequate to characterize the fundamental and power frequency harmonics. Figure 7 (a) shows measurements during a hot, humid day when air conditioners were presumably in heavy use. Field measurements at the same location during a cool, less humid day, shown in Figure 7 (b), reveal a significantly different distribution of field values with an average field about one-half that observed on the hot, humid day. The data, while anecdotal in the sense that measurements were performed in only one residence, is indicative of what can occur when there are significant changes in load currents. A mechanism that can produce short term temporal variations of the magnetic field is the movement of ferromagnetic objects (e.g., automobiles and trucks), past the measurement location.

Method: Three-axis and single-axis magnetic field meters are available with output connections that may be used in combination with commercially available data loggers to record magnetic fields at one or more locations as a function of time. Three-axis exposure meters and magnetic field waveform capturing instrumentation also may be used to periodically record field levels. Because of the dependence of magnetic field levels on load currents (which can vary by day, week, or season), the challenge is to determine a time interval for recording measurements that will capture enough variations of the field to obtain a valid statistical description. Conducting an initial pilot study in the measurement environment of interest can be useful for addressing the question of measurement sampling time.

An additional consideration should be taken into account when measurements are performed in electric mass transportation systems, or in other areas where there are variable speed motors. For example in subways, the magnetic field can be a function of the speed of the subway car [B13].

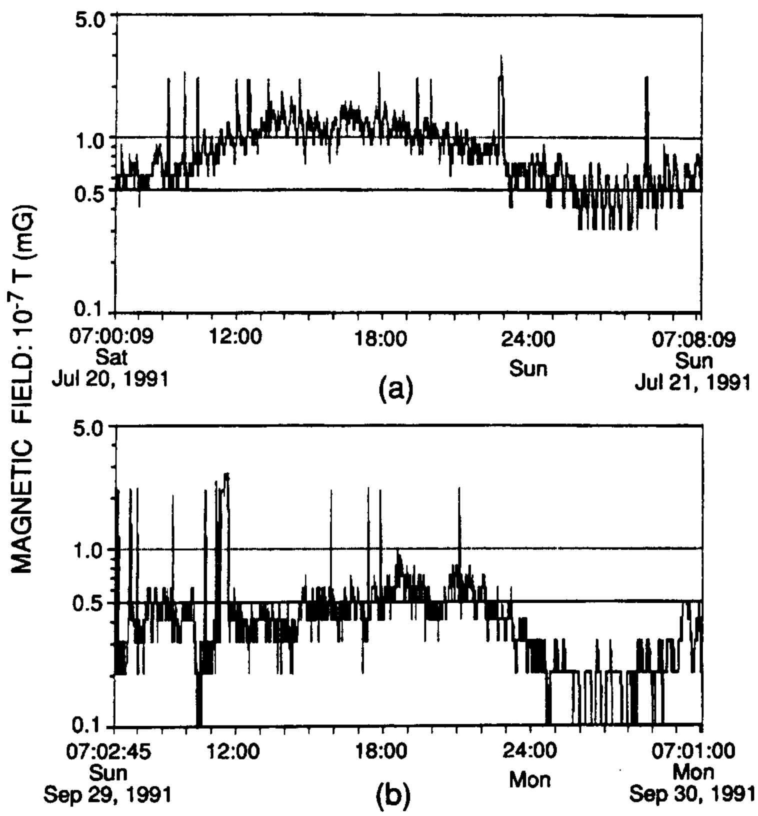


Figure 7— Twenty-four hour measurements of magnetic field at center of living room (a) during hot, humid weather and (b) during cool, dry weather

d) *Goal: Characterization of time-weighted-average (TWA) magnetic field.* A number of occupational and childhood cancer epidemiological studies that have examined the possibility of health effects from exposure to power frequency magnetic fields have considered the estimated TWA magnetic field as the candidate exposure "dose" or "metric" [B14, B23, B30, B37]. These and other studies have made determination of the TWA magnetic field a relevant measurement goal.

Method: Small three-axis exposure meters that are worn on the body and measure the time integral of the magnetic field may be used to measure the TWA magnetic field directly [B22]. Other three-axis exposure meters that record the magnetic field periodically may be used to determine the TWA magnetic field via analyses of the recorded field values. Less portable instrumentation combinations with recording capability can also be used to measure the TWA at locations of interest. Estimates of the annual TWA magnetic field have been calculated for residences from records of transmission line load currents and locations of the residences along the transmission line corridor [B14]. However, this approach does not include contributions to the field from local sources.

e) *Goal: Characterization of magnetic field intermittency.* Reports in the literature indicate that intermittent exposure to power frequency magnetic fields may be more effective in evoking certain biological responses than steady state fields [B7]. Such reports suggest that some index of the peaks and troughs (see Figure 7) of magnetic field levels may be a characteristic of the field that should be quantified.

Method: Field meters that can periodically measure and record the magnetic field should be used for accomplishing this goal. What is unclear is how frequently the field values should be recorded or over what time intervals should the field values be averaged. For example, measurements recorded every 15 s (Figure 7) will, in general, show more fluctuations than if hourly averages are used to characterize the fluctuations [B25].Bioeffects researchers may be consulted for guidance on how to define an index of fluctuations. Because of the availability of the recorded data, different indices of fluctuations may be calculated and reported, e.g., the number of field increases and decreases (exceeding some percentage value) using 1 min, 2 min, etc. average field values.

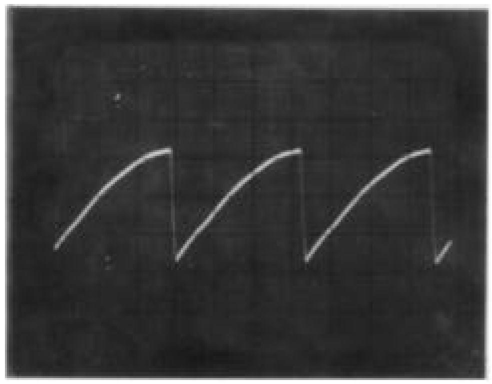
f) *Goal: Characterization of the incidence and duration of field levels exceeding a specified value.* Models that predict biological effects often assume that there is some threshold value of an agent below which, if applied, there is no effect. This model has its analogue for possible effects from exposures to magnetic fields.

Method: Field meters that periodically record the magnetic field may be used to accomplish this goal. The choice of what field level to use as a threshold value may require consultations with bioeffects researchers. As in e), the availability of recorded data allows the calculation and reporting of the frequency of occurrence of measured values that exceed more than one candidate threshold. Also, as for e), the results may depend on the frequency of recording the magnetic field levels.

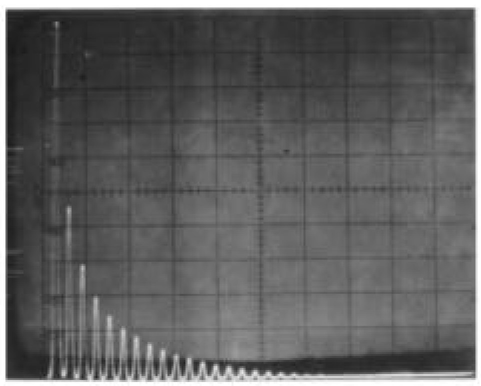
g) *Goal: Characterization of frequency content in magnetic field.* Since magnetic fields from electrical equipment often contain power frequency harmonics or frequencies unrelated to the power frequency, and magnetic field limits have been set as a function of frequency [B1], [B5], characterization of frequency content may be an important goal. An example of a magnetic field that is rich in harmonics and that is produced by a common electrical appliance is shown in Figure 8 (a). Figure 8 (a) illustrates a spot measurement of the extremely low-frequency (i.e., near 60 Hz) magnetic field waveform 60 cm from the front-center of an operating 26-in color television screen [B15]. The harmonic components in the field are shown in Figure 8 (b), which is a spectrum analyzer display for the waveform in Figure 8 (a). Harmonic components from the second (120 Hz), which amounts to 45% of the fundamental, to the nineteenth can be discerned. It is noteworthy that measurement of the rms value of this field with a field meter that only detects the fundamental component will be too low by more than 20%.

Method: Commercially available single-axis and three-axis magnetic field meters are sometimes provided with output connections that give the integrated signal from the probe. Such instrumentation, in combination with commercially available spectrum analyzers, may be used to characterize the frequency components in the magnetic field. Alternatively, wave-capturing instrumentation has software that allows the determination of the frequency content from the recorded data.[6] Three-axis instrumentation is also available that can be tuned to several harmonics of the power frequency. It should be noted that the frequency content of magnetic fields produced by variable speed electrical equipment, e.g., electric mass transportation systems, can change as a function of speed [B13].

[6]It is assumed that during such measurements, the frequency of sampling the waveform is adequate to avoid such problems as aliasing.



(a)



(b)

Figure 8— (a) Oscilloscope display of magnetic field waveform 60 cm from operating 26-in television screen; (b) normalized spectrum analyzer display for waveform in (a).

NOTE — In (a), the rms value of the field is 0.17 μT, vertical scale = 0.2 μT/div. horizontal scale = 5 ms/div. In (b), horizontal scale = 200 Hz/div.

h) *Goal: Characterization of magneticfield polarization* (see Figure 1). A full characterization of the magnetic field requires a determination of its polarization for a given frequency. The magnetic field polarization may be of interest within the context of human exposure because, for example, magnetic fields with different polarizations but the same resultant value can induce in biological systems electric fields and currents that are significantly different in terms of their temporal and geometric properties [B27].

Method: Single-axis field meters, three-axis field meters (that provide readings of an individual axis), and three-axis wave capturing systems all may be used to measure the rms values of the semi-major and semi-minor axes of the magnetic field ellipse to determine its polarization at a point in space. As previously noted, this procedure assumes that only a single frequency component of the magnetic field is being measured. With the presence of other frequencies, the rotating magnetic field vector no longer traces a simple ellipse [B24, B32]. Variations of the polarization as a function of time and location should be anticipated.

i) *Goal: Characterizing human magnetic field exposure.* This important goal has been placed at the end of the listing of goals in order to first describe the magnetic field parameters that may be of interest from the viewpoint of human exposure.

Method: A clear distinction should be made between characterizing one or more magnetic field parameters and exposure to those parameters. The latter is best determined by wearing a miniature field meter that periodically records the field parameter(s) of interest at a location of interest on the body. Estimates of human exposure to a given field parameter in a specified area may be made from a combination of spatial and temporal variation measurements of the parameter and information that describes patterns of human activity in the area (see [B12] for discussion of the electric field case). This approach fails to address exposures that occur outside the areas of field characterization.

Commercially available three-axis exposure meters that are worn on the body may be used to measure contemporary exposures to the field parameters identified in 5.1, a) through f), for several pass bands. Such instrumentation periodically records the resultant magnetic field value for times extending to several days, depending on the frequency of sampling the magnetic field, memory storage capacity, and battery life. The collected data may be down-loaded to a computer and software provided with the instrumentation, or specially developed, is used to determine exposure to the parameters described in 5.1, a) through f).

Past human exposures in specified areas may be estimated by having surrogates wearing exposure meters perform activities that were conducted in the past in the specified areas [B30, B31, B37]. This approach assumes that the magnetic field sources have not changed significantly over time.

5.2 Reporting magnetic field measurement results

The information that may be provided when reporting the results of measurements can vary, depending on the goals of the measurements. A clear indication of the measurement goals should be provided at the outset. The following information pertaining to the instrumentation also is desirable in all cases:

- Manufacturer
- Model/serial number
- Date
- Time
- Total measurement uncertainty
- Date of last calibration/calibration check
- Probe size/geometry (some exposure standards [B21] present limits in terms of a spatially-averaged field through the specification of a loop surface area)
- A clear indication of what field quantity is being reported, e.g., the maximum magnetic field, the resultant magnetic field, the vertical field component, TWA, etc. The recommended units are SI, with common units expressed in parentheses.

Other information that may be provided when appropriate includes:

- Magnetic field sampling frequency and descriptions of human activity when human exposure data is presented
- Drawings that describe the area and locations where measurements are performed
- Statistical information, e.g., the largest and smallest field values, median, geometric mean, standard deviation, etc.
- Measurement height; source identification; weather conditions

6. Electric field measurements

6.1 Electric field measurement goals and methods

The reader is referred to 5.1, as many of the points made for developing a magnetic field measurement plan are applicable for electric field measurements. For example, the requirement that measurement goals be defined early and the advisability of conducting a pilot study again applies for the reasons stated previously.

Direct measurement of human exposure to electric fields is more difficult than determining magnetic field exposure because miniature single-axis exposure meters that measure the electric field at the surface of the body [B6, B8, B17] are not readily available.[7] However, because of perturbations of the electric field by the body, the recorded field values are very sensitive to field meter location on the body and body orientation [B6, B26].[8] Such instrumentation has been used to determine electric field "enhancement factors," i.e., the ratio of perturbed electric field at the surface of the body to unperturbed electric field, for different locations and orientations of the body in a vertical electric field [B6]. Enhancement factors for humans and animals in vertical electric fields also have been reported by other investigators [B11, B36]. The enhancement factors have been used for scaling the electric field across different animal species when planning exposures for in vivo biological studies. Characterization of the unperturbed electric field (e.g., using a free-body meter) followed by appropriately scaled fields for *in vivo* (and *in vitro*) biological studies has been the pattern for investigating the possible effects of exposure to power frequency fields. Also, it is noteworthy that limits for human exposure to electric fields are given in terms of the unperturbed electric field [B1, B5, B21]. Thus, characterization of the unperturbed electric field is the focus of this guide. [9]

It should be noted that the electric fields of past interest have been mainly vertical electric fields produced by power lines and related high voltage equipment. The electric fields from such sources can be in excess of 10 kV/m [B2] and are much larger than electric fields typically found in residences. In residences, the electric fields can range in value from a few hundred V/m (e.g., near an electric blanket) to less than a few V/m away from electrical appliances [B4].

Below is a listing of possible measurement goals and possible methods for their accomplishment. As for characterizing magnetic fields (refer to 5.1), the listing should not be considered as complete since there can be a wide variety of goals and methods. In each case, the frequency pass band of the instrumentation is chosen for the frequency or frequencies of interest [see 6.1, g)].

Possible goals and methods are as follows:

a) *Goal: Characterization of electric field levels.* Limits on permissible electric field levels as a function of frequency and direction have been indicated in a number of documents [B1, B5] necessitating the determination of field levels with the greatest magnitude as well as possibly their direction in specified areas.

   Method: Free-body and electro-optic meters may be used to make spot measurements of the maximum or resultant electric field. Ground-referenced meters should be used for measurements on the ground plane or on surfaces at ground potential. Guidance exists for measuring the predominantly vertical power frequency electric field near ground level in the vicinity of power lines (IEEE Std 644-1994, [B18]). The vertical electric field is measured because this quantity is often used to calculate induction effects in objects close to ground level [B9]. Unlike spot measurements of magnetic fields from power lines, the measured values will not change greatly because the voltages remain nearly constant (sagging of the conductors because of large current loads and thermal expansion can lead to greater field levels).

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[7] Exposure meters that simultaneously measure the electric field and resultant magnetic field at the surface of the body have also been developed [B17].

[8] An exposure measurement system that employs an electrically conducting vest as the probe to sense an average field for the upper body region is also described in the literature [B11].

[9] A notable exception is described in IEEE Std 1140-1994 and [B28], which require the measurement of perturbed electric fields from VDTs using ground-references electric field meters above the ground plane. The rationale for this approach is that the grounded probe, a flat circular plate, approximates the surface of a grounded VDT operator. The relationship between the perturbed electric field value that is measured and the electric field values at the surface of the operator is unknown.

Some guidance for measuring power frequency electric fields away from power lines where the field geometry is less well-defined is given in [B18]. Estimates of the range of electric field levels may be obtained by performing spot measurements with all electrical appliances and equipment turned on and off in the area of interest [B4].

b) *Goal: Characterization of spatial variations.* The spatial distribution of electric fields away from power lines is typically unknown. Alternating electric fields will be nonuniform in most environments because the spatial dependencies from the field sources (energized conductors) are the same in some cases to that for magnetic fields.

   Method: Spatial variation measurements require the recording of the electric field components as a function of coordinate position. Standards exist for carrying out such measurements near power lines [IEEE Std 644-1994, B18] and VDTs [IEEE Std 1140-1994, B28]. While such measurements may be made with survey meters, instrumentation used in conjunction with "measurement wheels" is available for characterizing spatial distributions of electric fields in environments where physical obstructions do not hinder movement of the wheel. As the wheel rotates, it periodically triggers a single-axis free-body electric field meter that captures and transmits the waveform of the electric field (component) via a fiber optic cable to a portion of the detector circuit for storage. Software provided with such instrumentation permits the generation of plots of electric field strength profiles, equifield contours, statistical analyses of the field levels, etc., at a fixed height above the ground or floor. Such data will not capture the long-term temporal variations of the field profiles without repeated measurements. Variations of the field may occur if the probe is moved past electrically-charged surfaces, e.g., plastics and synthetic clothing. It should be noted that during measurements of the electric field with a single-axis field meter and measurement wheel, the direction of the field can change.

c) *Goal: Characterization of temporal variations.* The temporal variations of electric fields, in general, should not be as great as for magnetic fields. Electric fields are produced by conductors that are electrically energized. The electric field at a point will be the vector sum of contributions from all energized conductors in the vicinity of the measurements. Shielding effects by building materials, which can depend on weather conditions, e.g., wet structures during rainy weather, can contribute to the variability. Short-term variations will occur if there is movement of conducting objects (e.g., automobiles and trucks) past the measurement location.

   Method: Free body instrumentation is available that periodically records the electric field waveform at a point in space for later analyses to determine the temporal variations [see *Goal b)*]. Ground reference meters may be used with commercially available data loggers to record the electric field on grounded surfaces for later analyses. Similarly, optically isolated free-body electric field meters may be used with data loggers for above ground-plane measurements.

d) *Goal: Characterization of TWA electric field.*

e) *Goal: Characterization of electric field intermittency.*

f) *Goal: Characterization of field levels exceeding a specified value.*

   Method: These parameters may be determined for time intervals of interest by analyses of data collected with electric field meters with recording capabilities [see b) and c)]. The reader is referred to 5.1 for analogous measurements of the magnetic field.

g) *Goal: Characterization of frequency content in electric field.* Because limits for exposure to electric fields have been set as a function of frequency [B1, B5], characterization of frequency content can be an important goal.

   Method: Commercially available free-body instrumentation that can periodically record the waveform of the electric field have software that allows the determination of the frequency content from the recorded data. Signals from ground referenced electric field meters may be used with spectrum analyzers to determine the frequency content of fields characterized on grounded surfaces.

h) *Goal: Characterization of electric field polarization.* A full characterization of the electric field requires a determination of its polarization for a given frequency.

Method: Free-body and electro-optic field meters may be used to measure the rms values of the semi-major and semi-minor axes of the electric field ellipse to determine its polarization at a point in space. As noted earlier, this procedure assumes that only a single frequency component of the field is being measured. With the presence of other frequencies in the field, the rotating electric vector no longer traces a simple ellipse. Guidance for determining polarization near power lines is given in IEEE Std 644-1994 and [B18].

i) *Goal: Characterizing human electric field exposure.* It is recalled that there will be differences between perturbed electric field measurements obtained with exposure meters worn on the body, and unperturbed field measurements obtained with, for example, free-body-meters. The results obtained using the two approaches will yield significantly different results, e.g., different maximum, minimum, mean values, etc. While the focus of this guide has been the characterization of the unperturbed electric field, a recent epidemiological study has characterized human exposure by measuring the field at the surface of the body using exposure meters [B26].

Method: A distinction should be made between characterizing one or more field parameters, e.g., *Goals a)* through *h),* and exposure to those parameters. As already noted, because electric field exposure meters are not readily available and interpretation of the recorded data can be complicated, a direct determination of exposure may not be possible. An alternative approach, as noted for the magnetic field case, is to estimate exposure to one or more parameters in a specified area from a combination of spatial and temporal variation measurements of the parameter(s) and information that describes patterns of human activity in the area. This approach has led to, in one study, the determination of "activity factors" that may be used as part of a process to estimate long-term electric field exposure in an agricultural setting [B12].

6.2 Reporting electric field measurement results

The information that may be provided when reporting the results of measurements can vary, depending on the goals of the measurements. As for reporting the results of magnetic field measurements, a clear indication of the measurement goals should be provided at the outset. The following information pertaining to the instrumentation is also desirable in all cases:

— Manufacturer
— Model/serial number
— Date
— Time
— Total measurement uncertainty
— Date of last calibration/calibration verification
— Probe size/geometry
— A clear indication of what field quantity is being reported, e.g., the maximum electric field, the resultant electric field, the vertical field component, TWA, unperturbed field (e.g., free-body-meter measurement), perturbed field (exposure meter measurement), etc. The recommended units are SI units.

Other information that may be provided when appropriate includes:

— Descriptions of human activity when human exposure data is presented.
— Drawings that describe the area and locations where measurements are performed.
— Statistical information, e.g., the largest and smallest field values, median, geometric mean, etc.
— Measurement height; source identification; weather conditions

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