

IEEE Standard for Calibration of Electromagnetic Field Sensors and Probes, Excluding Antennas, from 9 kHz to 40 GHz

Sponsor

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Abstract: Consensus calibration methods for electromagnetic field sensors and field probes are provided. Data recording and reporting requirements are given, and a method for determining uncertainty is specified.

Keywords: calibration, electromagnetic, field probe, field sensor, probe antenna

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Introduction

(This introduction is not part of IEEE Std 1309-1996, IEEE Standard Method for the Calibration of Electromagnetic Field Sensors and Field Probes, Excluding Antennas, from 9 kHz to 40 GHz.)

This standard was prepared by the Working Group on Methods for Calibration of Field Sensors and Field Probes, Excluding Antennas, from 9 kHz to 40 GHz, and is sponsored by the Electromagnetic Compatibility Society.

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IEEE Standard for the Calibration of Electromagnetic Field Sensors and Field Probes, Excluding Antennas, from 9 kHz to 40 GHz

1. Overview

1.1 Scope

This standard provides calibration methods for electromagnetic (EM) field sensors and field probes, excluding antennas per se, for the frequency range of 9 kHz to 40 GHz. Field injection probe (transmitting) calibration is not covered by this standard. This standard is not applicable to EMI emission measurement antennas, such as active and passive whip antennas, used in the general frequency range of 9 kHz to 30 MHz.

This standard also provides alternative calibration methods that are appropriate to various frequency ranges and various user requirements. These methods are applicable to any (active, passive, photonic, etc.) field sensor or field probe. Methods are provided for frequency domain and time (transient) domain calibration.

Methods for creating standard electric and magnetic fields are described in clause 5. Each method has known calculated field strength and associated errors. Each standard field method is individually addressed. The field generation information was obtained from IEEE Std 291-1991 and from IEEE Std C95.3-1991,¹ with additional information from sources listed in the bibliography.

Most electromagnetic field measurements are made in the frequency domain, either at a single frequency or at a number of frequencies. The ever-increasing susceptibility of electronic circuits has awakened interest in transient electromagnetic phenomena such as electrostatic discharge (ESD), electromagnetic pulse (EMP), and system-generated transients, such as automotive ignition noise. The measurement of these transient fields requires electromagnetic field probes and sensors that can faithfully replicate the transient wave-shapes, thus requiring an equivalent bandwidth of decades. The calibration of time domain sensors necessitates procedures that are significantly different than those for the frequency domain sensors.

The electric or magnetic field sensor and/or field probe calibration requirements depend on the design and the manufacturer's specifications. The calibration shall address the amplitude response, frequency response, accuracy (uncertainty), linearity, and isotropy. Additionally the calibration may address response time, time constant, and response to signal modulation.

¹Information on references can be found in clause 2.

1.2 Purpose

This standard provides consensus calibration methods for electromagnetic field sensors and field probes. Calibration organizations and others need uniform calibration methods to obtain consistent results. The calibration methods of this standard will produce results readily traceable to a national standards authority such as the National Institute of Standards and Technology (NIST) in the United States.

1.3 Background

Antenna calibration is the subject of existing standards, such as ANSI C63.5-1988. Though field sensors and field probes are in a broad sense antennas, the uses of antennas, field sensors, and field probes are different.

Antennas are designed to transmit or receive with maximum coupling to the electromagnetic field, thus they perturb the electromagnetic field. Field sensors and field probes are designed to measure an electromagnetic field with minimal perturbation.

There is agreement on antenna calibration methods. Attempts to apply antenna calibration methods to field sensors and field probes have resulted in inconsistent results between calibration organizations and others. This standard is intended to provide consistent methods and results for different calibration services.

1.4 Grades of calibration

The extent to which a field probe or field sensor is calibrated and characterized depends on its intended use and the degree of detail required by the user. However, for each characteristic measured, the calibration method and specific test points measured (if applicable) and a statement of uncertainty (error) shall be provided to the user. Applicable characteristics of the calibration include, but are not limited to, the following:

- Method of calibration
- Type of calibration (time domain or frequency domain)
- Amplitude level(s) measured
- Frequencies measured
- Response time
- Time constant
- Modulation response
- Isotropy
- Uncertainty

1.5 Generic Probe Types

Field probes and sensors are grouped into one of two categories based on the location of the field measured with respect to the ground plane. This standard thus defines field probes and sensors as either being 'ground plane' or 'free field.' Detailed definitions are presented in clause 3 of this standard. Specific calibration instrumentation, procedures, and field generation methods may be different between these two groups of probes and sensors. This standard is applicable to both types of field probes and field sensors; the free field probes and sensors being placed in a field that completely surrounds them, and the ground plane field probes and sensors being mounted on the ground plane with respect to the field source.

There are two differences between time derivative (B -dot and D -dot) sensors and direct field reading (E -Field and H -Field) sensors. Traditionally, the first difference is that E -field sensors are the Thevenin equivalent circuit for an electrically small electric dipole, while the D -dot sensor is the Norton equivalent circuit. Similarly, the H -Field sensor is the Norton equivalent circuit for an electrically small electric dipole, while the B -dot sensor is the Thevenin equivalent circuit. The second difference is that the constitutive parameters ϵ and μ

Table 1—Generic EM field probes and sensors

Free field	Ground plane field
<i>E</i> -Field (dipole)	<i>E</i> -Field (monopole)
<i>H</i> -Field (loop)	<i>H</i> -Field (half-loop)
<i>D</i> -dot	<i>D</i> -dot
<i>B</i> -dot	<i>B</i> -dot

relating the electric and magnetic field quantities are, in general, not linear, time invariant, or isotropic; if they were, then Maxwell's equations would contain only two parameters instead of four. These constitutive parameters are tensor quantities that can change with time and field strength, and do indeed exhibit these non-constant properties in certain situations in which the sensors have been used (for example, in nuclear source regions). A more detailed explanation is contained in [B9]².

This standard also applies to field probes that indicate power density; it is realized that the response of these field probes is based on the strength of an *E*-Field or *H*-Field and that far-field conditions are assumed.

CAUTION

Depending upon the field strengths, frequency ranges, and other factors, the field intensities required to calibrate *E*-field and *H*-field probes may be hazardous. The user of this standard is advised to observe all appropriate safety measures for nonionizing radiation. See IEEE Std C95.1-1991, IEEE Std C95.3-1991, and the references cited in these documents, as well as other appropriate documents.

2. References

This standard shall be used in conjunction with the following publications.

ANSI C63.5-1988, Electromagnetic Compatibility—Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration of Antennas.³

ANSI C63.14-1992, Dictionary for Technologies of Electromagnetic Compatibility (EMC), Electromagnetic Pulse (EMP), and Electrostatics Discharge (ESD).

ANSI Z540-1-1994, Calibration—Calibration Laboratories and Measuring and Test Equipment—General Requirements.

IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).⁴

IEEE Std 291-1991, IEEE Standard Methods for Measuring Electromagnetic Field Strength of Sinusoidal Continuous Waves, 30 Hz to 30 GHz (ANSI).

²The numbers in brackets preceded by the letter B correspond to those of the bibliography in annex J.

³ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

⁴IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

IEEE Std C95.1-1991, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz (ANSI).

IEEE Std C95.3-1991, IEEE Recommended Practice for the Measurement of Potentially Hazardous Electromagnetic Fields—RF and Microwave (ANSI).

ISO/IEC Guide to the Expression of Uncertainty in Measurement (1995).⁵

National Conference of Standards Laboratories (NCSL) RP-12, Recommended Practice for Determining and Reporting Measurement Uncertainties, 1 Feb. 1994.⁶

NIST Handbook 150, National Voluntary Laboratory Accreditation Program, Procedures and General Requirements.⁷

3. Definitions

This clause contains only those definitions relating to field sensor and field probe calibration that are not listed in IEEE Std 100-1992 or in ANSI C63.14-1992.

3.1 antenna: A device used for transmitting or receiving electromagnetic signals or power. It is designed to maximize its coupling to the electromagnetic field; as a receiver, it is made to intercept as much of the field as possible. Those devices that are made to measure the power level of the electromagnetic field rather than its field components are included in this category.

3.2 field probe: An electrically small field sensor or set of multiple field sensors with various electronics (for example, diodes, resistors, amplifiers, etc.). The output from a field probe cannot be theoretically determined from easily measured physical parameters.

3.3 field sensor: An electrically small device without electronics (passive) that is used for measuring electric or magnetic fields, with a minimum of perturbation to field being measured. The field sensor transfer function (ratio of output signal-to-input electromagnetic field) can be theoretically determined from measured physical (geometrical) properties, such as length, radius, area, etc., as well as the electrical characteristics of the construction material. The measured physical properties must be traceable to internationally accepted standards via a national standards authority (for example, the NIST in the U.S.).

3.4 free field: The electromagnetic field in a volume far removed from physical objects, conductive or non-conductive; it is usually thought of, but not restricted to, a plane wave. For the case of a plane wave, the electrical and magnetic vectors are transverse to the propagation vector and to each other [transverse electromagnetic mode (TEM)], and their ratio yields the intrinsic impedance of free space. *Syn:* **free space field.**

3.5 free space field: *See:* **free field.**

3.6 frequency domain calibration: A result that is the transfer function of the sensor or probe. A continuous wave calibration is a transfer function at a single frequency.

3.7 ground plane field: The electromagnetic field in near proximity to a conducting surface, with the boundary conditions that the tangential electric field approach zero and the normal magnetic remain continuous. The total normal electric field is related to the surface charge density by Gauss' law, and the total tangential magnetic field to the surface current density by Ampere's law.

⁵ISO publications are available from the ISO Central Secretariat, Case Postale 56, 1 rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse. ISO publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

⁶NCSL publications are available from the National Conference of Standards Laboratories, 1800 30th Street, Suite 305B, Boulder, CO 80301-1032, USA.

⁷NIST publications are available from the National Institute of Standards and Technology Library, Gaithersburg, MD 20899, USA.

3.8 ortho-axis: An angle of 54.7° to the edges and centerlines of each face of the device under test (DUT). This angle is the ortho-angle that is the angle that the diagonal of a cube makes to each side at the trihedral corners of the cube [B14] (see figure 5 in 8.3.2.2).

3.9 response time: The time required for a field probe to reach 90% of its steady state value when the field is applied as a step function. The measurement includes test setup response time, thus giving worst case results.

3.10 time constant: The time required for a field probe output to reach a stable, repeatable reading. The measurement includes test setup, metering unit, cables, etc., thus is a worst case result. The measurements assume an exponential response of the field probe. The time constant is used specifically for burst peak field strength measurements.

3.11 time domain calibration: A result that is the impulse response function of the sensor or probe in the time domain.

3.12 transfer function: The ratio of the device output signal (voltage, current, frequency, meter reading, etc.) to the incident field or field vector of interest in the frequency domain. The transfer function is the Laplace (or Fourier) transform of the impulse response function.

3.13 transfer standard: An electrically small field probe or field sensor. This can be a short dipole for sensing E -fields or a small loop for H -fields, which has a known response over a given range of frequency and amplitude. This known response can be either accurately calculable quasi-static response parameters or a calibration performed to some specified accuracy and precision by an accredited calibration facility.

4. Measurement methods

4.1 Methods

This standard provides three calibration methods, but does not endorse any as a preferred method. The calibration organization may use any method listed and defined in table 2 to calibrate field sensors and field probes. However, calibration, as defined by this standard, requires the results to be accompanied by a description of the method used and by quantitative statements of uncertainty, as described in clause 6.

Table 2—Three calibration methods

Method	Description
A	Calibration using the Transfer Standard (a field sensor or field probe similar to the one being calibrated), that has traceability to a national standards laboratory, such as NIST in the U.S. The Transfer Standard is used to measure and calibrate the field used for calibrating the field sensor or field probe under test.
B	Calibration using Calculated Field Strengths. The Unit Under Calibration is placed in a calculated reference field based on the geometry of the field source and the field source measured input parameters.
C	Calibration using a Primary Standard (Reference) Sensor, that contains no active or passive electronic devices and has its calibration traceable to a national standards laboratory based on international standards. It is used to determine the field strength used to calibrate the Unit Under Calibration.

It should be noted that method C, and its resulting uncertainty, is only applicable to the field sensor calibrated and thus does not address uncertainty resulting from the characteristics of connectors, cables, and/or environmental disturbances and the like, that may add additional uncertainty in actual use.

4.2 Field sensor or field probe orientation during frequency domain calibration

4.2.1 Directional and positional effects

As part of the calibration, it is necessary to identify directional and positional effects on the measured level of the field intercepted. In addition, if so equipped and intended for use in normal operation, accessories to the field sensor and field probe, such as cable or metering module, shall be verified as not affecting the validity of the calibration. The accuracy may be affected by field perturbation, losses in the accessory (cables, metering modules,) etc.; each shall be checked for having directional and positional effects and accuracy effects on the measurement being made.

4.2.2 Calibration data collection

Calibration data shall be collected and reported, as a minimum, at the following field sensor (or field probe) alignment positions as indicated by the isotropy grade selected (see table A.4). It shall be noted, that in all cases, if there is a choice, the end of the field sensor (or field probe) containing the element(s) intercepting the applied field, is to be closest to the field source.

4.2.2.1 Maximum interception alignment

Each independent field sensor or field probe element shall be aligned for maximum interception of the applied field vector. For field sensors and field probes using dipoles for field interception, the dipole shall be considered the independent element. This alignment provides data on the base contribution of each field sensor or field probe independent element to the overall field measurement. The alignment also provides performance characteristics of each field sensor or field probe element.

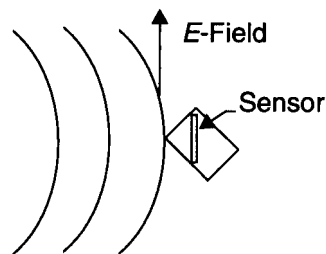


Figure 1—Maximum interception alignment

4.2.2.2 Physical major axis

The field sensor or field probe physical major axis is to be positioned perpendicular to the applied field vector. If the field sensor or field probe does not have a physical major axis, an orientation shall be selected and documented that reflects the positioning expected during normal use.

Once the field sensor or field probe is positioned and a field is established, the field sensor or field probe is rotated 360 ° around the physical major axis. The maximum measured field value, minimum measured field value, and the sensor orientation with respect to the incident field are to be recorded.

4.2.2.3 Physical minor axis

The field sensor or field probe physical minor axis is to be positioned so as to be perpendicular to the applied field vector. If the field sensor or field probe does not have a physical minor axis, an orientation shall be

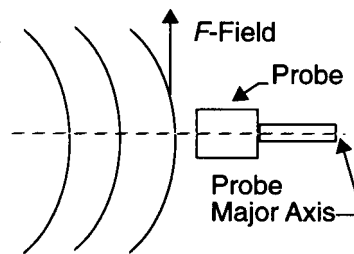


Figure 2—Physical major axis alignment

selected and documented that reflects the positioning expected during normal use. This orientation must be perpendicular to the one selected in 4.2.2.2 of this standard.

Once the field sensor or field probe is positioned and a field is established, the field sensor or field probe is rotated 360 ° around the physical minor axis. The maximum measured field value, minimum measured field value, and the sensor orientation with respect to the incident field are to be recorded.

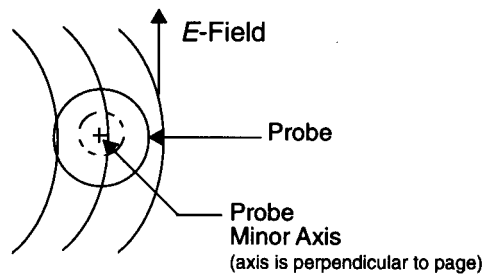


Figure 3—Physical minor axis alignment

4.3 Field probe or field sensor orientation during time domain calibration

For calibration purposes, the orientation of a particular time-domain field sensor depends on how it is going to be actually deployed. Given the wide variety of time-domain field sensor types, structural geometry, and the multitude of field sensor applications, there is not a fixed method for orientating a field probe for calibration. However, in many instances, the following calibration guidelines are quite useful.

- a) Usually information is sought about one or more vector components of the following four field quantities: the electric field intensity E , the electric flux density D , the magnetic flux density B , and the magnetic intensity field H [B29]. Different sensors have been developed and optimized to measure the various field quantities [B9]. In most sensor applications, information about a particular electromagnetic field component (its time derivative or some other linear operation(s) with respect to time) is of interest. Only in rare instances is information needed about all of the field components for a given measurement.
- b) For a field sensor calibration to be of maximum value, the calibration of a sensor should be performed in a manner that most closely simulates the way that it will be deployed in the actual measurement. All of these factors could significantly affect the measurement results obtained. Thus one should carefully address the role of the sensor orientation in space, means of mounting the sensor, cable connections (if any) to the sensor, as well as the orientation of the sensor when performing the calibration.

- c) In most cases, a given time-domain sensor can be calibrated by aligning it with respect to a given field component in the calibration setup to obtain a maximum response. Aligning a sensor in this fashion ensures maximum sensitivity, accuracy, and in many cases, minimum coupling to the undesired field components or other undesired field quantities.

5. Standard field generation methods

5.1 Frequency domain field generation

Under method A (calibration with a transfer standard) and method B (calibration using calculated field strengths), table 3 lists the devices and setups that shall be used to generate standard fields for calibrations. Annex B provides a detailed summary of these field generation methods. Annex B also provides constraints with respect to the physical parameters that must be considered when using the field generation methods listed. Additional information may be obtained from the listed references and the bibliographic references that are provided in the applicable clauses and subclauses of annex B.

Table 3—Methods of producing EM fields for frequency domain calibration

Field type	Frequency range	Field generation facility and device type	Controlling reference or standard	IEEE Std 1309-1996	Usage notes
<i>E</i> & <i>H</i>	9 kHz–200 MHz	TEM cell	IEEE Std C95.3-1991, 4.5.3	B.1	1
<i>H</i>	9 kHz–10 MHz	Helmholtz coil	IEEE Std C95.3-1991, 4.5.4	B.2	2
<i>E</i> & <i>H</i>	9 kHz–1 GHz	GTEM	—	B.6	3
<i>E</i>	200 MHz–450 MHz	Anechoic chamber/ open-ended waveguide	IEEE Std C95.3-1991, 4.5.1.3	B.3	—
<i>E</i>	450 MHz–40 GHz	Anechoic chamber/ pyramidal horn antennas	IEEE Std 291-1991, 2.5	B.4	—
<i>E</i>	300 MHz–2.6 GHz	Waveguide chamber	IEEE Std C95.3-1991, 4.5.2	B.5	4

NOTES

1—The TEM cell may be used up to 500 MHz provided the conditions specified in annex B are met. However, the preferred and most acceptable facility for *E*-Field generation above 200 MHz shall be the anechoic chamber with the open-ended waveguide and pyramidal horn antenna sources.

2—Helmholtz coils are not the preferred method of field generation, however, use shall be permitted when the required field strength cannot be generated in a TEM cell, and/or the field sensor or field probe is too large with respect to the TEM cell usage constraints noted in B.1. The use of Helmholtz coils is not applicable to ground plane field sensors and probes.

3—The Gigahertz Transverse Electric Magnetic (GTEM) cell is not a preferred field generation method. However, it may be used provided that a) the constraints and procedures in B.6 are followed, and b) in the event of conflict between calibration data, the data obtained using one of the other methods shall be deemed most acceptable.

4—A rectangular waveguide chamber may be used to calibrate field probes and sensors specifically used for microwave leakage field detection.

5.2 Time domain field generation

Under method C (calibration with a primary standard sensor), method B (calibration using calculated field strengths), and method A (calibration with a transfer standard), table 4 lists the test fixtures that shall be used to generate fields for calibrations. It is noted that these are different than those used for frequency domain calibrations because the requirements for reflections within the test cells are different. In the frequency domain the requirement is for small standing waves within the cell, which is equivalent to small standing wave ratio (SWR) due to impedance discontinuities at the input and output transitions, and also at transitions (such as bends) within the cell. In the time domain, the requirement is that impedance discontinuities be very small at the input transitions to the cell, and that reflections from the output sections, beyond the measurement point, be sufficiently late in time that they can be gated out of the data. For example, it has been found that the TEM cell may not meet these requirements due to the bends in the septum and the cell walls.

Time domain sensors are generally made and used for fast transients (high frequency), and are thus usually of the derivative response type, D -dot or B -dot. They are also very broadband, usually several decades in bandwidth. The test fixtures for calibration of these sensors are therefore also very broadband.

Table 4—Methods of producing EM fields for time domain calibration

Field type	Frequency range	Field generation facility and device type	Controlling reference or standard	IEEE Std 1309-1996
E & H	9 kHz–1 GHz	GTEM	None	B.6
E & H	100 kHz–20 GHz	Monocone	None	B.9
E & H	100 kHz–100 MHz	Parallel plate	None	B.7
E & H	100 kHz–20 GHz	Conical transmission line	None	B.8
E & H	9 kHz– 200 MHz	TEM	IEEE Std C95.3-1991, 4.5.3	B.1

6. Determining uncertainty

Measurement results shall be accompanied by quantitative statements of uncertainty. Uncertainty shall be determined per the methods shown in “ISO/IEC/OIML/BIPM Guide to the Expression of Uncertainty in Measurement (1993).” With respect to this, the approach described in 6.1 through 6.4 shall be used.

6.1 Standard uncertainty

Represent each component of uncertainty that contributes to the uncertainty of the measurement result by an estimated standard deviation u_i , termed standard uncertainty, equal to the positive square root of the estimated variance u_i^2 . Each component is either type A (statistically based) or type B (other method), as mentioned in [B66].

6.2 Combined standard uncertainty

Determine the combined standard uncertainty, u_c , of the measurement result, taken to represent the estimated standard deviation of the result, by combining the individual standard uncertainties u_i (and covariances as appropriate) using the *root sum of squares* (RSS) method.

Commonly, u_c is used for reporting results of determination of fundamental constants, fundamental metrological research, and international comparisons of realizations of SI units.

6.3 Expanded uncertainty

Determine an expanded uncertainty, U , by multiplying u_c by a coverage factor k : $U = ku_c$. The purpose of U is to provide an interval $y - U$ to $y + U$ about the result y within which the value of Y , the specific quantity subject to measurement and estimated by y , can be asserted to lie with a high level of confidence. Thus one can confidently assert that $y - U \leq Y \leq y + U$, which is commonly written as $Y = y \pm U$.

Expanded uncertainty U shall be used to report the results of all measurements other than those for which u_c has traditionally been employed. The value of k used for calculating U shall be 2. Using $k = 2$ gives a confidence level of approximately 95%.

6.4 Reporting uncertainty

Report U . (If only u_c is reported, due to traditional use, this must be noted on the calibration report.)

When reporting a measurement result and its uncertainty, include the following information in the calibration report:

- a) A list of all components of standard uncertainty, together with their degrees of freedom where appropriate, and the resulting value of u_c . The components should be identified according to the method used to estimate their numerical values as follows:
 - 1) those that are evaluated by statistical methods
 - 2) those that are evaluated by other methods
- b) A reference to or a detailed description of how each component of standard uncertainty is evaluated.

An example that can be used in determining the above mentioned items is provided in annex I.

7. Characteristics to be measured

7.1 Frequency domain calibration

7.1.1 Dynamic range (amplitude)

Calibration may be performed at one or more field strengths depending on the application. As an example, an application involving the measurement of fields from a microwave oven where there is one pass/fail field strength, calibration may be only needed at one amplitude to provide accurate measurement. As another example, an application involving EMI testing may require calibration at three amplitude levels per frequency at which calibration is performed, to provide accurate measurement for that application. The number of field strength amplitudes to be measured at each frequency of calibration shall be per agreement between the customer and the calibration organization. The number of field strength amplitudes to be measured at each frequency of calibration shall be documented in the calibration report. Annex A provides requirements for specifying grades of calibration and selection of calibration amplitudes.

7.1.2 Frequency response

Calibration may be performed at one or more frequencies, depending on the application. As an example, an application involving the measurement of fields from a microwave oven where there is one frequency of con-

cern, calibration may be only needed at one frequency to provide accurate measurement. As another example, an application involving EMI testing (where the probe is used over a wide range of frequencies) may require calibration at several frequencies, to provide accurate measurement for that application. The number of calibration frequencies shall be per agreement between the customer and the calibration organization. The frequency of each measurement shall be documented in the calibration report. Annex A provides requirements for specifying grades of calibration and selection of calibration frequencies.

7.1.3 Isotropy

All isotropic field probes shall be evaluated for their isotropic response. The isotropy of a field probe is difficult to measure, therefore anisotropy (A) is usually measured. Anisotropy [B43] is the maximum deviation from the geometric mean of the maximum response and minimum response. The field probe is to be operated in either its square law or its linear region to obtain valid data. Annex A provides requirements for specifying grades of calibration with respect to isotropy. The equations for anisotropy are as follows:

$$A = 10 \log_{10} \left[\frac{S_{\max}}{\sqrt{S_{\max} S_{\min}}} \right] \quad (1)$$

if S is the measured amplitude proportional in power density units.

or

$$A = 20 \log_{10} \left[\frac{S_{\max}}{\sqrt{S_{\max} S_{\min}}} \right] \quad (2)$$

if S is the measured amplitude in field strength units.

7.1.4 Response time (optional)

The response time of the field sensor (or field probe) is defined as the time required for the field sensor (or field probe) to indicate 90% of the steady state field value, when the field is applied as a step function (see figure 4). The time measurement shall include any analog filtering effects, analog-to-digital conversion rates, and sampling rates.

Response time must be considered in applications where the probe or sensor assembly may be exposed to a field for only a short time, such as: 1) a probe using multiple sensors to map a field where the output of each sensor is sampled and processed by the metering equipment, 2) EMI testing where the probe is part of an autoleveling system for swept frequency testing.

The response time is measured as the time between the application of the input signal and the first field sensor (field probe) indication that exceeds 90% of the steady state value.

This method includes the test setup response time in the field sensor (or field probe) response time, thus giving a worst case result.

Response time is not required to be measured unless requested. Annex A provides requirements for specifying grades of calibration with respect to response time.

7.1.5 Time constant (optional)

Some field sensors (field probes) are used for making burst peak measurements. Applications include energy density (E^2) measurements on rotating beam radars. For these applications, the field sensor's (or field

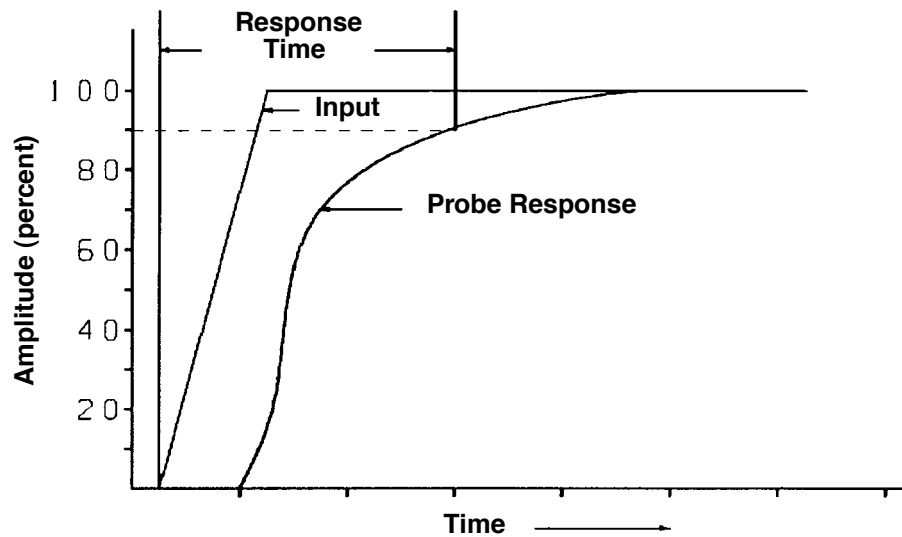


Figure 4—Typical response time curve

probe's) time constant must be known. The time constant is generally measured to the meter recorder output of such a probe. The general equation relating maximum hold meter indication to illumination period is

$$K = \frac{E_{\text{hold}}}{E_{\text{cw}}} = 1 - e^{-t/T} \quad (3)$$

where

E_{hold} is Maximum meter indication

E_{cw} is Continuous wave indication

K is Maximum hold indication ratio (actual maximum, if constantly illuminated)

T is Time constant

t is Illumination period

7.1.6 Modulation (Optional)

For EMC testing, modulation of the test field is often required. Depending on the procedures used in EMC testing, calibration of a field probe or sensor in a modulated field may be required. Other applications and uses of field probes and sensors may also require field strength measurements under modulated conditions. With respect to EMC testing, the modulation is usually AM or PAM.

Various forms of angle modulation, such as frequency modulation (FM), phase modulation (PM), frequency shift keying (FSK), etc., are sometimes used. Most field sensor and field probes will not respond to such modulation. Most field probes and field sensors see FM as if it were continuous wave (CW). Some complex field probes that work into receivers can detect these forms of modulation.

Calibration under the conditions of a modulated field is not required unless requested. Annex A provides requirements for specifying grades of calibration with respect to modulation.

7.2 Time domain calibration

Sensors and probes for making time domain transient measurements must be calibrated in such a manner as to determine how accurately they can measure a transient. Pulse fidelity is defined as how faithfully the output of the sensor or probe replicates the wave shape of the incident field. For example, if the incident field were a perfect step, what is the deviation of the output signal from this step, normalized to the sensitivity of the sensor? These deviations from ideal include the sensitivity, rise time, fall time, overshoot, and ringing of the sensor response. Time domain sensors are inherently broadband in frequency response, usually two decades of usable bandwidth or more, and can be used to make frequency domain measurements.

7.2.1 Amplitude

Amplitude calibration is the calibration of the sensitivity of the sensor or probe. The sensitivity is the transfer function of the sensor for converting an electromagnetic field component into an electrical signal, for example, from volts/meter into volts. The sensitivity for a given sensor is specified, and the deviation of the actual sensor response from its specified value must be calibrated. For primary standard sensors, this calibration is performed in terms of their geometry and Maxwell's laws. For other sensors and probes, it is performed by comparison to a primary standard sensor.

7.2.2 Dynamic range

Calibration may be performed at one or more field strengths, depending upon the application. As an example, many time domain sensors have been designed for the measurement of a simulated nuclear electromagnetic pulse (EMP) in which field strengths vary from a few kilovolts per meter to the breakdown strength of air (about 3 MV/m). Usually, calibration at very high field strengths is impractical, but linear performance of the sensors is assumed if they prove to be linear with field strength at lower levels; electrical flashover is the limiting nonlinear factor. The number of field strength amplitudes to be measured shall be per agreement between the customer and the calibration organization. Annex A provides requirements for specifying grades of calibration and selection of calibration amplitudes.

7.2.3 Rise time

Rise time is defined as the first transition duration. It should be measured with an instrumentation system that has a rise time of at least five times faster than that of the sensor being calibrated. If this is not possible, then the instrumentation system must be at least as fast as the sensor, and deconvolution techniques used to determine the sensor rise time.

7.2.4 Fall time (droop)

Fall time is defined as the last transition duration. It should be measured with an instrumentation system that has a step voltage time that is at least five times longer than the fall time of the sensor being calibrated.

7.2.5 Overshoot and ringing

Overshoot is the level to which the response of the sensor overshoots the final level measured in response to a step input. Some overshoot is necessary in order to realize fast rise times, but it should not be excessive. Ringing is the damped oscillation that occurs when a sensor response is underdamped. Overshoot and ringing occur simultaneously, and should be measured along with the rise time. Annex I describes the waveforms in more detail.

8. Procedures (measurement techniques)

8.1 Transfer standard sensors and probes

The principle of this method is to have a stable and reliable sensor (probe) that has been calibrated accurately for use as a “transfer standard.” This standard probe is used to measure the field strength produced by an arbitrary RF field-generating device, e.g., antenna or TEM cell, over the same location in the standard calibration field that the transfer standard probe occupied, and the uncalibrated probe’s meter reading is compared with the known, measured value of the field, based on data obtained with the transfer standard probe. The transmitter and field-generating device used during this process should generate a field that has the desired magnitude and that is constant with time, and the field should be uniform over the region where the probe under calibration is placed. Accuracies of about ± 2 dB to ± 3 dB are readily attainable with this method, and improved accuracy is possible if special care is taken. The advantages of this approach are convenience, reliability, and simplicity.

A potential source of error when using the transfer standard to calibrate another probe is the possible difference in the pickup patterns of the two sensors. Also, in the near field of a radiator, the effective size of the probe’s sensing area is important. Ideally, the transfer standard and probes under calibration should be identical and the calibration should be conducted in a field relatively free of spatial variations due to multipath interactions between the probe, the radiator, the anechoic chamber and the other field generating components, and near-field gradients. Practically, the transfer standard and the probe under calibration are not identical, and this needs to be accounted for in determining calibration uncertainty. In TEM cells or parallel plate transmission systems, capacitive coupling between the probe and the septum (center plate) and walls of the cell can create calibration errors.

The transfer standard probe should be stable, rugged, and not easily damaged. It should have a large dynamic range, and should cover a broad frequency range.

8.2 Transfer and working standard sensors and probes

The transfer standard probe or sensor can be used to calibrate a set of working standard probes or sensors. These shall be of the same type as the transfer standard, and compared directly to it in a test cell. The absolute calibration of these working standard probes will be less accurate than that of the transfer standard, and shall be carefully documented. These can then be used for routine calibrations of production probes and sensors, keeping the transfer standard protected from damage. The working standard probes shall be recalibrated with reference to the transfer standard on a scheduled basis, and a history of the measurements maintained.

8.3 Frequency domain calibration procedure

Under methods A and B (see 4.1, table 2), calibration involves placing the field sensor or probe under calibration in a known field with orientations described in 4.2, as the characteristics described in clause 7 are measured. The individual procedures and significant items of uncertainty are described for each method of field generation in annex B. The number of measurement points for each characteristic are defined based on the grades of calibration that are defined in annex A.

8.3.1 Lead/cable effect

The lead/cable attached to any field sensor/probe shall be positioned to minimize field pickup. Usually, this is accomplished by running the lead/cable perpendicular to the incident electric field vector or component, positioning the lead/cable end of the field sensor/probe away from the incident field source, and maximizing the distance between the incident field source and the lead/cable end of the field sensor/probe. The lead/cable placement shall be maintained for all calibration runs and shall be made available to all users and doc-

umented in the calibration report. Uncertainty due to lead/cable effects shall be considered and presented in the statement of measurement uncertainty described in clause 6.

Alternatively, if the calibrating organization can, by test or other methods, show that the lead/cable orientation has no significant effect, then this information shall be made available to all users and documented in the calibration report.

8.3.2 Frequency domain measurement procedures

Select the field generation facility and field producing device from table 3 for the required frequency range and field type.

The following constraints are recommended for accurate and repeatable measurements:

- a) Voltage standing wave ratio (VSWR) should be minimized. This can be measured with a dual directional coupler and power meters or with a network analyzer.
- b) Device impedance over the frequency range in use should be typically $50\ \Omega$ unless otherwise specified by the manufacturer. This impedance can be measured with a time domain reflectometer or a network analyzer.
- c) The chosen field generation facility shall be used in its single mode frequency range.
- d) The maximum test volume in the following facilities should be as follows:
 - 1) One-third of the height between the floor and the septum (center plate) for the TEM cell and GTEM cell [B20].
 - 2) One-third of the volume of the waveguide for the rectangular waveguide [B27].
 - 3) The quiet zone of the anechoic chamber.
 - 4) Six-tenths of the coil radius for Helmholtz coils [B13].

NOTE—The limitations stated in items 1) and 2) are due to loading effects.

- e) The harmonic content of the net applied power shall be at least 30 dB below the fundamental for valid CW measurements. This can be measured with a spectrum analyzer, RF receiver, or with a power meter and filters.
- f) Ground plane sensors and probes shall be properly bonded to the ground plane of the selected field generating facility.
- g) The field sensor (field probe) mounting fixture shall be constructed to minimize the field perturbation.

8.3.2.1 Frequency range and/or dynamic range measurements procedure

This measurement can be performed with the field sensors or the field probes. The field probes shall be appropriately aligned. The procedure for measurement is as follows:

- a) Prepare the field generation facility by confirming the calibration and functionality of the equipment needed for this test. Perform a system check with a check standard and control charts.
- b) Inspect the field sensor (field probe) to assure that it meets all site requirements. For example, check if the field probe exceeds the maximum size requirements for the facility.
- c) Place the field sensor (field probe) to be calibrated so that it is aligned with the incident field. The field sensor (field probe) orientation shall be selected and documented. The orientation selected shall be a repeatable position or be one expected during normal use.
- d) For each previously selected frequency and field level, set the frequency and field level required and record the response of the field sensor (field probe) for that particular frequency and field level. Proceed until data are obtained for all required configurations.