

# ELF Electric and Magnetic Field Measurement Methods

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## Abstract

This paper surveys the instrumentation, calibration procedures, measurement techniques, and standards which can be used to characterize extremely low frequency (ELF) electric and magnetic fields. While the focus of the paper is on power frequency and power frequency harmonic fields, the measurement methods discussed are appropriate in principle for other ELF frequencies.

## INTRODUCTION

During the early 1970's, reports originating in the Soviet Union described a variety of ill effects experienced by personnel working in 500 kV and 750 kV switchyards [1,2]. The effects were attributed to the presence of the ac electric fields as well as to the occurrence of spark discharges between the workers and ground. At about the same time questions were raised regarding the possible environmental impact of high voltage transmission lines in the U.S. by the American author L.B. Young [3]. In response to the concerns generated by these and similar reports, numerous bioeffect studies with ELF electric and magnetic fields were initiated in the U.S. by the Department of Energy [4], the Electric Power Research Institute, and during the early 1980's, the New York State Department of Health. The results of many of these and newer studies, which have focussed on magnetic field effects, are now readily found in the technical literature, but questions related to possible health effects from exposure to magnetic and electric fields remain unresolved [5].

The early concerns regarding possible health effects due to field exposure also focused interest on the characterization of electric and magnetic fields near power lines. In the late 1970's this interest led to the development of an IEEE standard which provides guidance for measuring electric and magnetic fields near ac power lines [6]. In more recent years, interest has been expanded from the vicinity of power lines to residential and occupational environments as well as transportation systems.

The field characteristics in these environments away from power lines can be significantly different. For example, while magnetic fields near ground level in the vicinity of transmission lines are predominately 60 Hz, change slowly as a function of location, and are of order  $10 \mu\text{T}$  in magnitude, magnetic fields in homes, the work place and in transportation systems have greater temporal variations and dynamic range, can contain significant levels of harmonics, and can be highly nonuniform. These differences will influence the design of instrumentation, calibration procedures as well as measurement techniques. The more complex nature of fields away from power lines also limits the usefulness of the IEEE standard noted above.

Following a brief description of electric and magnetic fields near ac power lines, the types of field meters and their principles of operation are surveyed. Consideration is given to features necessary in the design of instrumentation to adequately characterize electric and magnetic fields with harmonics and fields which are highly nonuniform. Calibration techniques for magnetic field meters which are used to characterize fields over the dynamic range of a few nanotesla

to about a millitesla are discussed. Measurement techniques in various environments as well as their limitations are also briefly discussed and examples of measurement results in several different environments will be presented.

## ELECTRIC AND MAGNETIC FIELDS NEAR AC POWER LINES

A single-circuit ac transmission line has three conductors (or conductor bundles) with multiple voltage phases. More than one circuit can sometimes be found in the same right-of-way. The electrical environment in the vicinity of the lines is characterized by several electrical parameters, including the electric field strength,  $E$ , and the magnetic flux density,  $B$ . The electric and magnetic fields of a three-phase transmission line have been calculated and illustrated by Deno [7] and a somewhat simplified sketch of the electric fields in the vicinity of a three-phase transmission line is given in Figure 1. Three conductors perpendicular to the plane of the page are shown above the ground plane in Figure 1 and the phase of the power frequency voltage applied to each conductor differs by  $120^\circ$  with respect to the conductor adjacent to it [e.g., sinusoidal voltages  $V\sin(\omega t)$ ,  $V\sin(\omega t + 120^\circ)$ , and  $V\sin(\omega t + 240^\circ)$  applied to adjacent conductors where  $V$  is the peak voltage,  $\omega$  is equal to  $2\pi f$  where  $f$  is the frequency, and  $t$  is the time].

In general, the electric field strength  $E$  at a point in space can be represented as a rotating vector which traces an ellipse in a plane perpendicular to the conductors as shown in Figure 1. Near ground level, the field ellipse degenerates to a nearly vertical line. In the absence of nearby objects or irregular terrain, the field strength changes slowly from ground level to a height of about 1 or 2 meters, i.e., the field is approximately uniform. At ground level the field vector oscillates along a line perpendicular to the ground. Because of this spatial independence of the electric field, laboratory simulations of the field at or near ground level can be made for calibration purposes or bioeffects studies with a parallel plate apparatus.

Although not shown in Figure 1, the magnetic field at a point near a three-phase transmission line can also be represented by a rotating vector in space but in contrast to the electric field, the vector  $B$  is a rotating vector even at ground level [7]. Thus,

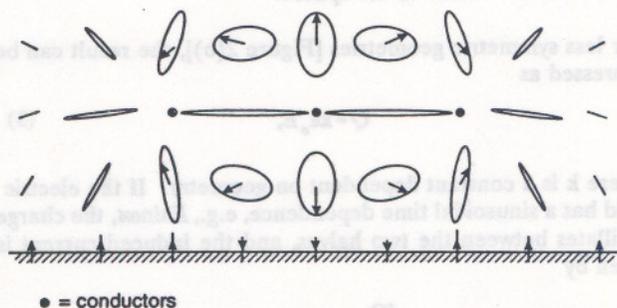


Figure 1. Electric field ellipses at representative points in vicinity of three-phase transmission line after Deno [7]. The electric field vector at a point in space rotates and traces an ellipse in a plane perpendicular to the conductors.

laboratory simulation of a three-phase transmission line magnetic field near ground level requires an apparatus which can generate a rotating field.

## ELECTRIC FIELD MEASUREMENTS

### Instrumentation

Two types of field strength meters that have been used for measuring ac power line electric fields are described in the literature: (1) self-contained meters, which measure the power frequency induced current or charge oscillating between two halves of an electrically isolated conductive body (free-body) in an electric field [8,9], and (2) ground-reference type meters, which measure the induced current to ground from a probe introduced into an electric field [10]. The free-body meter is suitable for survey-type measurements because it is portable, allows measurements above the ground plane, and does not require a known ground reference. Therefore, this type of meter has been recommended for outdoor measurements near power lines in the IEEE (U.S.) measurement standard [6]. Ground-reference type meters normally are used on grounded conducting surfaces [9,11].

Basically, an electric field strength meter consists of two parts, the probe or field sensor, and the detector. The probe produces an electrical signal proportional to the electric field which is then processed by the detector circuit. For free-body meters, the detector is usually contained in, or is an integral part of the probe and is battery operated. The electrical signal that is processed is the induced alternating current (ac) that moves between the conducting halves (electrodes) of the probe.

Briefly, the theory of operation of free-body meters can be understood by considering an isolated uncharged conducting body with two halves that is introduced in a uniform electric field  $E$ . The charge induced on one of the halves is

$$Q = \int_{S/2} D \cdot n \, dA, \quad (1)$$

where  $D$  is the electric displacement (equal to  $\epsilon_0 E$ , where  $\epsilon_0$  is the permittivity of free space),  $n$  is a unit vector normal to the surface of the body, and  $dA$  is an element of area on half of the body surface with total surface  $S$ . The case of spherical geometry [Figure 2(a)] yields the result that [12]

$$Q = 3\pi a^2 \epsilon_0 E, \quad (2)$$

where  $a$  is the radius of the sphere.

For less symmetric geometries [Figure 2(b)], the result can be expressed as

$$Q = k\epsilon_0 E, \quad (3)$$

where  $k$  is a constant dependent on geometry. If the electric field has a sinusoidal time dependence, e.g.,  $E \sin \omega t$ , the charge oscillates between the two halves, and the induced current is given by

$$I = \frac{dQ}{dt} = k\omega\epsilon_0 E \cos \omega t, \quad (4)$$

where  $\omega$  is the angular frequency,  $2\pi f$  and  $f$  is the frequency. Equation (4) shows that measurement of the induced current permits the determination of the electric field strength,  $E$ .

If there are harmonics in the electric field, there will be an additional term on the right hand side of Eq (4) for each harmonic. Because of the differentiation operation in Eq (4), each of the additional terms will be weighted by an associated harmonic number. For example, if there was 10% third harmonic in the field, the term  $3x(0.1)k\omega\epsilon_0 \cos \omega t$  would be added to the right side of Eq (4). Because of the weighting of

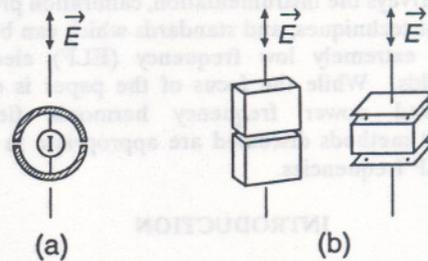


Figure 2. Examples of free body electric field strength meters. (a) The electric field strength is determined by measuring the induced current that moves between the hemispheres. (b) Geometries of commercial electric field meters used in U.S.

the harmonic term by the factor 3, the waveform of the signal from the probe will no longer reflect the waveform of the field. Consequently, an rms measurement of the induced current will not accurately represent the rms value of the electric field. The waveform does reflect, to a good approximation, the current induced in some biological systems.

To recover the waveform of the electric field, it is necessary for the detector to perform the inverse mathematical operation, namely integration. This can be accomplished by introducing a stage of integration in the detector. Thus, a circuit which contained a current-to-voltage converter, an integrator, and a voltmeter would have the major elements of a detector circuit. The frequency response of the probe-detector circuit combination can be made flat for the power frequency harmonics. The "corrective" action provided by the detector is essential to obtaining accurate rms values of the electric field as well as correct percentages of harmonics. It is noted that use of an integrating detector circuit means that a measurement proportional to the induced charge is being made to determine the electric field strength [see Eqs (3) and (4)]. While the above theory is developed assuming a uniform electric field, it can be shown that nonuniform fields can usually be measured with small error [13].

Probes can be of any shape; however, the shape of meters that have been commercially available in the U.S. are generally rectangular, as shown in Figure 2(b) with side dimensions ranging from about 7 cm to 25 cm. The meters are calibrated to read rms values of the component of the electric field along the main axis. An analog or digital display is mounted on the probe and read from a distance in order to minimize proximity effects of the observer.

While the IEEE standard recommends the use of free-body meters for characterizing power line fields, an International Electrotechnical Commission (IEC) standard describes the use of electro-optic type field meters which utilize the Pockel's effect to determine the electric field strength, as well as free-body and ground-reference type field meters [11]. The Pockel's effect field meter, which is quite small in dimensions (~2 cm in height), lacks sensitivity below electric field strengths of about 5 kV/m and is considerably more expensive to fabricate.

## Calibration of Electric Field Meters

Two measurement standards currently exist which provide guidance for the measurement of power frequency electric fields [6,11]. Both standards describe the use of parallel-plate apparatus for generating a known electric field for purposes of calibration. A nearly uniform electric field can be produced with parallel plates provided that the side dimensions of the plates is more than twice the plate spacing. The recommended geometry are parallel plates 1.5 m x 1.5 m, with a parallel-plate spacing of 0.75 m. Analytical [14] and numerical [15] analyses of the electric field indicate that the electric field strength at the center of the parallel plate system is within 1% of the uniform field value given by  $V/d$ , where  $V$  is the voltage across the plates and  $d$  is the parallel-plate spacing. With the above dimensions, it is assumed that the electric field meter which is calibrated has no diagonal dimension greater than 0.23 m. Once an electric field meter has been calibrated in a parallel plate apparatus, its calibration can be checked more conveniently using a current injection technique. Further details of the calibration process are given in the measurement standards cited earlier. In this regard, a primary objective of the standards is to provide the manufacturer or user of electric field meters with sufficient information to perform calibrations or calibration checks of their instrumentation.

### Sources of Measurement Error

Effects of handle leakage, humidity, temperature, harmonic content in the electric field, observer proximity, and reading an analog display from a distance may all contribute to errors in measurements when electric fields are being characterized [16]. The effect of the observer's proximity to the field meter probe was not fully appreciated during some early measurements of electric field strength. Figure 3 shows that perturbation, in percent, of the electric field strength reading as a function of distance between the observer and field meter, and the height of the field meter above ground. The data points, which were obtained beneath a 500 kV transmission line, represent perturbations by a 1.8 m tall observer at ground potential and the solid curves are corresponding theoretical predictions [17]. The perturbations depend markedly on both observer distance and field meter height.

Figure 4 shows an electric field strength meter with a handle 25 cm in length which was used to characterize electric fields in

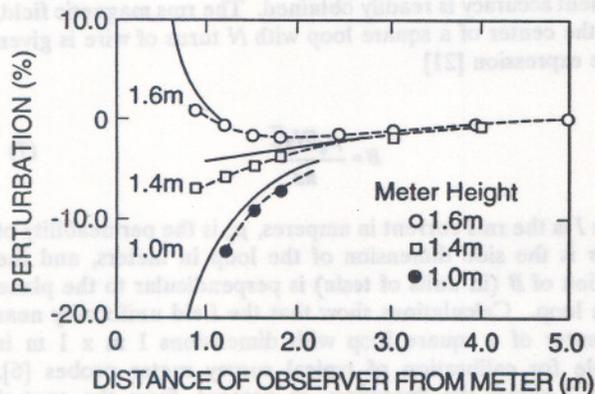


Figure 3. Perturbation due to 1.8 m tall grounded observer as function of meter/observer distance and meter height above ground. Theoretical values \_\_\_\_\_; measured values obtained under a 500 kV transmission line-----.

the early 1970's at a height of 1.8 m [2]. Other parameters which can introduce measurement errors are discussed in References [6], [11], and [16].

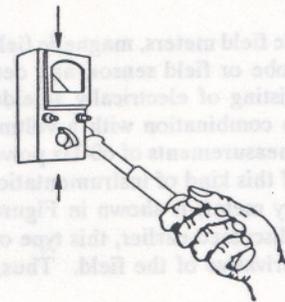


Figure 4. Electric field strength meter used to measure power frequency electric fields in early 1970's.

### Measurements of Power Line Electric Fields

What has become an accepted procedure for characterizing the electric field environment near a power line is the measurement of a lateral profile [6]. The lateral profile consists of measurements of the vertical electric field at a height of 1 m above the ground (other heights near ground level are permitted) across the right-of-way, along a line perpendicular to the conductors. During the measurements, the electric field meter is supported in the field at the end of a long insulating rod to minimize observer proximity effects (see next section). Figure 5 shows an example of a lateral profile for a three-phase transmission line. The vertical electric field is measured because this quantity is often used to compute induction effects in objects close to the ground.

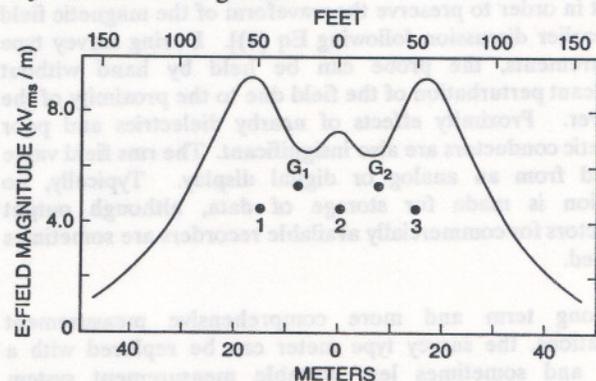


Figure 5. Lateral electric field profile of 3-phase transmission line. The phases of the voltages applied to conductors 1, 2, and 3 differ by  $120^\circ$  with respect to the adjacent conductor. Conductors  $G_1$  and  $G_2$  are ground wires.

Longitudinal profile measurements which are vertical electric field measurements along a line parallel to the conductors, represent another procedure recommended for characterizing the electric field environment near a power line.

### Electric Field Measurements Away From Power Lines

Some guidance for measuring power frequency electric fields away from power lines is provided by IEC Publication 833 [11]. However, accounts of measurements of ELF electric fields in environments away from power lines are relatively few (compared to magnetic field measurements) [18]; reports containing information on frequency (e.g., harmonic content) are rare [18(a)].

## MAGNETIC FIELD MEASUREMENTS

### Instrumentation

As for electric field meters, magnetic field meters consist of two parts, the probe or field sensor, and detector. Magnetic field probes, consisting of electrically shielded coils of wire, have been used in combination with a voltmeter as a detector for survey type measurements of 60-Hz power line magnetic fields. A diagram of this kind of instrumentation, sometimes referred to as a survey meter, is shown in Figure 6. Like the electric field probes discussed earlier, this type of magnetic field probe senses the derivative of the field. Thus, for measurements in

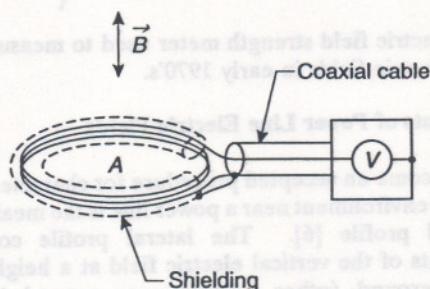


Figure 6. Schematic view of a magnetic field meter consisting of a coil-type probe with cross sectional area  $A$  and a voltmeter-detector.

environments away from transmission lines, where harmonic components in the magnetic field may not be negligible, an integrating amplifier can be incorporated into the detector circuit in order to preserve the waveform of the magnetic field [see earlier discussion following Eq (4)]. During survey type measurements, the probe can be held by hand without significant perturbation of the field due to the proximity of the observer. Proximity effects of nearby dielectrics and poor magnetic conductors are also insignificant. The rms field value is read from an analog or digital display. Typically, no provision is made for storage of data, although output connectors for commercially available recorders are sometimes provided.

For long term and more comprehensive measurement applications, the survey type meter can be replaced with a larger and sometimes less portable measurement system containing three orthogonally oriented coil probes for simultaneous measurements of the three spatial components of the field, and a commercial data storage system which permits later analysis of the measurements [18(a)].

The development in recent years of small magnetic field personal exposure meters, devices which can be worn to periodically measure and record the spatial components of the magnetic flux density, has also led to the use of miniature coil probes containing ferromagnetic cores for increased sensitivity. Other types of field meters with high permeability inductor probes, such as the fluxgate magnetometer which has been used to measure low level dc magnetic fields, can be adapted for ac field measurements.

The principal of operation of the magnetic field meter shown in Figure 6 is based on Faraday's law which describes the voltage produced at the ends of an open loop of wire placed in a time-varying magnetic field. Specifically, the voltage is equal to the negative of the time-rate-of-change of the flux,  $\phi$ , through the loop,

$$V = -\frac{d\phi}{dt} = -\frac{d}{dt} \int_A \mathbf{B} \cdot \mathbf{n} dA, \quad (5)$$

where  $\mathbf{B}$  is the magnetic flux density,  $\mathbf{n}$  is a unit vector perpendicular to the cross sectional area of the probe,  $A$ , and  $dA$  is an element of area. If the magnetic field is free of harmonics, e.g.,  $B = B_0 \sin \omega t$ , then

$$V = -\omega B_0 A \cos \omega t, \quad (6)$$

where  $\omega$  is the again the angular frequency and it is assumed that  $\mathbf{B}$  is perpendicular to the area of the loop. For  $N$  turns of wire in the loop, the voltage given by Eq (6) will develop over each turn and the total voltage will be  $-N\omega B_0 A \cos \omega t$ . Equation (6) shows that the sensitivity of the probe increases with cross sectional area. It is assumed that the induced current in the coil probe, after it is connected to the detector, is sufficiently small that the opposing magnetic field produced by it is negligible.

If there are harmonics in the magnetic field, there will be an additional term on the right side of Eq (6) for each harmonic and as for the electric field instrumentation discussed earlier, a stage of integration is required in the detector to recover the waveform of the magnetic field.

An additional consideration is the frequency response of the probe. Because of the inherent inductance, resistance and capacitance of the probe, the relationship between the voltage induced in the coil [Eq (6)] and the voltage entering the detector will be a function of frequency [19]. For accurate measurements of the magnetic field, this relationship should remain nearly constant over the frequency range of interest. The frequency response of coil probes is discussed further in References [19] and [20].

### Calibration

Calibration of a magnetic field meter is normally done by introducing the probe into a nearly uniform magnetic field of known magnitude and direction. Helmholtz coils have frequently been employed to generate such fields, but the more simply constructed single loop of many turns of wire with rectangular geometry has also been used [6]. The simplicity in construction is at the expense of reduced field uniformity, but sufficient accuracy is readily obtained. The rms magnetic field,  $B$ , at the center of a square loop with  $N$  turns of wire is given by the expression [21]

$$B = \frac{\mu_0 I N \sqrt{2}}{\pi s} \quad (7)$$

where  $I$  is the rms current in amperes,  $\mu_0$  is the permeability of air,  $2s$  is the side dimension of the loop in meters, and the direction of  $\mathbf{B}$  (in units of tesla) is perpendicular to the plane of the loop. Calculations show that the field uniformity near the center of a square loop with dimensions 1 m x 1 m is suitable for calibration of typical survey meter probes [6]. Figure 7 shows the departure, in percent, from the central magnetic field value in the plane of a 1 m x 1 m loop, and at 3 cm above and below the plane of the loop (in parenthesis). Also shown in Figure 7 is an outline (scale drawing) of a magnetic field probe 10 cm in diameter. The departure of the magnetic field from the central value over the cross sectional area of the 10 cm probe is less than 1%.

Establishing a known magnetic field for calibrating the more sensitive scales of a magnetic field meter (e.g.,  $0.2 \mu\text{T}$  range) is usually complicated by the presence of ambient fields that are of order  $0.1 \mu\text{T}$ . This problem can be overcome by using an alternative calibration technique known as voltage injection. With this approach, voltages [Eq (5)] corresponding to signals that are produced by small magnetic fields are injected into the detector circuit. Further details of this approach can be found in References [20] and [22].

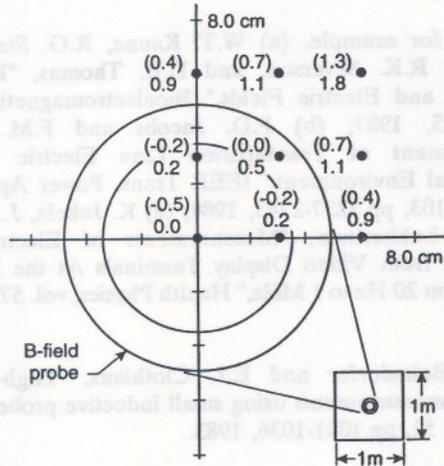


Figure 7. Enlarged central region of square loop 1 m x 1 m showing scale drawing of magnetic field probe 10 cm in diameter. The percentage departure of  $B_z$  from the central value is indicated at representative points in the plane of the loop and at points 3 cm above and below the plane of the loop (parentheses).

#### Sources of Error and Measurement Uncertainty

The sources of error during measurements of magnetic fields near a power line are fewer than for the electric field case. Because there are no significant observer proximity effects, the observer can hold the field meter and thereby reduce errors due to reading an analog display from a distance (as during electric field measurements).

During measurements of magnetic fields away from power lines, it is useful to distinguish between measurement uncertainties associated with calibration and instrument design, and uncertainties due to spatial and temporal variations. The uncertainties in the first category are normally associated with measurement accuracy and can be made small (e.g.,  $<5\%$ ) by careful instrument design and calibration procedures. There is less control over the second category of uncertainty because the magnetic fields can have, for example in a residence, unknown spatial and temporal variations. The second category of uncertainty may be better referred to as measurement variability, distinct from measurement accuracy. Thus, while a spot measurement at some location may be performed with good accuracy, it will not be possible to specify with confidence what the variability will be without further measurements (see below).

#### Measurements of Power Line Magnetic Fields

The procedures for characterizing magnetic fields near a power lines parallel those for the electric fields discussed earlier. That is, measurements of lateral and longitudinal profiles at a height of 1 m above the ground are

recommended [4]. However, the magnetic field probe is oriented for the maximum reading because this quantity can be used for estimating the maximum induction effects in objects near ground.

#### Magnetic Field Measurements Away from Power Lines

At present, there are no standards that provide protocols for measuring ELF magnetic fields in environments away from power lines. Magnetic fields away from power lines can be more complex compared to transmission line fields because of, as noted above, greater temporal and spatial variations. In addition, while the harmonic content in magnetic fields from transmission lines is usually a few percent or less, in environments away from power lines, the harmonic content can be significant.

Information on the temporal variation of the magnetic field at a point can be obtained by periodically recording the field value at the same location. Figure 8 shows 24 hour histories of the resultant magnetic field (i.e., root-mean-square of three spatial components) at the center of a living room on two days during which the load currents varied significantly because of weather conditions. The data were obtained with a three-axis meter that recorded the field at a height of 1 m above the floor. Figure 8(a) shows measurements during a hot and humid July day in the metropolitan Washington area, when air conditioners were presumably in great use. The data were recorded every 15 seconds and the short-term variations, which could last as long as several minutes, could not be attributed to any known sources in the residence. Field measurements at the same location during a cooler, less humid day in September [Fig. 8(b)], reveal a significantly different range of values with an average field of about one-half as large as that during the July observations. The anecdotal data shown in Figure 8 demonstrates that the temporal variability can exceed by far the uncertainties associated with the calibration process and field meter design.

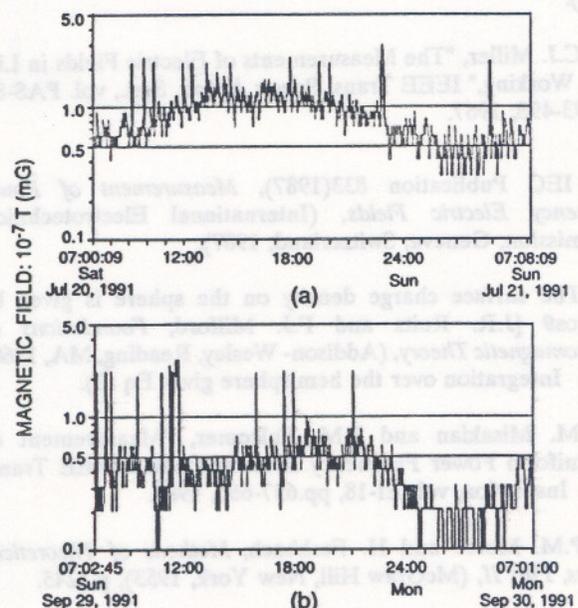


Figure 8. Twenty four hour measurements of magnetic field at center of living room (a) during hot and humid weather and (b) during cool dry weather.

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