



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

IEEE Electromagnetic Compatibility Society

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

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

Keywords: calibration, electric field measurement, electromagnetic, field probe, field sensor, measurement instrumentation uncertainty

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Introduction

This introduction is not part of IEEE Std 1309-2005, IEEE Standard for Calibration of Electromagnetic Field Sensors and Probes, Excluding Antennas, from 9 kHz to 40 GHz.

This standard provides calibration methods for electromagnetic (EM) field sensors and probes, excluding antennas per se, for the frequency range of 9 kHz to 40 GHz. The original version of this standard was developed and released in 1996 in response to the electromagnetic compatibility (EMC) test and measurement community's need for standard (consensus) methods of calibration for commonly used EM field sensors and probes. This version of the standard provides updates to the original 1996 version to clarify items that some users may have found difficult to understand, to expand details and examples with respect to determining and expressing calibration uncertainty, and to present additional technical background information. Also, this version includes calibration methods for specific field probes used for commercial electronic products radiated immunity testing and *H*-field probe calibrations applicable to ANSI C63.19 [B1]^a testing.

This standard provides calibration methods that are appropriate to various frequency ranges and user requirements. Methods for creating standard electric and magnetic fields used for calibration are presented. Because the specific calibration needs for a particular field probe or sensor depend on its intended use, a method to specify and communicate calibration requirements is provided. This standard also provides details for determining and expressing calibration uncertainty.

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IEEE Standard for Calibration of Electromagnetic Field Sensors and 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 probes, excluding antennas per se, for the frequency range of 9 kHz to 40 GHz. Field injection probe (i.e., transmitting) calibration is not covered by this standard. This standard is not applicable to electromagnetic interference (EMI) emission measurement antennas, which have sometimes been referred to as probes, such as active and passive rod and loop antennas, generally used in the frequency range of 9 kHz to 30 MHz. Calibration of immersible and implantable probes for specific absorption rate (SAR) testing is not considered in this standard; IEEE Std 1528TM-2003 [B57]¹ should be consulted for guidance on SAR probe calibrations.

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

Methods for creating standard electric and magnetic fields are described in Clause 5. Each method has calculable field strengths and associated uncertainties. Each standard field method is individually addressed. The field generation information was obtained from IEEE Std 291TM-1991² and from IEEE Std C95.3TM-2002, with additional information from sources listed in the bibliography.³ Further information on probe calibration methods and applications guidance for frequencies below 100 kHz is given in IEEE PC95.3.1TM [B53], IEEE Std 1308TM-1994 [B54], and IEEE Std 1460TM-1996 [B55]. Calibration methods for probes used for electronic-product radiated immunity testing in accordance with IEC 61000-4-3 [B49] are

¹Numbers in brackets correspond to the numbers of the bibliography in Annex J.

²Information about references can be found in Clause 2.

³For information purposes, it is noted that other documents describing probe calibrations have recently been developed or published. ISO Technical Report 10305-1 [B57] describes test setups similarly to IEEE Std 1309, but includes additional low-frequency setups. ISO Technical Report 10305-2 [B58] is a direct adoption of IEEE Std 1309-1996. VDI/VDE/DGQ DKD 2622 Part 10 [B120] describes frequency domain calibrations and measurement uncertainties using transverse electromagnetic (TEM) and gigahertz transverse electromagnetic (GTEM) cells. Finally, draft IEC 61000-4-33 [B51] has a thorough description of setups and issues for time domain probe calibrations and use for EM pulse testing.

described in Annex D. Calibration methods for probes used for testing near-fields of mobile telephones in accordance with ANSI Std C63.19-2001 [B1] are described in Annex E.

Most EM 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 EM 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 EM field probes and sensors that can accurately replicate the transient wave shapes, thus requiring an equivalent bandwidth of decades. The calibration of time domain sensors necessitates procedures that are significantly different from those for the frequency domain sensors.

The electric or magnetic field sensor and/or 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.

1.2 Purpose

This standard provides consensus calibration methods for EM field sensors and probes. Calibration organizations and other users need uniform calibration methods to obtain consistent results. The calibration methods of this standard will produce results readily traceable to a national measurement institute.⁴

1.3 Background

Antenna calibration is the subject of existing standards, such as IEEE Std C63.5™-2004. Although field sensors and probes are antennas in a broad sense of the term, actual applications of antennas, field sensors, and field probes are generally different.

Antennas are designed to transmit or receive with a maximum coupling to the EM field, and thus antennas typically perturb the EM field. Field sensors and probes are designed to measure with minimal perturbation of the EM field.

Antenna calibrations are based on various standards containing various procedures for determining antenna factors and other antenna parameters. However, attempts at applying antenna calibration methods to field sensors and probes usually produce inconsistent results among calibration organizations and other laboratories. IEEE Std 1309 is intended to provide consistent methods and results for the various probe calibration methods in use worldwide.⁵

1.4 Grades of calibration

The extent to which a field probe or 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, the specific test points measured (if applicable), and a statement of uncertainty (i.e., error) shall be provided to the user. This standard uses a concept of *grades of calibration*, having corresponding alphanumeric designations to represent the selection and extent of parameters evaluated in a calibration. Applicable characteristics of the calibration include, but are not limited to, the following (see Clause 7, 9.5, and Annex A):

⁴National measurement institute refers to, for example, the National Institute of Standards and Technology (NIST) in the United States, the National Physical Laboratory (NPL) in the United Kingdom, Physikalisch-Technische Bundesanstalt (PTB) in Germany, National Measurement Institute (NMI) in Australia, etc.

⁵Examples of probe and field strength measurement interlaboratory comparisons are given in Agnello, et al. [B2], de Vreede, et al. [B33], and Kanda, et al. [B65].

- Type of calibration (time domain or frequency domain)
- Amplitude level(s) measured
- Frequencies measured
- Response time
- Time constant
- Modulation response
- Isotropy
- Immersion of entire probe or sensors only
- Measurement uncertainty of the calibration

Annex A provides guidelines to describe the extent of the measurements (i.e., calibration grade) for each probe characteristic.

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 a 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. 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 sensors; the free field probes and sensors are placed in a field that completely surrounds them, and the ground-plane field probes and sensors are mounted on the ground plane with respect to the field source. The generic categories of EM field probes and sensors are given in Table 1.

Table 1—Generic categories of 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 (dipole)	<i>D</i> -dot (monopole)
<i>B</i> -dot (loop)	<i>B</i> -dot (half-loop)

B-dot and *D*-dot probes and sensors measure the time derivative of the magnetic field flux density and the electric field flux density, respectively. Some sensors and probes are designed to directly measure the electric field (*E*) or the magnetic field (*H*). *E*-field sensors and probes are the Thevenin equivalent circuit for an electrically small dipole antenna, while the *D*-dot sensor or probe is the Norton equivalent circuit. Similarly, the *H*-field sensor is the Norton equivalent for an electrically small loop antenna, while the *B*-dot is the Thevenin equivalent. These fields are related by $D = \epsilon_r \epsilon_0 E$ and $B = \mu_r \mu_0 H$. In general, $\epsilon_r \epsilon_0$ and $\mu_r \mu_0$ will be fixed quantities over the intended usage range of the probe or sensor. There are specialized cases where ϵ_r and μ_r will not be linear, time invariant, or isotropic such as for source region EMP (see Baum, et al. [B15]). For purposes of this standard, ϵ_r and μ_r are assumed to be constant parameters.

This standard applies also to field probes that display power density [i.e., maximum permissible exposure (MPE)]. Typically, the response of these field probes is based on *E*-field or *H*-field strength, and far-field conditions are assumed when calculating power density from field strength. More information on probe calibration, use, and measurement uncertainties for evaluations of radio frequency (RF) EM fields with respect to human exposure reference levels is given, for example, in IEEE Std C95.3™-2002 and Merewood [B96].

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 non-ionizing radiation. See IEEE Std C95.1™-1999, IEEE Std C95.3-2002, and the references cited in those standards, as well as other appropriate documents.

2. Normative references

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

ANSI Std Z540-1-1994, Calibration Laboratories and Measuring and Test Equipment—General Requirements.⁶

ANSI Std Z540-2-1997, U.S. Guide to the Expression of Uncertainty in Measurement.

IEEE Std C63.5™-2004, American National Standard for Electromagnetic Compatibility—Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration of Antennas (9 kHz to 40 GHz).^{7, 8}

IEEE Std C63.14™-1998, American National Standard Dictionary for Technologies of Electromagnetic Compatibility (EMC), Electromagnetic Pulse (EMP), and Electrostatics Discharge (ESD).

IEEE Std C95.1™-1999, IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz—Supplement.

IEEE Std C95.3™-2002, IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields with Respect to Human Exposure, 100 kHz–300 GHz.

IEEE Std 291™-1991, IEEE Standard Methods for Measuring Electromagnetic Field Strength of Sinusoidal Continuous Waves, 30 Hz to 30 GHz.⁹

ISO (BIPM/IEC/IFCC/ISO/IUPAC/IUPAP/OIML) *Guide to the Expression of Uncertainty in Measurement*, 1995 (referred to as *the GUM*).¹⁰

ISO/IEC 17025:1999, General requirements for the competence of testing and calibration laboratories.¹¹

NCSL RP-12, Recommended Practice for Determining and Reporting Measurement Uncertainties, 1994.¹²

⁶ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

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⁹Administratively withdrawn by IEEE in January 2004; may be available from IEEE or, for example, at some university technical libraries.

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¹¹ISO/IEC publications are available from the ISO Central Secretariat, Case Postale 56, 1 rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse (<http://www.iso.ch/>). ISO/IEC publications are also available in the United States from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://global.ihs.com/>). Electronic copies are available in the United States from the American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

NIST Handbook 150, National Voluntary Laboratory Accreditation Program Procedures and General Requirements, July 2001.¹³

NIST Technical Note (TN) 1297-1994, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results.

UKAS LAB 34:2002, The Expression of Uncertainty in EMC Testing.¹⁴

UKAS M3003:1997, The Expression of Uncertainty and Confidence in Measurement.

3. Definitions

For the purposes of this standard, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B52], should be referenced for terms not defined in this clause. This clause contains or defines only definitions relating to field sensor and probe calibration that are not listed in IEEE Std C63.14-1998. The terms “probe” and “sensor” as defined in this clause are for the purposes of this standard; in industry, these terms are often used interchangeably.

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

3.2 field probe: (A) An electrically small field sensor or set of multiple field sensors with various electronics (e.g., diodes, resistors, amplifiers). The output from a field probe cannot be theoretically determined from easily measured physical parameters. Field probes include *B*-dot and *D*-dot sensors that require a balanced-to-unbalanced transformer (balun) on the output of the sensor (note that not all *B*-dot and *D*-dot sensors require a balun). (B) A minimally perturbing device used for measuring a component of a radio frequency (RF) field in a medium. A probe contains the following components: 1) An electrically small (in the medium) sensor (or sensors) for detecting the RF field component of interest; 2) A means for converting the RF signal to a proportional dc or slowly varying ac signal; 3) A balanced high-impedance resistive transmission line to extract the rectified signal.

3.3 field sensor: An electrically small device without electronics (i.e., passive) that is used for measuring electric or magnetic fields, with a minimum of perturbation to the field being measured. The field sensor transfer function [i.e., ratio of output-signal-to-input-electromagnetic (-EM) field] can be theoretically determined from measured physical (i.e., geometrical) properties (e.g., length, radius, area) 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.

3.4 flashover: A disruptive discharge around or over the surface of an insulating member, between parts of different potential or polarity, produced by the application of voltage where the breakdown path becomes sufficiently ionized to maintain an electric arc.

3.5 free field: The electromagnetic (EM) 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

¹²NCSL publications are available from the National Conference of Standards Laboratories, 1800 30th Street, Suite 305B, Boulder, CO 80301-1032, USA, (<http://www.ncsli.org/>).

¹³NIST publications are available from the National Institute of Standards and Technology, Gaithersburg, MD 20899, USA, (<http://www.nist.gov>).

¹⁴UKAS publications are available from the United Kingdom Accreditation Service, 21-47 High Street, Feltham, Middlesex, UK, (<http://www.ukas.com/>).

electric and magnetic vectors are transverse to the propagation vector and to each other [i.e., transverse electromagnetic (TEM) mode], and their ratio yields the intrinsic impedance of free space. *Syn:* **free-space field**.

3.6 free-space field: *See:* **free field**.

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

3.8 ground-plane field: The electromagnetic (EM) 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's law, and the total tangential magnetic field to the surface current density by Ampere's law.

3.9 isotropy (probe): A measure of the degree to which the response of a field probe is independent of the polarization and direction of propagation of the incident field. Isotropy is the ratio, typically expressed in decibels, of the highest to lowest indication from the probe exposed to a constant field strength when the probe orientation is varied through the range of angles defined in the test specification.

3.10 maximum permissible exposure (MPE): The root-mean-square (rms) and peak electric and magnetic field strengths, their squares or the plane wave equivalent power densities associated with these fields, and the induced and contact currents to which a person may be exposed without harmful effect and with an acceptable safety factor. In some guidelines, they are referred to as *investigation levels* or *reference levels*.

NOTE—Probes used for measuring MPE are often called *power-flux-density probes* or *power-density probes*.¹⁵

3.11 ortho-angle: The angle between the three-dimensional (i.e., spatial) diagonal of a cube and each of the adjacent cube edges, equal to 54.7°. When the individual orthogonal sensing elements of an isotropic probe assembly are aligned with the three cube edges, the spatial diagonal of that cube may be described as the ortho-axis of the assembly. When the probe assembly is rotated through 360° about its ortho-axis, in a linearly polarized electric or magnetic field, it is possible to respectively align each axis of the sensor with the field vector (i.e., maximum coupling), while the two remaining axes are normal to the field (i.e., minimum coupling). Such an orientation and rotation is used to determine a measure of the isotropy or rotational response of the probe assembly. *See also:* **ortho-axis, isotropy**.

3.12 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, which is the angle between the diagonal of a cube and the edge of each side at the trihedral corners of the cube. *See also:* **ortho-angle**.

3.13 physical major axis: The direction along the real or “virtual” handle of the field probe.

NOTE—This term may not be applicable to all types of field probes.

3.14 physical minor axis: The direction orthogonal to the physical major axis.

NOTE—This term may not be applicable to all types of field probes.

3.15 readout device: An electronic apparatus for acquiring the probe output signal and converting it to a signal that can be read by the data acquisition and analysis apparatus. *Syns:* **readout electronics, meter, recorder, display, monitor electronics**.

3.16 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 and thus gives worst-case results.

¹⁵Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

3.17 transverse electromagnetic (TEM) waveguide: Open or closed transmission line system, in which a wave is propagating in the TEM mode to produce a specified field for testing or probe calibration purposes. Examples include TEM cell, gigahertz transverse electromagnetic (GTEM) cell, two-plate stripline, three-plate stripline. *Syns:* **TEM device, transmission line simulator, EMP simulator.**

3.18 time constant: A measure of the time required for a field probe output to reach a stable, repeatable reading. The measurement includes test setup, metering unit, cables, etc., and thus is a worst-case result. The measurements assume an exponential response of the field probe. The time constant is the time required to reach $(1 - 1/e)$ of the steady-state value (approximately 63.2%). The time required to reach 95% of the steady-state value is approximately equal to three time constants. The time constant is used specifically for burst peak field strength measurements.

3.19 time domain calibration: A result that is the response function of the probe or sensor to a time domain transient (i.e., pulse).

3.20 transfer function: The ratio of the device output signal (e.g., voltage, current, frequency, meter reading) 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. *Syns:* **response, sensitivity, probe factor, calibration factor.**

3.21 transfer standard: An electrically small field probe or sensor. This device 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 Calibration methods

This standard provides three general calibration strategies, 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 probes. However, calibration, as defined by this standard, requires the results to be accompanied by a description of the method used and quantitative statements of uncertainty, as described in Clause 6.

Table 2—Three calibration methods

Method	Description
A	Calibration using the transfer standard (i.e., a field sensor or probe similar to the one being calibrated), which has traceability to a national standards laboratory (see 8.2). The transfer standard is used to measure and calibrate the field used for calibrating the field sensor or probe under calibration.
B	Calibration using calculated field strengths. The probe under calibration is placed in a reference field calculated based on the geometry of the field generator and the field generator measured input parameters (see Clause 5).
C	Calibration using a primary standard (i.e., reference) sensor, which contains no active or passive electronic devices, with a response that is mathematically calculable from the shape, size, and Maxwell's equations and, therefore, has its calibration traceable to a national standards laboratory, based on international standards for length and other appropriate physical quantities (see IEC Draft 61000-4-33 [B51] and Sower [B116]). A primary standard sensor is used to determine the field strength that is used to calibrate a probe under calibration.

Method A, calibration with a transfer standard, is also known as the standard probe method; Method B, calibration using calculated field strengths, is also known as the standard field method (see IEEE Std C95.3-2002). It should be noted that Method C, along with its resulting uncertainty, is applicable only to the field sensor calibrated (i.e., primary standard sensor) and thus does not address uncertainty resulting from the characteristics of connectors, cables, and/or environmental disturbances and the like, which may add additional uncertainty in actual use.

4.2 Field sensor or 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 probe response. Directional and positional effects include isotropy and other qualitative differences in response depending on probe system orientations relative to field sources. In addition, if so equipped and intended for use in normal operation, accessories necessary to operate the sensor or probe, such as cable or meter unit, shall be verified as not affecting the validity of the calibration. The accuracy may be affected by field perturbation and by losses in the accessory (e.g., cables, meter units); each accessory shall be checked for having directional and positional effects and accuracy effects on the measurement being made. In general, these statements apply only to free field probes and sensors and not to ground-plane field probes and sensors because for ground-plane device cables are typically routed on or under the ground plane.

4.2.2 Calibration data collection

Calibration data shall be collected and reported, at a minimum, for the field sensor or probe alignment positions¹⁶ described in 4.2.2.1, 4.2.2.2, and 4.2.2.3 as indicated by the isotropy grade selected (see Table A.4). In all cases, the part of the field sensor or probe containing the element(s) and intercepting the applied field shall be closest to the field source.

4.2.2.1 Maximum reception alignment

Each independent field sensor or probe element shall be aligned for maximum reception of the applied field vector (see Figure 1). For example, for field sensors and probes using dipoles for reception, the dipole shall be considered the independent element. This alignment provides data on the base contribution of each individual field sensor or probe element independent of the overall sensor or probe response. This alignment also provides performance characteristics of each field sensor or probe element. If orientation of the field sensor or probe elements is not described or illustrated in the manufacturer's documentation, the maximum reception alignment shall be determined experimentally.

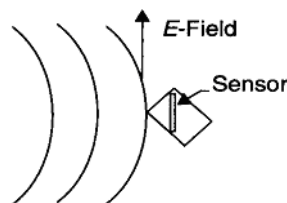


Figure 1—Maximum reception alignment (E-field example)

¹⁶An alternative that has been used to describe probe orientation during calibration is the notation PE (i.e., handle along the *E*-field vector), PH (i.e., handle along the magnetic field vector), and PS (i.e., handle in direction of propagation). Usually these orientations yield the upper and lower bounds of anisotropy.

4.2.2.2 Physical major axis alignment¹⁷

The physical major axis of a field sensor or probe shall be positioned perpendicular to the applied field vector and parallel to the propagation direction (see Figure 2). If the field sensor or 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 probe is positioned and a field is established, the field sensor or 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 at the maximum and minimum response positions are to be recorded.

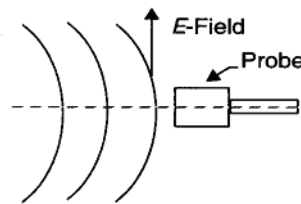


Figure 2—Physical major axis alignment (E-field example)

4.2.2.3 Physical minor axis alignment

The physical minor axis of a field sensor or probe shall be positioned perpendicular to the applied field vector and perpendicular to the propagation direction (see Figure 3). If the field sensor or probe does not have a physical minor axis, an orientation shall be selected and documented that reflects the positioning expected during normal use. This orientation must be perpendicular to the one used for testing in accordance with 4.2.2.2.

Once the field sensor or probe is positioned and a field is established, the field sensor or 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 at the maximum and minimum response positions are to be recorded.

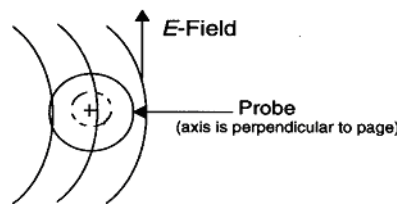


Figure 3—Physical minor axis alignment (E-field example)

¹⁷Physical major axis alignment is analogous to orientations for polarization ellipticity of IEEE Std C95.3-2002 and for axial isotropy of IEEE Std 1528-2003 [B56].

4.3 Field probe or sensor orientation during time domain calibration¹⁸

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 strength E , the electric flux density D , the magnetic flux density B , and the magnetic field strength H (see Johnk [B59]). Different sensors have been developed and optimized to measure the various field quantities (see Baum, et al. [B15]). In most sensor applications, information about a particular EM field component [e.g., 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. Certain parameters could significantly affect the measurement results obtained. Thus the role of the following parameters should be carefully addressed: sensor orientation in space, means of mounting the sensor, cable connections (if any) to the sensor, and 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

Table 3 lists the devices and setups that shall be used to generate standard fields for probe and sensor calibrations under Method A (i.e., calibration with a transfer standard), Method B (i.e., calibration using calculated field strengths), and Method C (i.e., calibration with a primary standard). 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 various field generation methods. Additional information may be obtained from the reference and bibliographic documents that are referenced in the applicable subclauses of Annex B. Annex D and Annex E contain additional information for some of these setups for specific test requirement applications.

Table 3 indicates which field generation devices can be used for frequency domain calibrations, time domain calibrations, or both. Each device/setup listed in Table 3 has its own advantages and disadvantages as discussed in the usage guidelines following Table 3 and in Annex B.

In the frequency domain, the test devices that can be used for both time and frequency domain calibrations will ideally have small standing waves [i.e., a small voltage standing wave ratio (VSWR)]. The VSWR is influenced by impedance discontinuities at the input and output sections as well as by transitions, e.g., bends in the conductors or walls. For these same devices in the time domain, minimal impedance discontinuities are important for very fast rise times (i.e., less than approximately five nanoseconds for laboratory-sized calibration devices). These discontinuities can occur at the input and output (i.e., termination) of the field generation device as well as at transitions within the device. In practice, these VSWR and impedance discontinuities are interrelated. Both should be taken into account in the design of the field generation device.

¹⁸Similar considerations apply for some frequency domain probe calibrations.

Table 3—EM field generation setups for probe and sensor calibrations

Field type	Usage (T=time, F=frequency)	Frequency range	Field generation setup (site and transducer)	Related standard cross- reference	Annex B cross- reference (in this standard)	Usage guidelines
<i>E & H</i>	T, F	9 kHz– 200 MHz	TEM cell	IEEE Std C95.3-2002, 5.5.1.3	B.1	2, 6, 8
H	F	9 kHz– 10 MHz	Helmholtz coil	IEEE Std C95.3-2002, 5.5.1.4	B.2	3, 8
E	F	200 MHz– 450 MHz	Anechoic chamber/ open-ended waveguide	IEEE Std C95.3-2002, 5.5.1.1	B.3	4
E	F	450 MHz– 40 GHz	Anechoic chamber/ pyramidal horn antennas	IEEE Std 291- 1991, 2.5; IEEE Std C95.3-2002, 5.5.1.1	B.4	4
E	F	300 MHz– 2.6 GHz	Waveguide chamber	IEEE Std C95.3-2002, 5.5.1.2	B.5	7
<i>E & H</i>	T, F	9 kHz–1 GHz	GTEM	IEEE Std C95.3-2002, 5.5.1.3.7	B.6	5, 6, 8
<i>E & H</i>	T, F	9 kHz– 100 MHz	Parallel plate	None	B.7	8, 9
<i>E & H</i>	T, F	9 kHz– 20 GHz	Conical transmission line	None	B.8	8, 9
<i>E & H</i>	T	100 kHz– 20 GHz	Monocone	None	B.9	10
Usage guidelines 1) Related standards shall be consulted for details not contained in this standard. 2) The TEM cell methods shall be used up to 200 MHz provided the conditions specified in Annex B are met. However, the preferred and most acceptable facility for <i>E</i>-field generation above 200 MHz shall be the anechoic chamber with the open-ended waveguide and pyramidal horn antenna sources. Open-ended waveguide and pyramidal horn antenna methods are not well suited for probes and sensors mounted on a ground plane. For ground-plane field probes and sensors, the parallel plate transmission line with conical feed sections shall be used up to 1 GHz provided the constraints in B.7 are met. Above 1 GHz, the conical transmission line or the monocone shall be used. 3) Helmholtz coils are not a preferred field generation method. However, use shall be permitted when the required field strength cannot be generated in a TEM cell and/or the field sensor or 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. 4) Some anechoic chambers are applicable for electronic-product electromagnetic compatibility (EMC) testing at frequencies below 200 MHz, but consensus methods for standard field generation in anechoic chambers for frequencies below 200 MHz and suitable for probe calibrations have not been defined. 5) The GTEM cell is not a preferred field generation method. However, it can be used provided that the constraints and procedures in B.6 are followed and provided that, in the event of conflict between calibration data, the data obtained using one of the other methods shall be deemed most acceptable.						

Table 3—EM field generation setups for probe and sensor calibrations (*continued*)

Field type	Usage (T=time, F=frequency)	Frequency range	Field generation setup (site and transducer)	Related standard cross-reference	Annex B cross-reference (in this standard)	Usage guidelines
Usage guidelines (<i>continued</i>)						
6) TEM and GTEM cells can be used at higher frequencies with Method A (i.e., transfer standard) (see 8.2).						
7) A rectangular waveguide chamber may be used to calibrate field probes and sensors specifically used for microwave leakage field detection (i.e., MPE). This technique is valid down to dc (0 Hz).						
8) The upper frequency limit is a function of parallel plate separation and length of the conical feed sections.						
9) This technique is valid only for time domain calibrations meeting the transient pulse width limits given in B.9.						

In a well-designed field generation device, both time and frequency domain calibrations can be performed (within the constraints and usage guidelines for Table 3 and Annex B). This capability is due to the reciprocity between time and frequency domains, as demonstrated by Fourier transforms (i.e., forward and inverse). Some of the field generation methods listed in Table 3 show 9 kHz as the lower limit. For applications where mathematical calculations are anticipated using Fourier transforms, it may be desirable to have frequency information to frequencies lower than 9 kHz. For example, any monopolar transient has frequency content down to and including dc, and lightning transients have significant low frequency content. Usage guidelines following Table 3 indicate which field generation device may be used below 9 kHz.

Field generation devices for free field probes and sensors may not be appropriate for ground-plane field probes and sensors. The usage guidelines following Table 3 include information about applicability of each method for the two types of probes and sensors.

6. Calibration uncertainty

In all calibration reports and certificates, the calibration uncertainty shall be stated, at a minimum, as follows:

“The expanded uncertainty of the calibration is $U = [x.xx \text{ dB}]$, with a coverage factor $k = [k]$, and a level of confidence of $[xx]\%$.”

NOTE—Insert the actual uncertainty and its dimension in place of “[x.xx dB]” and the actual coverage factor in place of “[k].” Insert the expected confidence in place of “[xx]%. The coverage factor k is usually 2 for typical calibrations, but may have other values if requested by the client or if necessary to assure the required degree of confidence.

Uncertainty shall be estimated using the methods shown and described in the GUM or ANSI Std Z540-2-1997. For the purposes of this standard, the uncertainty estimation approaches described in 6.1 through 6.4 and explained in Annex H shall be used.

6.1 Standard uncertainty

Each influence quantity (i.e., component of uncertainty) that contributes to the uncertainty of the measurement result shall be represented by an estimated standard deviation u_i , designated as standard uncertainty, and equal to the positive square root of the estimated variance u_i^2 . Each influence quantity is either Type A (i.e., statistically based) or Type B (i.e., other method), as discussed in Annex H and in NIST TN 1297-1974.

6.2 Combined standard uncertainty

The combined standard uncertainty u_c of the measurement result, taken to represent the estimated standard deviation of the result, shall be determined by combining the individual standard uncertainties u_i (and covariances as appropriate) using the equation for the propagation of uncertainty, i.e., the root sum of squares (RSS) method, as discussed in Annex H. Typically, u_c is used for reporting the uncertainty of results in determination of fundamental constants, fundamental metrological research, and international comparisons of realizations of International Standard (SI) units.

6.3 Expanded uncertainty

An expanded uncertainty, U , shall be determined by multiplying u_c by a coverage factor k , i.e., $U = k(u_c)$. 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, the assertion that $y - U \leq Y \leq y + U$, which is typically written as $Y = y \pm U$, can be confidently made.

Expanded uncertainty U shall be used to report the results of all measurements. The value of k used for calculating U shall be 2 or larger. Using $k = 2$ usually gives a level of confidence of 95% (see NIST TN 1297-1974 and Table H.3 in this standard).

6.4 Reporting uncertainty

The calibration report shall include U , k , and the level of confidence. This information is the minimum that shall be reported in a certificate of calibration. When reporting a measurement result and its uncertainty, the following information shall be included in the calibration report:

- a) A list of all influence quantities for the standard uncertainty, together with their degrees of freedom where appropriate, and the resulting value of u_c . The influence quantities shall 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 influence quantity of standard uncertainty is evaluated.

Examples containing these items of information are provided in Annex H.

7. Characteristics to be measured

7.1 Frequency domain calibration parameters

7.1.1 Dynamic range and amplitude calibration levels

Calibration may be performed at one or more field strengths depending on the intended application. One example is a probe for the measurement of fields from a microwave oven, which has only one pass/fail field strength, in which case calibration may be needed only at one amplitude level to provide accurate measurements. Another example is an application involving EMI testing that may require calibration at three amplitude levels per frequency at which calibration is performed. The number of field strength amplitudes to be measured at each frequency of calibration shall be in accordance with the agreement between the client 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.

Dynamic range calibrations are used to account for response linearities. Many probes use detector diodes at the dipole feed point to rectify the sensor voltage output. The rectified signal is transmitted through resistive transmission lines to a voltage-measuring system. At low field strength levels, the output voltage is proportional to the square of the amplitude of the incident field; at higher signal levels, the output voltage is not linearly proportional to E^2 , but becomes proportional to E . The compressed response may lead to an underestimation of the actual response at high field strength conditions. In final-use conditions, diode compression should be compensated with a linearization algorithm applied to each detector signal, based on parameters determined during calibration.

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 concern, calibration may be needed only at one frequency to provide accurate measurement. As another example, an application involving EMI testing (i.e., 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 in accordance with the agreement between the client 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.

Many probes used for MPE testing are designed to have a “shaped” frequency response. Shaped frequency response probes are designed to follow typical frequency-varying RF exposure limits, in contrast to many conventional probes that are usually designed for a flat response versus frequency. Calibration frequencies should be selected appropriately to cover the various shaped probe response bands. See Clause 5 of IEEE Std C95.3-2002 for more details about MPE probes.

7.1.3 Isotropy

The isotropic response shall be evaluated for all isotropic field probes. Because isotropy of a field probe is difficult to measure, usually the anisotropy (A) is measured. Anisotropy is the maximum deviation from the geometric mean of the maximum response and minimum response (see Lawton [B79]). 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:

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

where S is the measured amplitude in power density units, or

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

where S is the measured amplitude in field strength units.

The calibration report shall state isotropy as $\pm x.xx$ dB and provide a detailed description of how isotropy measurements were made.

7.1.4 Response time (optional)

The response time of the field sensor or probe is defined as the time required for the response to indicate 90% of the steady-state field value with the field 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. This method includes the test setup response time in the field sensor or probe response time and thus gives a worst-case result.

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 in the following cases:

- A probe using multiple sensors to map a field where the output of each sensor is sampled and processed by the readout device
- EMI testing where the probe is part of a feedback system to adjust signal generator power for swept frequency testing

Evaluation of response time as a part of calibration is optional unless requested by the client. Annex A provides requirements for specifying grades of calibration with respect to response time.

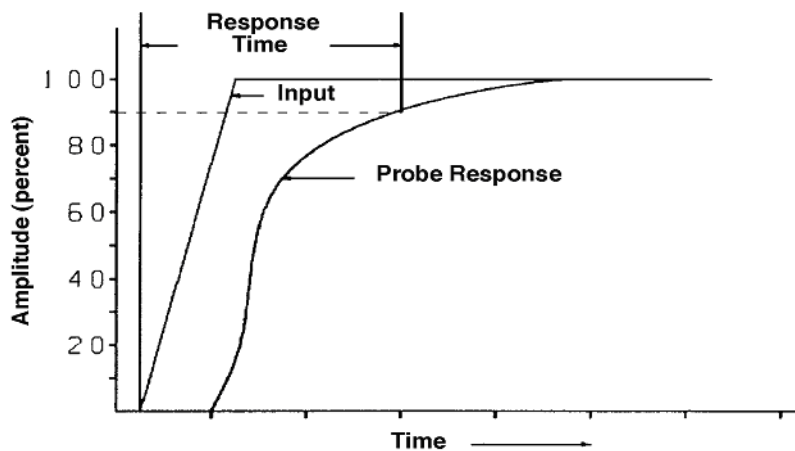


Figure 4—Typical response time curve

7.1.5 Time constant (optional)

Some field sensors or probes are used for making burst peak¹⁹ measurements. Applications include energy density (E^2) measurements on rotating-beam radars. For these applications, the time constant of the field sensor or probe must be known. The time constant is generally measured up to the meter recorder output of such a probe. The general equation relating the ratio of maximum-hold meter indication to illumination period (i.e., pulse width) is

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

¹⁹Burst peak measurements are most often used to determine peak field strength exposure in a pulsed field environment, or an environment of a burst of very short pulses, where the pulse widths are much less than the pulse repetition period.

where

- E_{hold} is maximum meter indication
- E_{CW} is continuous wave (CW) indication
- K is maximum hold indication ratio (i.e., actual maximum, if constantly illuminated)
- T is time constant
- t is illumination period (i.e., pulse width)

For rotating-beam radar tests, the illumination period t , in seconds, is equal to the beamwidth, in degrees, divided by the sweep rate, in revolutions per minute, multiplied by 0.167 (see Annex G). Equation (3) assumes that the pulse repetition rate is sufficiently low so it does not affect the time constant being measured. This assumption can be validated using time constant measurements with different pulse repetition rates.

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. Usually the root-mean-square (rms) value of the E - or H -field is the desired measurand. Other applications and uses of field probes and sensors may also require field strength measurements under modulated conditions. Evaluation of modulation response characteristics as part of calibration is optional, unless requested by a client or test specification. Annex A provides requirements for specifying grades of calibration with respect to modulation. With respect to EMC testing, the modulation is usually amplitude modulation (AM) or pulse modulation.

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

7.2 Time domain calibration parameters

Sensors and probes for making time domain transient measurements shall be calibrated to determine how accurately they can measure a transient. Pulse fidelity is defined as how accurately 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 function, the deviation of the output signal from this step function, normalized to the sensitivity of the sensor, shall be characterized. These deviations from ideal include effects due to the sensitivity, rise time, fall time, overshoot, and ringing of the sensor response. Time domain sensors have an inherently broadband frequency response, e.g., usually two decades of usable bandwidth or more, and can be used to make frequency domain measurements. Free field sensors and probes sometimes require the use of a balanced-to-unbalanced transformer (balun), which shall be included in the calibration.

7.2.1 Amplitude

Amplitude calibration is the calibration of the sensitivity²⁰ of the sensor or probe. The sensitivity is the transfer function of the sensor for converting an EM field component into an electrical signal, e.g., 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 based on analytical calculation in terms of device geometry and Maxwell's equations. For other sensors and probes, amplitude calibration is performed by comparison testing to a primary standard sensor.

²⁰Sensitivity as used here refers to the classical definition for a measuring device of the ratio of the magnitude of the device response, e.g., voltage, to the magnitude of the quantity measured, e.g., field strength squared (see 3.18).

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 EMP in which field strengths vary from a few kilovolts per meter to the breakdown strength of air (about 3 MV/m) (see Baum, et al.[B15]). 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 in accordance with the agreement between the client 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 duration of first transition in a pulsed waveform. Rise time shall be measured with an instrumentation system that has a rise time at least five times faster than the response time of the sensor being calibrated. If this setup is not possible, then the response time of the instrumentation system shall be at least as fast as the sensor response time, and deconvolution techniques shall be used to determine the sensor rise time.

7.2.4 Fall time (droop)

Fall time is defined as the later/last part of the transient in a pulsed waveform. Fall time shall be measured with an instrumentation system that has a decay time that is at least five times faster than the decay time of the transient signal being measured.

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 shall not be excessive. Ringing is the damped oscillation that occurs when a sensor response is underdamped. Overshoot and ringing occur simultaneously and shall be measured along with the rise time. Annex I describes the waveforms in more detail.

8. Procedures (measurement techniques)

The calibration procedures discussed here are applicable to techniques in both the frequency domain (e.g., CW, swept CW, stepped CW, white noise) and in the time domain (e.g., impulse, step, damped sine). The results obtained using any one method can be applied to any other by the appropriate mathematical processes (i.e., Fourier transforms). Signal generation used to produce the fields (e.g., CW signal generator, network analyzer, impulse generator, step generator, random-noise generator) and the measurement of the signals from the sensors (e.g., spectrum analyzer, network analyzer, transient digitizer) are relatively straightforward with modern test equipment.

Many sensors that require calibration have a broadband frequency response, i.e., sensor output signals ranging from an octave to several decades of useful bandwidth. This characteristic implies, for reasons of hardware and personnel resources optimization, that the calibration process shall utilize equipment that can automatically cover a multitude of frequencies, rather than one single frequency at a time. This broadband requirement precludes the use of standard half-wave dipoles as the primary standards. However, dipoles can be used as single-frequency calibration checks for broadband reference standard sensors and for field sensors under calibration.

At frequencies below approximately 20 MHz to 30 MHz, calibrations should be performed in the frequency domain. At these frequencies, calibration fixtures can be constructed for reasonably low field perturbation effects, and instrumentation is readily available to most test facilities (see Lawton and Ondrejka [B80]).

At higher frequencies, calibrations may be performed in the time domain using transient measurement techniques. The reason for this alternative is that test cells (e.g., TEM waveguides) have significant reflections at these frequencies, which are difficult to remove from CW measurements. In the time domain, reflections can be removed by windowing the data, analyzing only the portion containing the sensor response, and omitting portions of the response that contain reflection effects. The field-generating setup must have large enough dimensions so that the response is flat between the incident field and the first reflections from the terminator and so that the time between these reflections is greater than the probe response time. The time (i.e., transient) domain field sensor or probe design shall allow it to respond well to pulses.

8.1 Transfer standard sensors and probes

The principle of this method is to have a stable and reliable sensor or probe that has been calibrated accurately for use as a *transfer standard*. 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. The transfer standard shall be calibrated using the same method as used for the calibration artifact. The standard probe is used to establish a field strength in a specific test region produced by an arbitrary field-generating device, e.g., antenna or TEM device. The response of the uncalibrated probe in this test region is then compared with the known value of the field as measured with the transfer standard probe. The transmitter and field-generating device used during this process shall generate a field that has the desired magnitude and that is constant with time, and the field shall 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. Transfer standard and other traceability issues are discussed further, for example, in Glimm, et al. [B40], Loader, et al. [B85], and Münter, et al. [B99].

A potential source of error when using the transfer standard to calibrate another probe is the possible difference in the receiving patterns of the two sensors. Also, in the near field of a radiator, the effective size of the probe sensing area is important. Ideally, the transfer standard and any probes under calibration should be identical, and the calibration should be performed in a field region that is relatively free of spatial variations caused by multipath interactions between the probe, the radiator and anechoic chamber or other field-generating components, and near-field gradients. Practically, the transfer standard and the probe under calibration are not identical, and this difference needs to be taken into account when determining calibration uncertainty. In TEM and GTEM cells and parallel plate striplines, capacitive coupling between the probe and the septum (i.e., center plate conductor) and walls of the waveguide can create calibration errors.

8.2 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 devices shall be of the same type as the transfer standard and compared directly to it in a test cell (e.g., TEM waveguide). The absolute calibration of these working standard probes will be less accurate than the absolute calibration of the transfer standard and shall be carefully documented. These devices can then be used for routine calibrations of production probes and sensors so the transfer standard is protected from damage. The working standard (i.e., “everyday use”) 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 Method A and Method B (see Table 2 in 4.1), 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 is defined based on the grades of calibration that are defined in Annex A.

8.3.1 Lead and cable effects

Lead and cable component examples include resistive feed lines from sensor head to readout device and include coaxial cables for some passive probes with standard connectors. The lead or cable attached to any field sensor or probe shall be positioned to minimize field pickup. Usually, this positioning is accomplished by running the lead or cable perpendicular to the incident electric field vector or component, positioning the lead or cable end of the field sensor or probe away from the incident field source, and maximizing the distance between the incident field source and the lead or cable end of the field sensor or probe. The lead or cable placement shall be maintained for all calibration runs and shall be made available to all users and documented in the calibration report. Uncertainty due to lead or cable effects shall be estimated and presented in the statement of uncertainty described in Clause 6. Alternately, if the calibrating organization can, by test or other methods, show that the lead or cable orientation has no significant effect, 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 setup from Table 3 (in Clause 5) for the required frequency range and field component. The following constraints are recommended for accurate and repeatable measurements:

- a) The VSWR of the field generator shall be minimized to obtain lowest uncertainties in calibration field strengths. VSWR can be measured with a dual directional coupler and power meters or with a network analyzer. A low VSWR does not automatically guarantee that field uniformity is good. Field uniformity shall also be verified using independent reference probes or antennas, and standing-wave effects may need to be corrected (see Bronaugh [B23] and Mantiplay [B88]).
- b) Input and characteristic impedance over the frequency range in use shall be 50 Ω typically unless otherwise specified by the manufacturer of the field generator. Impedance can be measured with a time domain reflectometer or a network analyzer.
- c) The selected field generation facility shall be used in its single-mode frequency range (e.g., only the TEM mode in a TEM waveguide or only the TE₁₀ mode in a rectangular waveguide).
- d) The maximum test volume shall be as follows:
 - 1) One-third of the height between the floor and the septum for TEM cell and GTEM cell (see Crawford and Workman [B30])
 - 2) One-third of the volume of the waveguide for rectangular waveguide (see Hill [B46])
 - 3) The quiet zone of an anechoic chamber
 - 4) Six-tenths of the coil radius for Helmholtz coils (see Bronaugh [B19])

NOTE—The limitations stated in item 1) and item 2) are due to loading effects (e.g., capacitive coupling, field perturbations).

- e) The harmonic content of the net applied power shall be at least 20 dB below the fundamental for valid CW measurements. This value can be measured with a spectrum analyzer, RF receiver, or with a power meter and filters.
- f) Ground-plane field sensors and probes shall be properly bonded to the ground plane of the selected field-generating facility in accordance with documented probe or sensor setup and use requirements.

- g) The field sensor or probe mounting fixture shall be constructed to minimize the perturbation of the field. The effects of uncertainty due to field perturbations by the mounting fixture shall be quantified and included in the measurement uncertainty estimations.
- h) For battery-powered field probes, it is important to check the charge state before, during, and after completion of the calibration. If rechargeable batteries are charged before calibration, sufficient time must be allowed for the batteries to cool before commencing the calibration.

8.3.2.1 Frequency range and/or dynamic range measurement procedure

This measurement can be performed with field sensors or probes. The field probes shall be appropriately aligned. The procedure for frequency range and/or dynamic range 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 or probe to assure that it meets all site requirements. For example, check whether the field probe exceeds the maximum size requirements for the facility.
- c) Place the field sensor or probe to be calibrated so that it is aligned with the incident field. The field sensor or 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 or probe for that particular frequency and field level. Proceed until data are obtained for all required configurations.

NOTE—Ensure the sensor or probe is zeroed before the application of power, for probes containing the zeroize function.

8.3.2.2 Isotropic response measurement procedure

Isotropic response measurement is designed for field probe characterization and does not provide coherent information for individual field sensors (e.g., single-element directional-pattern devices). Probes based on the three-orthogonal-dipole design should be rotated around the ortho-axis (e.g., probe handle, rigid or flexible feed-line assembly, “virtual handle”), as shown in the example in Figure 5 (see Bassen and Smith [B7] and Bronaugh [B20]). If the probe is not based on the three-orthogonal-element design, then the rotational axis should be selected and documented to reflect isotropicity as encountered during normal use of the probe. Figure 5 also illustrates the ortho-angle definition.

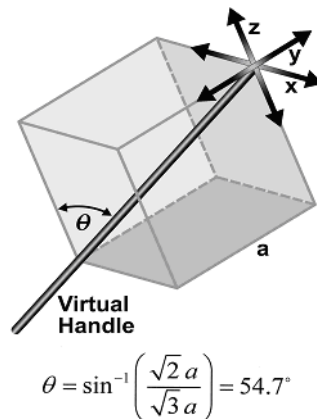


Figure 5—Ortho-angle (θ) and virtual handle (cube diagonal)

NOTE—The ortho-angle is defined as $\theta = \operatorname{arcsec}(|A|/a) = \arccos(a/|A|) = 54.7^\circ$, where $|A|$ is the length of the cube diagonal and a is the cube side length.

The procedure for isotropy 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 (see *e-Handbook of Statistical Methods* [B101]).
- b) Inspect the field probe to assure that it meets all site requirements. For example, check whether the field probe exceeds the maximum size requirements for the facility.
- c) Place the field probe to be calibrated so that one element is aligned with the incident field and the other two elements are cross-polarized to the incident field. This orientation is usually done by positioning the handle of the probe along the diagonal of a cube. If the field probe is not based on the three-orthogonal-element design, then another appropriate orientation shall be selected and documented.

NOTE—To achieve the ortho-angle probe handle position, special access holes may need to be cut at locations other than the standard door position for many conventional TEM cells.

- d) For each previously selected frequency and field level, rotate the field probe through a full revolution of 360° to obtain the maximum and minimum responses. The probe is rotated so that each axis is aligned with the incident field vector while the other axes are successively cross-polarized. Proceed until data are obtained for all required configurations.
- e) The rotation can be done by one of two methods:
 - 1) The field probe can be rotated by a certain angle and then stopped, and the response recorded with the field probe stationary. The field probe is then rotated to its next position. Note that this angle shall be small enough to assure that a smooth response versus rotation is obtained.
 - 2) The field probe can be continuously rotated while its response is recorded simultaneously. In this case, the speed of rotation must be slow enough to allow the field probe response to stabilize before the response is recorded, and enough data shall be recorded to assure that a smooth response versus rotation is obtained.
- f) For each frequency and field level, search the recorded values to find the minimum and maximum values. Use these values in Equation (1) or Equation (2), as applicable (see Randa, et al. [B104]), to determine the anisotropy of the field probe.

8.3.3 Response time measurement procedure

Refer to Figure 4 for an illustration of the response time parameters. The procedure for response time measurement is as follows:

- a) Set up the equipment as shown in Figure 6.
- b) Apply a CW signal to the probe, and adjust the level for a stable reading on the meter.
- c) Remove the CW signal. Calculate 90% of the field probe meter reading measured in step b).
- d) Place the pulsed RF generator in single-shot mode, and set the pulse width equal to the expected response time.
- e) Apply one pulse, and record the highest field probe meter reading.
- f) If the reading in step e) is less than the 90% of the value calculated in step c), increase the pulse width. If the reading is greater than the 90% of the value calculated in step c), decrease the pulse width.
- g) Repeat step e) and step f) until the pulse width selected consistently produces a field probe meter reading equal to the 90% of the value calculated in step c). This pulse width is equal to the field probe response time.

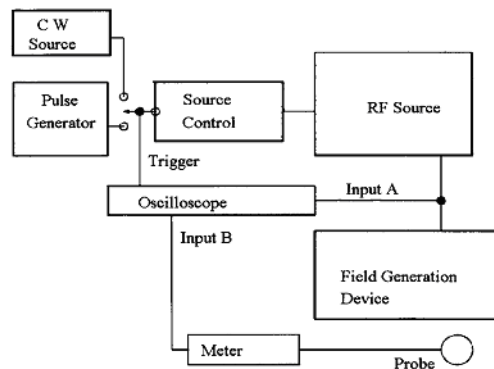


Figure 6—Typical probe response time and time constant measurement setup

8.3.4 Field sensor or probe time constant measurement procedure

Refer to Equation (3) for the general equation relating maximum hold meter indication to illumination period. The procedure for field sensor or probe time constant measurement is as follows:

- Set up the equipment as shown in Figure 6.
- Apply a CW signal to the probe, and adjust the level for a stable reading on the meter.
- Remove the CW, set the meter to maximum hold mode, and set the range switch to an appropriate higher sensitivity.
- Set the pulse generator repetition rate to 2 pulses per second (PPS) and a pulse width t of 0.01 s.
- Apply pulse to control the field source (i.e., pulse modulation). Record the maximum hold reading divided by the CW reading as K .
- Repeat step d) and step e) for pulse width t settings of 0.02 s to 0.1 s.
- Calculate the time constant T using $T = -t/\ln(1 - K)$ for each recorded K value.

NOTE 1—A typical value for pulse generator repetition rate is 2 PPS. The repetition rate should be much less than the reciprocal of the probe response time.

NOTE 2—Typical values for pulse width are 0.01 s, 0.02 s, and 0.1 s. The pulse widths may be determined by end-user requirements. The pulse widths used for measuring the time constant shall be representative of the pulse widths in which the field probe will be used.

NOTE 3—Typical values for T are 0.2 s to 0.3 s for thermocouple-based probes.

NOTE 4—Ensure that the meter is zeroed prior to the application of power.

8.4 Time domain calibration procedure

The sensor calibration shall be performed using time domain signals. Time domain calibration shall be performed using Method A (i.e., transfer standard) or Method C (i.e., reference sensor) (see 4.1) in which the measured response of the sensor is compared to the response of a well-characterized reference sensor. The transfer standard shall be calibrated using the same method as used for the calibration artifact. These direct “substitution” techniques allow the effects of the entire measurement system to be removed from the sensor calibration. Thus, only the characteristics of the sensor, i.e., the unit impulse response function or the unit step response function, are left. Final sensor characteristics are obtained using deconvolution techniques (see Annex F). Discussions of other issues in time domain probe calibrations are given, for example, in Bao [B5],

Cerri, et al. [B26], Esselle and Stuchly [B34], Johnk and Ondrejka [B60], Judd [B61], Judd and Farish [B62], Lawton, et al. [B81], and Middlekoop [B97].

In addition to the instrumentation requirements given in 7.2, the following requirements also apply:

- a) It is possible to capture the transient time domain waveform on a single-shot basis if the transient digitizer has sufficient sampling speed. As a minimum, there shall be five sampled points on the transient rise time. Some digitizers that do not have sufficient sampling speed can still be used if the digitizer is capable of building up a properly sampled waveform by digitizing the transient waveform repeatedly. In this case, the pulse generator generating the transient waveform should provide a stable, repetitive pulse. The pulse-to-pulse jitter shall be less than 1% of the rise time, with the long-term drift approximately the same. A pulse repetition frequency of 10 kHz to 100 kHz is required depending on the sampling system.
- b) A transmission line simulator that matches the pulse generator output impedance (typically 50 Ω) into which the sensors can be mounted (i.e., ground-plane field versions) or emplaced (i.e., free field versions) is required. The simulator must have a sufficient clear (i.e., reflection-free) time in order to adequately characterize the sensor responses, or it must have minimal reflections from the termination. A conical transmission line simulator is preferred (see Baum [B12]). A cone-and-ground-plane simulator can also be used (see Baum [B14]).
- c) A fast transient recorder is required. This device can be a transient digitizer for slower waveforms. For faster sensors and waveforms, a sampling system must be used.
- d) A means to digitize the sampling oscilloscope data is needed, if applicable, along with interfaces to control the sweep of the sampling system and to input the acquired data into a computer.
- e) Software to process the acquired data arrays is needed.

8.4.1 Amplitude

Amplitude calibration shall be performed by Method A (i.e., comparison of measured sensor output amplitude to the amplitude of a transfer standard). This calibration shall be performed with a time domain instrumentation system. The only difference between the measurements of the two sensors shall be the substitution of one sensor for another; all other parameters of the measurement setup shall remain undisturbed, including sensor location and field level (i.e., pulse generator output).

8.4.2 Dynamic range and amplitude calibration levels

Calibration shall be performed at one or more field strengths, depending upon the requirements of the client. The number of field strength amplitudes to be measured shall be in accordance with the agreement between the client and the calibration organization. Annex A provides requirements for specifying grades of calibration and selection of calibration amplitudes.

8.4.3 Rise time

Rise time is defined as the first transition duration. Rise time shall be measured with an instrumentation system that has a rise time at least five times faster than the response time of the sensor being calibrated. If this setup is not possible, then the response time of the instrumentation system shall be at least as fast as the response time of the sensor, and computational deconvolution techniques shall be used to determine the sensor rise time (see Annex F and Annex I).

8.4.4 Fall time (droop)

Fall time is defined as the later or last part of the transient. Fall time shall be measured with an instrumentation system that has a decay time that is at least five times faster than the decay time of the transient being measured.

8.4.5 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. Ringing is the damped oscillation that occurs when a sensor response is underdamped. Overshoot and ringing occur simultaneously and shall be measured along with the rise time. Annex I describes the waveforms in more detail.

9. Documentation

9.1 Proper documentation

Proper documentation of calibration results is essential for a complete calibration process. A calibration shall be performed within a quality system such as defined in ISO 17025:1999 or ANSI Std Z540-1-1994. This structure contains the elements necessary for the procedures, equipment, and status of each part of the calibration process to be traced and duplicated. It also enables calibration verification, if necessary.

9.2 Test documentation

The calibration facility shall document the procedures, equipment used, existing environmental conditions, verification of the test facilities status, and verification of the equipment status. This documentation will allow tracking and reproduction to confirm or repeat a calibration, when necessary.

9.3 Calibration interval

The calibration interval depends on the individual instrument and its use. The purpose of defining a calibration interval is to provide a period for recalibration, based on probe or sensor characteristics (e.g., long-term stability, drift) and an assumed usage of the instrument. The probe manufacturer provides a recommended initial calibration interval. The calibration interval may be changed based on historic performance data of the sensor or probe, based on the “As Received” indication on the calibration certificates over an extended period of time, or in accordance with procedures contained in applicable calibration quality system standards, e.g., ANSI Std Z540-1-1994.

9.4 Out-of-tolerance notification

When a field sensor or probe is found to be out of tolerance when received for calibration, the results shall be documented, and the organization requesting calibration notified. In addition, the calibration laboratory shall perform internal checks to ensure that test equipment, transfer standards, etc., do not cause an erroneous out-of-tolerance indication.

9.5 Certification to client or end user

The documentation provided to the organization requesting calibration may vary based on user requirements or requests. The calibration certification shall contain, at a minimum, the following:

- a) Name of calibrating laboratory, location of laboratory, and date of calibration
- b) Full identification of field sensor or probe calibrated (i.e., make, model, serial number, accessories, configuration)
- c) Parameters calibrated or calibration procedure used
- d) Statement of “As Received” condition (e.g., in or out of tolerance, damage, actual data)

- e) Traceability statement, standards used
- f) Environmental conditions (e.g., temperature, humidity)
- g) Signature, seal, or other identifying mark of calibration technician or engineer
- h) Other test conditions and results requested or required by client
- i) Calibration method, type, and grade (see Annex A)
- j) Frequency points measured, field levels, and data at each point
- k) Statement and estimation of uncertainty and the application of this uncertainty when determining compliance of the probe or sensor with its specifications
- l) Probe mounting methods and/or orientation details
- m) Calibration applicability specifications (e.g., range around each frequency point, if applicable) and supporting documentation