IEEE Std 1309-1996

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

Sponsor
IEEE Electromagnetic Compatibility Society

Approved 20 June 1996

IEEE Standards Board

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, measurement, instrumentation uncertainty, electric field measurement

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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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Annex C Field sensor and field probe calibration factors
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Annex DE Deconvolution
Annex EF Time-domain pulse fidelity
Annex FG Burst-peak field measurements
Annex GH Bibliography

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(Pending IEEE Stds Style Guide rule: “Annexes shall appear in the order in which they are referenced in the body of the standard” – I did not yet check main-body order of reference. The proposed ordering above is to put uncertainty closer to front due to its significance, and to group time-domain topics next to each other)
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. Specific Absorption Rate (SAR) probe calibration is not covered by this standard. IEEE Std 1528 should be consulted when calibrating SAR probes. Calibration of immersible and implantable probes for specific absorption rate (SAR) testing is not considered in this standard. IEEE Std 1528 [B57] should be
consulted for guidance on SAR probe calibrations.

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.

Recently other important documents describing probe calibrations have been published, namely ISO Technical Reports 10305-1 [B61] and 10305-2 [B62], VDI/VDE/DGQ/DKD 2622 Part 10 [B135], draft IEC 61000-4-33 [B60], and IEEE Std C95.3-2002.

Should say something here about 1309 relation to these other documents - similarities, differences, precedence, overlap, significance of 1309, etc. To do so, 1309 WG probably needs to acquire and evaluate these.

I do not have final ISO versions, but FYI intro to 8/97 draft 10305-1 states:

“"The need of a standardized method for the calibration of field strength measuring devices was seen in the responsible ISO subcommittee. As no such standard was available from either ISO or IEC, Technical Report ISO 10305 was published in 1992, which was based on document NBSIR 75-804, edition January 1975 amended. This document being incomplete, new calibration methods were independently developed by IEEE and in Germany. It was decided to publish the two documents [TH i.e., the then-new ca. 1996 drafts from IEEE and from Germany] as a Technical Report replacing the first edition of ISO/TR 10305:1992. … If IEC publishes a general calibration procedure as an International Standard, this TR may be withdrawn as there is no anticipated need for having special calibration methods for use in the automotive industry.""

In other words, please note that 10305 is not specific to automotive!!

Methods for creating standard electric and magnetic fields are described in Clause 5. Each method has known calculable 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. Probe calibration methods for lower frequencies are described in IEEE Std 1308-1995 [B56].

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.

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.

1 Information on references can be found in Clause 2.
such as the National Institute of Standards and Technology (NIST) in the United States, the National Physical Laboratory in the United Kingdom, Physikalisch-Technische Bundesanstalt in Germany, CSIRO in Australia, etc. Specific Absorption Rate (SAR) probe calibration is not covered by this standard. IEEE Std 1528 should be consulted when calibrating SAR probes. Calibration of immersible and implantable probes for specific absorption rate (SAR) testing is not considered in this standard. IEEE Std 1528 [B57] should be consulted for guidance on SAR probe calibrations.

1.3 Background

Antenna calibration is the subject of existing standards, such as ANSI C63.5-19881998. Though field sensors and field probes are antennas in a broad sense, the uses, 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 electromagnetic field, and thus they typically perturb the electromagnetic field. Field sensors and field probes are designed to measure with minimal perturbation of an electromagnetic field with minimal perturbation.

There is agreement on several antenna calibration methods have been agreed upon in the EMC industry. However, attempts to at applying antenna calibration methods to field sensors and field probes have resulted in usually produce inconsistent results between among calibration organizations and other laboratories. Examples of probe field strength measurement interlaboratory comparisons are given in [B1], [B34], [B40], [B72]. This standard is intended to provide consistent methods and results for different calibration services the various probe calibration methods in use worldwide.

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 (see Clause 7 and Annex A):

--- 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 Measurement uncertainty of the calibration

Annex A provides a method guidelines to describe the extent of the measurements (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 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.
Table 1—Generic EM field probes and sensors

<table>
<thead>
<tr>
<th>Free field</th>
<th>Ground plane field</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E )-field (dipole)</td>
<td>( E )-field (monopole)</td>
</tr>
<tr>
<td>( H )-field (loop)</td>
<td>( H )-field (half-loop)</td>
</tr>
<tr>
<td>( D )-dot (dipole)</td>
<td>( D )-dot (monopole)</td>
</tr>
<tr>
<td>( B )-dot (loop)</td>
<td>( B )-dot (half-loop)</td>
</tr>
</tbody>
</table>

There are two differences between time derivative \( (B \text{-} \dot{}} \text{ and } \( D \text{-} \dot{}} \) sensors and direct field reading \( (E \text{-} \text{Field and } H \text{-} \text{Field}) \) 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 \( \varepsilon \) and \( \mu \) 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] \( B \)-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 \( D = \varepsilon_0 \varepsilon_r E \) and \( B = \mu_0 \mu_r H \). In general, \( \varepsilon_0 \varepsilon_r \) and \( \mu_0 \mu_r \) will be fixed quantities over the intended usage range of the probe or sensor. There are specialized cases wherein \( \varepsilon_0 \) and \( \mu_0 \) will not be linear, time invariant, or isotropic such as for source region EMP [B15]*. For purposes of this document, \( \varepsilon_0 \) and \( \mu_0 \) will be assumed to be constant parameters.\(^*\)

**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 C95.1-1999, IEEE Std C95.3-2002, 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, as dated.

---

\(^*\) The numbers in brackets preceded by the letter B correspond to those of the bibliography in #Annex J.

\(^*\) The numbers in brackets preceded by the letter B correspond to those of the bibliography in #Annex J.
ANSI C63.5-1988, Electromagnetic Compatibility—Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration of Antennas. 4


NOTE - AUG03 1309 WG COMMENTS PROPOSES TO REPLACE Z540-1 BY REFERENCE TO Z540-2 – NOT ACCEPTED BECAUSE 9.1 CITES Z540-1.


National Conference of Standards Laboratories (NCSL) RP-12, Recommended Practice for Determining and Reporting Measurement Uncertainties, 1 Feb. 1994. 7

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

NIST Handbook 150, National Voluntary Laboratory Accreditation Program, Procedures and General Requirements. 8


UKAS LAB 34:2002, The Expression of Uncertainty in EMC Testing, United Kingdom Accreditation

4 ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.
5 IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA. (http://www.ieee.org/).
6 ISO publications are available from the ISO Central Secretariat, Case Postale 56, 1 rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse. (http://www.iso.org/). 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.
7 NCSL publications are available from the National Conference of Standards Laboratories, 1800 30th Street, Suite 305B, Boulder, CO 80301-1032, USA. (http://www.ncsli.org/).
8 NIST publications are available from the National Institute of Standards and Technology Library, Gaithersburg, MD 20899, USA. (http://www.nist.gov/).

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3. Definitions

This clause contains or defines only those definitions relating to field sensor and field probe calibration that are not listed in IEEE Std 100-1992 or in ANSI C63.14-1998. The terms “probe” and “sensor” are defined below for application within this Standard only. In industry, these terms are often used interchangeably.

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 E-field probe: A minimally-perturbing structure containing an electrically small E-field sensor, or a set of multiple E-field sensors, and the components necessary to transform the sampled RF signal into a proportional direct current or voltage. An elemental E-field probe consists of a thin dielectric substrate containing a sensor, such as an electrically short (in tissue) dipole, a diode to rectify the RF signal and a balanced high-resistance transmission line to extract the rectified signal. The dipole elements and the high resistance leads are usually applied to the substrate using thin film techniques; diodes and any other discrete components are bonded to the thin film elements. An isotropic probe consists of three such devices arranged in an "I"-beam, or "H"-beam) or a "delta" (triangular beam) configuration (preferred) with the axis of each dipole orthogonal to the axes of each of the others, e.g., aligned along the diagonals of a cube.

3.3 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. This includes B-dot and D-dot sensors that require a Balanced to Unbalanced (balun) transformer on the output of the sensor (note: not all B-dot and D-dot sensors require a balun).

3.4 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.).

3.5 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.

3.6 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 calibration is a transfer function at a single frequency.

3.8 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.

3.9 **maximum permissible exposure (MPE):** The 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.

3.10 **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). **ortho-angle:** The angle that the diagonal of a cube makes to each side at the trihedral corners of the cube. This angle is widely used in transverse electromagnetic (TEM) device testing because its coefficients give a vector sum of unity when three orthogonal readings are made and summed. When applied to a TEM device, the ortho-angle may alternately be described as the angle of a ray passing through the center of the test volume of the cell, such as that its azimuth is 45 ° to the centerline of the TEM device and its elevation is 45 ° above the horizontal plane of the TEM device. Thus, it is 54.7 ° to the edges of each face of a cube centered in the test volume. This assumes that the cube in question is aligned with the Cartesian coordinate system of the TEM device. Note - When associated with the equipment under test (EUT), this angle is usually referred to as the ortho-axis [B20].

**NOTE:** the ortho-angle is typically used for field sensors in many three-orthogonal-dipole isotropic field probes, with sensors spaced apart by 120 ° in the cross-section plane containing the three feed-points.

3.11 **physical major axis:** … direction along real or “virtual” handle, etc …

3.12 **physical minor axis:**

3.13 **probe isotropy:** Pertaining to the degree to which the response of an E-field or magnetic field probe is independent of the polarization and direction of propagation of the incident wave. **Axial isotropy** is the ability of a probe to respond equally to a TEM plane wave impinging from a direction along the probe axis. **Hemispherical isotropy** is the ability of a probe to respond equally to TEM plane waves impinging with arbitrary polarization from directions around the surface of a hemisphere, and includes axial isotropy. For axial isotropy – **Syn:** ellipse ratio (deprecated).

3.14 **readout device:** 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.

3.15 **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.

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

3.17 **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.

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

3.123.19 **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. *Syns: response, sensitivity, probe factor, calibration factor.*

3.13 Transfer standard (field probe or sensor): 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 Calibration 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>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>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.</td>
</tr>
<tr>
<td>B</td>
<td>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.</td>
</tr>
<tr>
<td>C</td>
<td>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.</td>
</tr>
</tbody>
</table>

Method A, calibration with a Transfer Standard, is also called a Transfer Probe method; Method B, calibration using calculated field strengths, is also called a Standard Field method; and Method C, calibration with a primary Standard, is also called a Standard Probe method. It should be noted that Method C, and its resulting uncertainty, is only applicable to the field sensor calibrated (primary reference standard) 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

TH: AGREE WITH BASSEN #2 – I TRIED TO FIGURE OUT WHAT “POSITIONAL EFFECTS” REFERS TO, BUT I COULD NOT.

STATING EXAMPLES OF WHAT POSITIONAL EFFECTS ARE MIGHT HELP.  
DIRECTIONAL SEEMS EASY TO FIGURE – IS THAT CO-POLARIZATION VS OFF-POLARIZED?

FOR POSITION – IS THAT OF PROBE/SENSOR WITH RESPECT TO FIELD SOURCE?

As part of the calibration, it is necessary to identify directional and positional effects on the measured level.
of the field intercepted probe response. In addition, if so equipped and intended for use in normal operation, accessories necessary to operate the sensor or probe 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. In general, these statements apply only to free field probes and sensors, and not to ground-plane mounted probes and sensors, since cabling for these types cables are typically routed on or under the ground plane.

4.2.2 Calibration data collection

Calibration data shall be collected and reported, as at a minimum, at for 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 of optional probe positions are possible, the end part of the field sensor (or field probe) containing the element(s) and intercepting the applied field, shall be closest to the field source.

4.2.2.1 Maximum interceptionreception alignment

Each independent field sensor or field probe element shall be aligned for maximum interceptionreception of the applied field vector (see Figure 1). For example, for field sensors and field probes using dipoles for field interceptionreception, the dipole shall be considered the independent element. This alignment provides data on the base contribution of each individual field sensor or field probe independent element to independent of the overall field measurementprobe response. The This alignment also provides performance characteristics of each field sensor or field probe element.

![Figure 1—Maximum interceptionreception alignment (E-field example)](image)

4.2.2.2 Physical major axis

The field sensor or field probe physical major axis is shall be positioned perpendicular to the applied field vector and parallel to the propagation direction (see Figure 2). 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 at the maximum and minimum response positions 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 and perpendicular to the propagation direction (see Figure 3). If the field sensor or field 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 selected used for testing per 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.

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 field intensity $H$ [B63]. Different sensors have been developed and optimized to measure the various field quantities [B15]. 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. The following parameters 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 lists the devices and setups that should be used to generate standard fields for probe and sensor calibrations under Method A (calibration with a Transfer Standard), Method B (calibration using calculated field strengths), and Method C (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 listed references and the bibliographic references that are provided in the applicable clauses and subclauses of Annex B.

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 5 has its own advantages and disadvantages as discussed in the Table 3 Notes and 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, for example, bends in the conductors or walls within the device. For these same devices in the time domain, minimal impedance discontinuities are important for very fast risetimes (less than approximately five nanoseconds for laboratory–sized calibration devices). These discontinuities can occur at the input and output (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.

In a well–designed field generation device, both time and frequency domain calibrations can be performed (within the constraints given in theand NOTES in Table 3 and Annex B). This is due to the reciprocity
between time and frequency domains, as demonstrate by per-Fourier transforms (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 Transform, it may be desirable to have frequency information to frequencies lower than 9 kHz. For example, any mono-polar transient has frequency content down to and including DC and lightning transients have significant low frequency content. Table 3 NOTES indicate which field generation device can be used below 9 kHz.

Field generation devices for free field probes and sensors may not be appropriate for ground-plane mounted probes and sensors. Table 3 includes suitability information about applicability of each method for the two types of probes/sensors.

**Table 3—Methods of producing EM fields generation setups for frequency domain P probe and S sensor calibrations**

<table>
<thead>
<tr>
<th>Field Type</th>
<th>Usage (Time, Freq)</th>
<th>Frequency range</th>
<th>Field generation setup (site and transducer) facility and device type</th>
<th>Controlling reference or standard</th>
<th>IEEE Std 1309-1996xxxx Annex B reference</th>
<th>Usage Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>E &amp; H</td>
<td>T,E</td>
<td>9 kHz-200 MHz</td>
<td>TEM cell</td>
<td>IEEE Std C95.3-1991</td>
<td>B.1</td>
<td>5</td>
</tr>
<tr>
<td>H</td>
<td>F</td>
<td>9 kHz-10 MHz</td>
<td>Helmholtz coil</td>
<td>IEEE Std C95.3-1991</td>
<td>B.2</td>
<td>5</td>
</tr>
<tr>
<td>E</td>
<td>E</td>
<td>200 MHz-450 MHz</td>
<td>Anechoic chamber/open-ended waveguide</td>
<td>IEEE Std C95.3-1991</td>
<td>B.3</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>F</td>
<td>450 MHz-40 GHz</td>
<td>Anechoic chamber/pyramidal horn antennas</td>
<td>IEEE Std C95.3-1991</td>
<td>B.4</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>F</td>
<td>300 MHz-2.6 GHz</td>
<td>Waveguide chamber</td>
<td>IEEE Std C95.3-1991</td>
<td>B.5</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>T,F</td>
<td>... GHz</td>
<td>Co-conical coaxial cell</td>
<td></td>
<td>B.6</td>
<td>3,5</td>
</tr>
<tr>
<td>E &amp; H</td>
<td>T,F</td>
<td>9 kHz-1 GHz</td>
<td>GTEM</td>
<td>IEEE Std C95.3-1991</td>
<td>B.6</td>
<td>5,6</td>
</tr>
<tr>
<td>E &amp; H</td>
<td>T,E</td>
<td>100 kHz-100 MHz</td>
<td>Parallel plate</td>
<td>None</td>
<td>B.7</td>
<td>5,6</td>
</tr>
<tr>
<td>E &amp; H</td>
<td>T,F</td>
<td>100 kHz-20 GHz</td>
<td>Conical transmission line</td>
<td>None</td>
<td>B.8</td>
<td>5,6</td>
</tr>
<tr>
<td>E &amp; H</td>
<td>T</td>
<td>100 kHz-20 GHz</td>
<td>Monocone</td>
<td>None</td>
<td>B.9</td>
<td>2</td>
</tr>
</tbody>
</table>

**NOTES**

1— The TEM cell may be used up to 500-100 MHz provided the conditions specified in Annex B are met. However, the preferred and most acceptable facility for E, H field generation above 200 MHz shall be the anechoic chamber with the open-ended waveguide and pyramidal horn antenna sources. For ground plane mounted probes/sensors, the parallel plate may be used up to 1 GHz provided the constraints in Annex B.7 are met. Above 1 GHz, the conical transmission line or the monocone should be used.

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 Tranverse 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 (MPE).

5— This technique is valid down to DC (0 Hz).

6— Upper frequency limit is a function of parallel plate separation and length of conical sections.
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 transient (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

<table>
<thead>
<tr>
<th>Field Type</th>
<th>Frequency-range</th>
<th>Field generation facility and device type</th>
<th>Controlling reference or standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>E &amp; H</td>
<td>9 kHz-1 GHz</td>
<td>GTEM</td>
<td>None</td>
</tr>
<tr>
<td>E &amp; H</td>
<td>100 kHz-20 GHz</td>
<td>Monocone</td>
<td>None</td>
</tr>
<tr>
<td>E &amp; H</td>
<td>100 kHz-100 MHz</td>
<td>Parallel plate</td>
<td>None</td>
</tr>
<tr>
<td>E &amp; H</td>
<td>100 kHz-20 GHz</td>
<td>Conical transmission line</td>
<td>None</td>
</tr>
<tr>
<td>E &amp; H</td>
<td>9 kHz-200 MHz</td>
<td>TEM</td>
<td>IEEE Std C95.3-1991, 4.5.3</td>
</tr>
</tbody>
</table>

6. Determining Calibration uncertainty

Measurement results shall be accompanied by quantitative statements of uncertainty. In all calibration reports and certificates, the calibration uncertainty shall be stated, as a minimum, as follows:

“The expanded calibration uncertainty, \( U = [x.xx \text{ dB}] \), 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 customer or if necessary to assure the required degree of confidence.

Uncertainty shall be determined per estimated using the methods shown and described in the ISO/IEC/JISBIPM Guide to the Expression of Uncertainty in Measurement (1993)” (hereafter called the GUM) or ANSI/NCSL Z540-2. Other presentations of the the same concepts are given for example in [B36], NIST TN 1297-1994, UKAS LAB34:2002, and UKAS M3003:1997. With respect to this, the approach described in 6.1 through 6.4 and explained in Annex H shall be used.

6.1 Standard uncertainty

Represent each influence quantity (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 \( u^2_i \). Each component-influence quantity is either type A (statistically...
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 equation for the propagation of uncertainty, i.e., the root sum of squares (RSS) method, as discussed in Annex H.

(Commonly, \( u_c \) is used for reporting the uncertainty in 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 \( k \): \( U = k u_c \). 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 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 or larger. Using \( k = 2 \) usually gives a level of confidence level of approximately 95%. (See NIST TN 1297 and Table H.3 in Annex H.)

6.4 Reporting uncertainty

Report \( U, k, \) and the level of confidence. (If only \( u_c \) is reported, due to traditional use, this must be noted on the calibration report.) This is the minimum that shall be reported in a Certificate of Calibration. In a Calibration Report, when reporting a measurement result and its uncertainty, include the following information in the calibration report:

a) A list of all component influence quantities of for the standard uncertainty, together with their degrees of freedom where appropriate, and the resulting value of \( u_c \). The component 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; and,
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.

An example that can be used in determining containing the above-mentioned items is provided in Annex H.

7. Characteristics to be measured

7.1 Frequency domain calibration parameters

7.1.1 Dynamic range (amplitude)

 Calibration may be performed at one or more field strengths depending on the intended application. As an example, an application involving a probe for 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.

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 the resistive lines to the 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 factors 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 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.

Many MPE probes are designed to have a so-called “shaped” frequency response. Shaped 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 C95.3 Clause 5 for more details about MPE probes.

### 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 usually the anisotropy (A) is usually measured. Anisotropy \([B91][B88]\) 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:

\[
A = 10 \log_{10} \left[ \frac{S_{\text{max}}}{\sqrt{S_{\text{max}} S_{\text{min}}}} \right] \text{ dB} \tag{1}
\]

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

or

\[
A = 20 \log_{10} \left[ \frac{S_{\text{max}}}{\sqrt{S_{\text{max}} S_{\text{min}}}} \right] \text{ dB} \tag{2}
\]

S IS SYMBOL FOR POWER DENSITY – SUGGEST TO REPLACE BY “I” (intensity), ALSO USE...
if $S_I$ is the measured amplitude in field strength units. For non-symmetric distributions, the maximum isotropy deviation is taken as the greater of either the positive or negative deviations. Evaluation of the full spherical isotropy is typically not done, because it involves response measurements as the probe is re-oriented to all possible directions over the $4\pi$ solid angle. Axial isotropy (field vector normal propagation direction which is parallel to the physical major axis) measurements are generally easier to accomplish, and will represent the isotropy error in actual measurements if the probe is aligned similarly as it was in the calibration.

**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) response 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 readout device, 2) EMI testing where the probe is part of an autoleveling feedback system to adjust signal generator power 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.

**Evaluation of $R_{response}$ time as a part of calibration** is not required to be measured 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**

![Response Time Graph]

**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 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 the ratio of maximum–hold meter indication to illumination period (pulse width) is

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

where

- $E_{\text{hold}}$ is Maximum meter indication
- $E_{\text{cw}}$ is Continuous wave indication
- $K$ is Maximum hold indication ratio (actual maximum, if constantly illuminated)
- $T$ is Time constant
- $t$ is Illumination period (pulse width)

The above equation assumes that the pulse repetition rate is sufficiently slow so as to not affect the time constant being measured. This assumption can be validated using time constant measurements using different pulse repetition rates. Can validate or invalidate this assumption.

### 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 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. With respect to EMC testing, the modulation is usually AM or PAM pulse modulation.

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 other forms of modulation.

For pulse-modulated signals, the compensation for diode compression (linearization) should be carried out on the temporal signal and the output should follow the amplitude modulation [B47]. Since the resistive lines and the amplifier capacitance act as a low pass filter (video bandwidth), the envelope modulation of the signal at the amplifier input may be attenuated. If the system measures a time-averaged detector signal that is below the diode compression level, the peaks of a modulated signal could still be above this level. Various algorithms can be employed to compensate for the diode compression. Even though good linearization is typically achieved using polynomials, in some cases the use of piece-wise curvilinear functions may be necessary ([B29], [B54], [B114]).

Calibration under the conditions of a modulated field is not required unless requested. Evaluation of modulation response characteristics as part of calibration is optional, unless requested by a client. Annex A provides requirements for specifying grades of calibration with respect to modulation.

### 7.2 Time domain calibration parameters

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 function, what is the deviation of the output signal from this step function, normalized to the sensitivity of the sensor? must 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 are 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.

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 based on analytical calculation in terms of their device geometry and Maxwell’s laws. For other sensors and probes, amplitude calibration is performed by comparison testing to a primary standard sensor.

7.2.2 Dynamic range

AMPLITUDE AND DYNAMIC RANGE APPEAR TO BE THE SAME THING?

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) [B15], [B60]. 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 duration of first transition duration in a pulsed waveform. 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 response time of the instrumentation system must 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 last transition duration in a pulsed waveform. It should be measured with an instrumentation system that has a decay time that is at least five times faster than that of the transient signal being measured. 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 under-damped. Overshoot and ringing occur simultaneously, and should be measured along with the rise time.

8. Procedures (measurement techniques)
I vaguely recall that in drafting sessions for 1996 version Annexes D & E were in main body of document but were relegated as superfluous to Annexes. Annexes D, E are re-located to here – not so much for normative purposes, but because these seem to have insufficient substance to warrant full individual Annexes. Also some minor grammatical re-writes are done in the following.

The calibration procedures discussed here are applicable to techniques in both the frequency domain (CW, swept CW, stepped CW, white noise) and in the time domain (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 (CW signal generator, network analyzer, impulse generator, step generator, random-noise generator) and the measurement of the signals from the sensors (spectrum analyzer, network analyzer, transient digitizer) is relatively straightforward with modern test equipment.

Many sensors that require calibration have a broadband frequency response, meaning sensor output signals anywhere from an octave to several decades of useful bandwidth. This implies, for reasons of hardware and personnel utilization 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. These can, however, be used as single-frequency calibration checks for broadband reference standard sensors and for the field sensors under calibration.

At frequencies below approximately 20-30 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 facilities [B89].

At higher frequencies, calibrations may be performed in the time domain using transient measurement techniques. The reason for this 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, and only analyzing the portion containing the sensor response, and omitting portions of the response that contain the reflection effects. The field generating setup must have large enough dimensions such that the response is flat between the incident field and the first terminator reflections, and is the time between these reflections is greater than the probe response time. The time-(transient-) domain field sensor/field 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 (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/device, 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 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 waveguide. 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 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. Transfer standard and other traceability issues are discussed further for example in [B46], [B93], [B106].

A potential source of error when using the transfer standard to calibrate another probe is the possible
difference in the pickup-receiving 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 any probes under calibration should be identical and the calibration should be conducted in a field region that is relatively free of spatial variations caused by multipath interactions between the probe, the radiator and the anechoic chamber and 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. ---- HOW? DOES NOT APPEAR TO BE DESCRIBED IN EXAMPLES OF THIS STANDARD ----

In TEM cells, GTEMs, or parallel plate transmission systems, TEM waveguides, capacitive coupling between the probe and the septum (center plate conductor) and walls of the cell waveguide 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 (e.g., TEM waveguide). 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 (“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 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 and cable effects

The lead/cable (e.g., resistive feed-lines from sensor head to readout device) 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, parallel to the propagation direction, positioning the lead/cable end-part 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-part 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 documented 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 and supporting details or references 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 setup from Table 3 for the required frequency range and field type component.

The following constraints are recommended for accurate and repeatable measurements:

a) Voltage standing wave ratio (VSWR) of the field generator should be minimized, to obtain lowest uncertainties in calibration field strengths. This 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. E-field uniformity should also be verified, using independent reference probes or antennas, and standing-wave effects may need to be corrected [B24],[B97].

b) **Device Input and characteristic** impedance over the frequency range in use should be typically 50 Ω unless otherwise specified by the manufacturer of the field generator. This impedance can be measured with a time domain reflectometer or a network analyzer.

c) The **chosen-selected** field generation facility shall be used in its single-mode frequency range (e.g., only TEM mode in a TEM waveguide, only TE10 mode in a rectangular waveguide).

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 [B32].

2) One-third of the volume of the waveguide for the rectangular waveguide [B50],[B52].

3) The quiet zone of the anechoic chamber.

4) Six-tenths of the coil radius for Helmholtz coils [B19].

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

e) The harmonic content of the net applied power shall be at least 30-20 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 of the field.

### 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 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.

### 8.3.2.2 Isotropic response measurements procedures
This measurement is designed for field probe characterization and does not provide coherent information for individual field sensors (single element directional-pattern devices). For probes based on the three-element-orthogonal-dipole design, the rotational axis should be about the axis handle, should be rotated around the ortho-axis (probe handle or rigid or flexible feed-line assembly, or a "virtual handle"), as shown in Figure 5. If the probe is not based on the three-element-orthogonal-element design, then the rotational axis should be selected and documented to reflect isotropicity as required encountered during normal use of the probe.

![Diagram](image)

**Fig. 5.** (a) Three orthogonal dipoles with a common center. (b), (c), (d) Practical arrangements of three orthogonal dipoles with displaced centers.

---

**NOTE**—The ortho-angle is defined as $\Theta = \text{arcsec} \left( \frac{|A|}{a} \right) = \arccos \left( \frac{a}{|A|} \right) \approx 54.7$ degrees.

---

**Figure 5**—Ortho-angle ($\Theta$) and virtual handle [B7]
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 [B109].

b) Inspect the 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 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 is usually done by placing the probe’s handle of the probe at along the diagonal of a cube. If the field probe is not based on the three-element—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 on 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 such that each axis is aligned with the incident field vector while the other axes are successively cross-polarized. Proceed until data is 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, stopped, and then 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. Note that here in this case the speed of rotation shall must be slow enough to allow the field probe response to stabilize before the response is recorded, and that enough data shall be recorded to assure that a smooth response versus rotation curve is obtained.

f) For each frequency and field level, search the recorded values to find the minimum and maximum values. Use these values in equations (1) or (2), as applicable [B117], to determine the anisotropy of the field probe.

8.3.3 Response time

Refer to Figure 4 for a description—illustration of the response time parameters. The procedure is as follows:

a) Set up equipment as shown in Figure 6.

b) Apply CW signal to probe, adjust level for a stable reading on 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% value calculated in step c), increase the pulse width. If the reading is greater than the 90% value calculated in step c), decrease the pulse width.

g) Repeat steps e) and f), until the pulse width selected consistently produces a field probe meter reading equal to the 90% 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/field probe time constant measurement

Refer to Equation (3) for the general equation relating maximum hold meter indication to illumination period.

a) Set up equipment as previously shown in Figure 6.

b) Apply CW signal to probe, adjust level for a stable reading on meter.

c) Remove CW, set meter to maximum hold mode and set range switch to appropriate higher sensitivity.

d) Set pulse generator repetition rate to two pulses-per-second (2-PPS)* and a pulse width ($t$) of 0.01** s.

e) Apply pulse to control the field source (pulse modulation). Record maximum hold reading divided by the CW reading as $K$.

f) Repeat d) and e) for pulse width ($t$) settings of 0.02 s ** to 0.1 s **.

g) Calculate $T = \frac{t}{\ln(1-K)}$ for each recorded $K$ value.

*Typical value. The repetition rate should be much less than the reciprocal of the probe response time.

**Typical value. The pulse widths may determined by users 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.

NOTES

1—Typical values for $T$ are 0.2—0.3 s for thermoelectric units—thermocouple-based probes.

2—Insure meter is zeroed prior to application of power.
8.4 Time domain calibration procedure

The sensor calibration shall be performed using time domain signals. It shall be performed using the substitution technique, Methods A or Method B-C (see 4.1) in which the measured response of the sensor is compared to that of a well-characterized reference sensor, the characteristics of which are well known. The response of the reference sensor, and that of the measurement system, should be significantly faster (two to five times) than that of the sensor being calibrated. These direct "substitution" techniques allow for the effects of the entire measurement system to be removed from the sensor measurement, leaving only the characteristics of the sensor, i.e., the unit-impulse response function, or the unit step-response function. This final sensor characteristics are obtained process is performed by using deconvolution techniques (Annex F). Discussions of other issues in time-domain probe calibrations are given for example in [B5], [B28], [B37], [B60], [B64], [B67], [B68], [B90], [B103].

In addition to the instrumentation requirements given in section Clause 7.2, the following requirements also apply: Instrumentation requirements are as follows:

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 should be 5 sampled points on the transient risetime. 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 must be less than 1% of the risetime, with the long term drift approximately the same. A pulse repetition frequency of 10-100kHz is required depending on the sampling system. A stable, repetitive pulse generator that produces a very fast step or impulse waveform. The rise time must be significantly faster than the sensor being measured. The pulse-to-pulse jitter must be less than 1% of the rise time, and the long-term drift is approximately the same. A pulse repetition frequency of 10—100 kHz is required for the sampling system. A trigger output must be provided that has adequate pre-trigger time to capture the data on the sampling oscilloscope.

b) A transmission-line simulator that matches the pulse generator output impedance (typically 50Ω) into which the sensors can be mounted (ground-plane versions) or emplaced (free-field versions). The simulator must have a sufficient clear (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 [B12]. A cone-and-ground-plane simulator can also be used [B14].

c) A fast transient recorder is required. This can be a transient digitizer for slower waveforms. For the faster sensors and waveforms, a sampling system must be used.

d) A means to digitize the sampling scope data is needed, if applicable, and 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, comparison of measured sensor output amplitude to that 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 (pulse generator output).

8.4.2 Dynamic range

AMPLITUDE IS SUBSET OF DYNAMIC RANGE — THEREFORE COMBINE 8.4.1 AND 8.4.2, WITH
Calibration shall be performed at one or more field strengths, depending upon the requirements of the customer. 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.

### 8.4.3 Rise time

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

### 8.4.4 Fall time (droop)

Fall time is defined as the later/last part of the transient. It should be measured with an instrumentation system that has a decay time that is at least 5 times faster than that 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 under-damped. 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 control structure such as described in ANSI/NCSL 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. The objective of a stated calibration interval is to provide reasonable assurance that the field sensor/field probe performance has not deviated from its specification or initial calibration status within the calibration interval. The probe manufacturer provides a recommended initial calibration interval.

ED B., DON H. - ANY LAB ACCREDITATION CONFLICTS WITH 1309 GIVING GUIDANCE ON CAL INTERVALS?

If the “As Received” field sensor (field probe) is found to be within the specified tolerance for two or more intervals, the calibration interval can be increased.

If the “As Received” field sensor (field probe) is outside its specified tolerance, the interval is reduced until a suitable interval is found that assures the user that the field sensor/field probe will remain calibrated during normal use.

9.4 Out-of-tolerance notification

When a field sensor (field 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 their equipment, transfer standards, etc., are not causing an erroneous out-of-tolerance indication.

9.5 Certification to 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/probe calibrated (make, model, serial number, accessories, or configuration)

c) Parameters calibrated or calibration procedure used

d) Statement of “As Received” condition (for example, in or out-of-tolerance, damage, actual data, etc.)

e) Traceability statement, standards used

f) Environmental conditions (temperature, humidity, etc.)

g) Signature, seal, or other identifying mark of calibration technician or engineer

h) Other test conditions and results requested or required by customer

i) Calibration method and type

j) Frequency points measured, field levels, and data at each point

k) Statement and determination of uncertainty

l) Probe mounting methods/orientation details
m) Calibration applicability specifications (range around each frequency point if applicable, etc.) and supporting documentation
Annex A
(normative)

Grades of calibration

A.1 Grades of calibration

As-Because the amount or extent of calibration needed for various characteristics of a field probe or sensor will vary considerably between applications, this standard allows the use of various grades of calibration for each characteristic. It should be noted that the term grade is synonymous with the terms levels and echelons that, in addition to grade, are used in other standards to delineate such concepts.

It is not the intent of this standard to impose or recommend grades of calibration for a type of probe or sensor, as because this requirement will vary with applications. Thus, the calibration requirements or grades that reflect the probe or sensor’s application shall be specified by agreement between the calibration organization and the requesting organization.

The grade of calibration for each characteristic, and the frequency range over which the calibration is applicable, must be stated in the calibration report. If a probe or sensor is described as being calibrated as required by IEEE Std 1309-1996 this standard, the description must also include the appropriate grades of calibration and the frequency range over which the calibration is applicable, or list the specific frequencies at which measurements were made, and the conditions and data specific to each.

The characteristics discussed in A.1.1 through A.1.7 determine the grade of calibration.

A.1.1 Calibration type

The two types of calibration are defined in Table A.1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD</td>
<td>Calibration in the time domain. Calibration is done using a time varying field, usually a gated pulse. The probe or sensor output or indication is a plotted waveform in time, the abscissa of the plot showing time and the ordinates showing amplitude and phase. The calibrating organization shall provide a description of the time domain waveforms used for calibration in the calibration report. The calibration report shall also describe measurement results related to risetime, fall time, and overshoot and ringing characteristics.</td>
</tr>
<tr>
<td>FD</td>
<td>Calibration is done using a field that is measured in the frequency domain. This field may be modulated or unmodulated.</td>
</tr>
</tbody>
</table>

A.1.2 Minimum number of frequencies (frequency response)

There are eight grades of calibration with respect to the minimum number of frequencies at which calibration is performed, as shown in Table A.2.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Usage Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>One single frequency</td>
<td>—</td>
</tr>
</tbody>
</table>
F2 | Three frequencies as follows: first octave, mid-decade and last octave | —  
F3 | Three frequencies per decade | 1  
F4 | 10 frequencies per decade | 1, 2  
F5 | 30 frequencies per decade | 1, 2  
F6 | 100 frequencies per decade | 1, 2  
FX | Not applicable, time domain (TD) calibration | —  
FZ | User specified | —  

NOTES

1—Frequencies shall include the start, and end points of the calibrated frequency range. The decade start frequency shall be specified and used to determine the linearly spaced remaining frequencies. Linear spacing within the decade is specified due to the fact that most spectrum analyzers, network analyzers, and other test equipment display on linear scales.

2—Logarithmic spacing may be used if requested by the user, or if required by the application, and shall be so noted in the calibration report.

**Linear Frequency Steps**

**Procedure:**

To calculate frequency steps as a linear function of frequency, use the following formula:

\[
F_n = F_s + (n-1) \frac{F_e - F_s}{N-1}
\]

Where:
- \(F_s\) is the starting frequency (the 1st frequency);
- \(F_e\) is the ending frequency (the Nth frequency);
- \(F_n\) is the nth frequency (the frequency at step n);
- \(N\) is the number of steps; and,
- \(n\) is the step number or index.

**Example:**

The linear range is from 1.5 to 6 MHz, i.e., \(F_0\) is 1.5 MHz and \(F_e\) is 6 MHz. The desired number of frequencies \(N\) is 4. The step indices are 1, 2, 3 & 4.

\[
F_n = 1.5 + (n-1) \frac{6.0 - 1.5}{4-1} = 1.5 + (n-1) \times 1.5
\]

The resulting frequencies are 1.5 MHz, 3.0 MHz, 4.5 MHz, and 6.0 MHz.

**Logarithmic Frequency Steps**

**Procedure:**

To calculate frequency steps as a logarithmic function of frequency, use the following formulae:
Three Frequencies per Octave
This is a typical MIL-STD-461 requirement.

\[ F_n = F_s 2^n \]
\[ n : 0 \rightarrow N \]
\[ N = 3 \frac{\log(F_e) - \log(F_s)}{\log(2)} \]

Note: increase \( N \) to the next higher integer to assure at least three frequencies per octave. There will actually be four frequencies in the range at the rate of three per octave, because the starting frequency is not counted.

Where:
- \( F_s \) is the starting frequency (the 1st frequency);
- \( F_e \) is the ending frequency (the \( N \)th frequency);
- \( F_n \) is the \( n \)th frequency (the frequency at step \( n \));
- \( N \) is the number of steps; and,
- \( n \) is the step number or index.

Example: If the range is from 1.0 to 10 MHz, i.e., \( F_s \) is 1.0 MHz and \( F_e \) is 10 MHz. The desired number of frequencies \( N \) is 10. The step indices are 0, 1, 2, 3 … 10. The 10th frequency (\( \approx 10.1 \) MHz) is rounded off to 10 MHz.

The resulting frequencies are: 1, 1.26, 1.59, 2, 2.52, 3.17, 4, 6.04, 6.34, 8, 10 MHz.

Frequencies per decade:

\[ F_n = F_s 10^m \]
\[ n : 0 \rightarrow N \]
\[ N = m \left[ \log(F_e) - \log(F_s) \right] \]

Note: for fractional \( N \), increase it to the next higher integer to assure at least \( m \) frequencies per decade throughout the range.

Where:
- \( F_s \) is the starting frequency (the 1st frequency);
- \( F_e \) is the ending frequency (the \( N \)th frequency);
- \( F_n \) is the \( n \)th frequency (the frequency at step \( n \));
- \( N \) is the number of steps;
- \( m \) is the number of frequencies per decade; and,
- \( n \) is the step number or index.

Example: If the range is from 1.0 to 10 MHz, i.e., \( F_s \) is 1.0 MHz and \( F_e \) is 10 MHz. The desired number of frequencies \( N \) is 10. The number of frequencies per decade is 10. The step indices are 0, 1, 2, 3 … 10.

The resulting frequencies are: 1, 1.26, 1.58, 2, 2.51, 3.16, 3.98, 5.01, 6.31, 7.94, 10.0 MHz.

Percentage Frequency Steps
Calculation Procedure

To calculate frequency steps as a percentage of the first or a previous frequency, use the following formula:

\[ f_n = f_0 \left(1 + \frac{s}{100}\right)^{n-1} \]

Where: 
- \( f_n \) is the nth frequency;
- \( f_0 \) is the beginning frequency (n=1);
- \( s \) is the per cent step; and,
- \( n \) is the step number.

For example, if \( f_0 \) is 0.15 MHz and \( s \) is 10 %, then:

\[ f_n = f_0 \times 1.1^{n-1} \]

The upper step \( N \) is found by:

\[ N = \frac{\lg \left( \frac{f_N}{f_0} \right)}{\lg \left(1 + \frac{s}{100}\right)} + 1 \]

Thus if \( f_N = 80 \) MHz, \( f_0 = 0.15 \) MHz, and \( s = 10 \) %, then:

\[ N = \frac{\lg \left( \frac{80}{0.15} \right)}{\lg \left(1 + \frac{10}{100}\right)} + 1 = \frac{\lg(533.33)}{\lg(1.1)} + 1 = \frac{2.727}{0.04139} + 1 = 66.88 \]

Round to nearest integer: \( N = 67 \).

A.1.3 Minimum number of field levels (dynamic range)

For selected frequencies at which calibration is performed, the amplitude linearity may need to be considered. In each selectable amplitude range, the three grades of calibration with respect to amplitude are defined in Table A.3.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>One level for each selected frequency point or time domain pulse type. The level chosen shall be the linear mean of the probe’s (sensor’s) dynamic range unless otherwise noted in the calibration report.</td>
</tr>
<tr>
<td>A2</td>
<td>Three levels for each selected frequency point or time domain pulse type as a minimum. The levels chosen</td>
</tr>
</tbody>
</table>

Table A.3—Amplitude calibration grades
shall be
— 1) A level that is within 10% of the probe’s or sensor’s specified sensitivity
— 2) A level that is within the linear mean of the probe’s or sensor’s dynamic range
— 3) A level within 10% of the probe’s or sensor’s specified maximum indication capability

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3</td>
<td>More than three levels for each selected frequency point or time domain pulse type. As a minimum, the levels stated for grade A2 shall be used with additional field strength levels stated in the calibration report.</td>
</tr>
</tbody>
</table>

A3 More than three levels for each selected frequency point or time domain pulse type. As a minimum, the levels stated for grade A2 shall be used with additional field strength levels stated in the calibration report.

NOTE—Selected frequencies do not necessarily have to include all the frequencies under the grade chosen in table A.2. Under the dynamic range description, the appropriate grade is listed along with the frequencies at which it applies.

A.1.4 Isotropy

For the selected each frequency at which calibration is performed, there are five grades of calibration with respect to isotropy (Table A.4). If isotropy is to be measured, it should be measured once in each selectable probe meter range using the middle (arithmetic mean) field amplitude value for that meter range. Refer to Figures 1, 2, and 3 for illustration of axes axes.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I0</td>
<td>Isotropy not measured (for single axis probes and sensors only)</td>
</tr>
<tr>
<td>I1</td>
<td>Isotropy at maximum interception-reception alignment (orthogonal)</td>
</tr>
<tr>
<td>I2</td>
<td>Isotropy at physical major alignment (rotate around the handle or mounting device)</td>
</tr>
<tr>
<td>I3</td>
<td>Isotropy at physical minor alignment (rotate around normal to mounting device)</td>
</tr>
<tr>
<td>IX</td>
<td>Isotropy after rotation about an axis specified by user</td>
</tr>
</tbody>
</table>

Table A.4—Isotropy measurement grades

Usually Isotropy is measured only at one single frequency, or at very few frequencies; however the number of frequencies at which isotropy could be measured depends from Manufacturer recommendations and User needs. The calibration report shall clearly specify the frequencies at which isotropy is measured.

A.1.5 Response time (optional)

For each frequency at which calibration is performed, there are two grades of calibration (Table A.5) with respect to measurement of probe’s response time. If response time is to be measured, it should be measured once in each selectable probe meter range using the middle (arithmetic mean) field amplitude value for that meter range. It should be noted that this item is specifically intended for verification of a probe or sensor’s specified response time (i.e., determine whether is the indication on the probe is valid within xx seconds after exposure to a given field).

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>Response time not measured</td>
</tr>
<tr>
<td>R1</td>
<td>Response time measured</td>
</tr>
</tbody>
</table>

Typically Response Time is usually measured only at one frequency; however Manufacturer recommendations or User needs/Client requests may suggest to verify call for evaluation of Response Time at more frequencies. The calibration report shall clearly specify the frequencies at which Response time is measured.

A.1.6 Time constant (optional)
For the selected frequency at which calibration is performed, there are two grades of calibration (Table A.6) with respect to measurement of probe’s time constant. If time constant is to be measured, it should be measured once in each selectable probe meter range using the middle (arithmetic mean) field amplitude value for that meter range. It should be noted that this item is not specifically intended for verification of a probe or sensor’s specified response time (i.e., determine whether the indication on the probe is valid within xx seconds after exposure to a given field), but rather has the specific objective of providing data (a time constant) that can be used to allow accurate field strength measurement of a field with known modulation/windowing characteristics (i.e., measurement of field strength from a radar transmitter). The calibration report shall describe the pulse characteristics used for the time constant measurements.

Table A.6—Time constant measurement grades

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>Time constant not measured</td>
</tr>
<tr>
<td>T1</td>
<td>Time constant measured</td>
</tr>
</tbody>
</table>

**Typically** the time constant is measured at one single frequency, or at very few frequencies; however the number of frequencies at which time constant could be measured depends upon manufacturer recommendations and user needs. The calibration report shall clearly specify the frequencies at which time constant is measured.

**A.1.7 Modulation (optional)**

For the selected frequency at which calibration is performed, there are three grades of calibration with respect to modulation, as shown in Table A.7. The calibration report shall describe modulations used for calibration.

Table A.7—Modulation measurement grades

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0</td>
<td>No modulation, CW field used</td>
</tr>
<tr>
<td>M1</td>
<td>Modulated field. In addition to the CW field calibration (modulation to be specified)</td>
</tr>
<tr>
<td>MX</td>
<td>Not applicable, time domain (TD) calibration</td>
</tr>
</tbody>
</table>

**A.1.8 Illumination (immersion) conditions**

For the selected frequency at which calibration is performed, there are two calibration conditions with respect to immersion, as shown in Table A.8. The calibration report shall document all fixtures, orientations, and incident-field polarizations.

Table A.8— Illumination (immersion) conditions

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>Partial illumination for sensor head only</td>
</tr>
<tr>
<td>FI</td>
<td>Full illumination of sensor head, resistive feed-lines, monitor electronics</td>
</tr>
</tbody>
</table>

**A.2 Grades of calibration notation summary**

The notations for the grades of calibration are summarized as follows:
A.3 Cautions and examples

Before specifying grades of calibration for a probe or sensor and other descriptive information specifying the calibration details, the user is advised to consider the probe application to determine the number of measurements required, and hence the cost associated with resources required for the resulting calibration.

Probe orientation during calibration needs to be carefully specified and documented. Use of the probe in other orientations other than what was specified and used during actual calibration can result in significant errors for some probes (i.e., as high as up to 6 dB). The final calibration report should include a photos and/or diagrams showing the position and orientation relationship of the probe relative to the applied calibration field applied to give the end user a accurate reference guidance to the end-user on how to position the probe during use in actual testing.

Isotropic response data is strictly valid only for the frequencies calibrated at which it was evaluated for, and typically is not be considered applicable for other frequencies within the range of operation of the probe operating range, unless specifically calibrated for isotropic response at those other frequencies.

Interpolation of correction factors from calibration data for final use of the probe from calibration data may incur larger errors than at the actual calibration points provided (i.e., errors may be as high as 6 dB at the interpolated points). Additional influence quantities Measurement uncertainty shall be accounted for in measurement uncertainty when interpolation is utilized.

The following are examples of three calibrations the measurements that would be required under this standard.

As an example, an $E$ field probe with two user-selectable amplitude ranges that is to be calibrated over the frequency range of 1 MHz to 1 GHz per method B, type FD, F2 frequency grade, A2 level grade at each frequency selected for the frequency response calibration, M0 modulation (CW), and R0 response time (no measurement), a total of 60 frequency-amplitude points will have to be measured (10 frequencies × 3 levels each × 2 ranges) with an isotropicity (anisotropicity) measurement at three frequency points. This type of calibration may be needed for the probe used as a laboratory transfer standard. Such a calibration may be time consuming and expensive.

As another example, if the same probe was used for EMI radiated $E$ field susceptibility testing, a calibration using method A, type FD, F1 frequency grade, A2 dynamic range grade at one frequency point (i.e., 300 MHz), M0 modulation (CW), I1(1) (300 MHz), and R0 response time (no measurement) may be appropriate. This would require a total of 18 frequency-amplitude points to be measured with isotropicity, and a three point dynamic range measurement to be made at one frequency point.

If the same probe was only used to measure field-strength at only one frequency with only one field strength of concern, as may be the case of a probe used for RF leakage on microwave oven, a method A, type FD, F1 frequency grade, A1 level grade, M0 modulation (CW), I1(1), and R0 response time (no measurement)
measurement), a total of one frequency-amplitude point will have to be measured, with an isotropicity (anisotropicity) measurement at this one point.

Example 1: Isotropic $E$-field probe used for automated EMI testing, 1 MHz to 1 GHz, with two selectable amplitude ranges (20 V/m and 200 V/m). The probe consists of one isotropic sensor unit and a meter unit. F3, A2, M0, R1, I1, T0 calibration specified.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>F3</td>
<td>Frequency – calibrate at 3 frequencies per decade</td>
</tr>
<tr>
<td>A2</td>
<td>Amplitude / dynamic range – calibrate at three field strengths at each frequency</td>
</tr>
<tr>
<td>M0</td>
<td>Modulation – calibrate only with a CW field</td>
</tr>
<tr>
<td>R1</td>
<td>Response time – make response time measurements</td>
</tr>
<tr>
<td>I1</td>
<td>Isotropy – Measure isotropy at maximum interception/reception alignment at each frequency</td>
</tr>
<tr>
<td>T0</td>
<td>Time constant – Do not measure time constant</td>
</tr>
</tbody>
</table>
Measurements to perform:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Probe Range Setting</th>
<th>Field Amplitude &amp; Type</th>
<th>Measure Isotropy</th>
<th>Measure Response Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MHz</td>
<td>Range 1 (20 V/m)</td>
<td>1 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 MHz</td>
<td>Range 1 (20 V/m)</td>
<td>10 V/m CW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>1 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>10 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>100 V/m CW</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>1 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>200 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5 MHz</td>
<td>Range 1 (20 V/m)</td>
<td>1 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>10 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>20 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>100 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>200 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 MHz</td>
<td>Range 1 (20 V/m)</td>
<td>1 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>10 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>20 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>100 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>200 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55 MHz</td>
<td>Range 1 (20 V/m)</td>
<td>1 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>10 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>20 V/m CW</td>
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<td></td>
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<tr>
<td>55 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>100 V/m CW</td>
<td></td>
<td></td>
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<tr>
<td>55 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>200 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 MHz</td>
<td>Range 1 (20 V/m)</td>
<td>1 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>10 V/m CW</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>100 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>20 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>100 V/m CW</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>100 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>200 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>550 MHz</td>
<td>Range 1 (20 V/m)</td>
<td>1 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>550 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>10 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>550 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>20 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>550 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>100 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>550 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>200 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 MHz</td>
<td>Range 1 (20 V/m)</td>
<td>1 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>10 V/m CW</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>1000 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>100 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 MHz</td>
<td>Range 2 (200 V/m)</td>
<td>200 V/m CW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Example 2: Isotropic E-field sensor, thermal detector based probe used for EMI site survey field strength measurements from radar sources with a 60 V/m (3.4 kV/m peak) range and a 600 V/m (34 kV/m peak) range over the 300 MHz to 26 GHz frequency range. The probe consists of one isotropic sensor unit and a meter unit. F2, A2, M0, R0, I1, T1 calibration specified.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>F3</td>
<td>Frequency – calibrate at 3 frequencies per decade</td>
</tr>
<tr>
<td>A2</td>
<td>Amplitude / dynamic range – calibrate at three field strengths at each frequency</td>
</tr>
<tr>
<td>M0</td>
<td>Modulation – calibrate only with a CW field</td>
</tr>
<tr>
<td>R0</td>
<td>Response time – do not make response time measurements</td>
</tr>
<tr>
<td>I1</td>
<td>Isotropy – Measure isotropy at maximum interception alignment at each frequency</td>
</tr>
<tr>
<td>T1</td>
<td>Time constant – Measure time constant</td>
</tr>
</tbody>
</table>

Measurements to perform:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Probe Range Setting</th>
<th>Field Amplitude &amp; Type</th>
<th>Measure Isotropy</th>
<th>Measure Response Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 MHz</td>
<td>Range 1 (60 V/m)</td>
<td>1 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 MHz</td>
<td>Range 1 (60 V/m)</td>
<td>30 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 MHz</td>
<td>Range 1 (60 V/m)</td>
<td>60 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 MHz</td>
<td>Range 2 (600 V/m)</td>
<td>10 V/m CW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>300 MHz</td>
<td>Range 2 (600 V/m)</td>
<td>300 V/m CW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>300 MHz</td>
<td>Ranges 1 &amp; 2</td>
<td>600 V/m , PM w/ 2PPS, 0.01 s PW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>300 MHz</td>
<td>Ranges 1 &amp; 2</td>
<td>600 V/m , PM w/ 2PPS, 0.02 s PW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>300 MHz</td>
<td>Ranges 1 &amp; 2</td>
<td>600 V/m , PM w/ 2PPS, 0.1 s PW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>3 GHz</td>
<td>Range 1 (60 V/m)</td>
<td>1 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 GHz</td>
<td>Range 1 (60 V/m)</td>
<td>30 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 GHz</td>
<td>Range 1 (60 V/m)</td>
<td>60 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 GHz</td>
<td>Range 2 (600 V/m)</td>
<td>10 V/m CW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>3 GHz</td>
<td>Range 2 (600 V/m)</td>
<td>300 V/m CW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>3 GHz</td>
<td>Ranges 1 &amp; 2</td>
<td>600 V/m , PM w/ 2PPS, 0.01 s PW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>3 GHz</td>
<td>Ranges 1 &amp; 2</td>
<td>600 V/m , PM w/ 2PPS, 0.02 s PW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>3 GHz</td>
<td>Ranges 1 &amp; 2</td>
<td>600 V/m , PM w/ 2PPS, 0.1 s PW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>26 GHz</td>
<td>Range 1 (60 V/m)</td>
<td>1 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 GHz</td>
<td>Range 1 (60 V/m)</td>
<td>30 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 GHz</td>
<td>Range 1 (60 V/m)</td>
<td>60 V/m CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 GHz</td>
<td>Range 2 (600 V/m)</td>
<td>10 V/m CW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>26 GHz</td>
<td>Range 2 (600 V/m)</td>
<td>300 V/m CW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>26 GHz</td>
<td>Ranges 1 &amp; 2</td>
<td>600 V/m , PM w/ 2PPS, 0.01 s PW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>26 GHz</td>
<td>Ranges 1 &amp; 2</td>
<td>600 V/m , PM w/ 2PPS, 0.02 s PW</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>26 GHz</td>
<td>Ranges 1 &amp; 2</td>
<td>600 V/m , PM w/ 2PPS, 0.1 s PW</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>
Annex B

PER IEEE STDS STYLE GUIDE TABLE AND FIGURE NUMBERING SCHEME FOR ANNEXES, AND RECENT EXPERIENCE WITH IEEE STD 1528 EDITS: ALL EQUATIONS IN ANNEXES NEED RE-NUMBERING TO FORMAT E.G., (B.12), WITH NUMBERING RE-STARTING AT X.1 IN EACH SEPARATE ANNEX (X = A, B, C, …). 1309 WG SHOULD DO THIS, NOT ASSUME THAT IEEE EDITOR WILL TAKE OF IT.

(normative)

**Methods of field generation and field calculations**

Field generation setups and calculation methods

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, for example, IEEE Std C95.1-1999, IEEE Std C95.3-1991, and the references cited in these documents as well as other appropriate documents.

B.1 Electric and magnetic field generation using a TEM cell, 9 kHz—500 MHz

The rectangular transverse electromagnetic or TEM cell is the preferred method for generating $E$- and $H$-fields from 9 kHz to 200 MHz. TEM cells may be used for frequencies up to 500 MHz if the probe or sensor dimensions are small enough to ensure fit within a uniform field region. The TEM cell can be used down to DC (0 Hz). Some TEM cells have been demonstrated for operation up to 1 GHz [B102], [B106], [B128]. TEM cells can be used for frequencies down to DC (0 Hz). Numerous references describe TEM cell use, including [B41], [B42], [B58], [B75], [B77], [B93], [B97]. Many other TEM waveguide devices have been devised, some of which are applicable for probe calibrations and are described in later clauses of this annex, and others described for example in [B39], [B44], [B59], [B136].

This device is TEM cells are fully shielded, and does not emit energy that may be hazardous to personnel or cause interference with nearby electronic equipment. Other advantages are the excellent long-term stability of the calibration system and the moderate cost (compared with an anechoic chamber). The basic TEM cell is a section of two-conductor transmission line that is operating in the transverse electromagnetic mode, hence the name. As shown in Figure B.1, the main body section of the cell consists of a rectangular outer conductor and a flat septum (center plate) located midway between the top and bottom walls. The dimensions of the main section and the tapered ends of the cell are chosen to provide a characteristic impedance of 50 $\Omega$ along the entire length of the cell [B31]. When the cell is properly designed and terminated in a reflection-free load, the input VSWR is usually less than 1.5:1 for frequencies below the higher-order mode cutoff limit. In the center of the calibration volume, halfway between the septum (center plate) and the top (or bottom) wall, the $E$-field will be vertically polarized and quite uniform. Also, the wave impedance (E/H) will be close to the free space value of 377 $\Omega$. Introduction of the probe or sensor into this region will alter the field distribution in the vicinity of the probe, but the total uncertainty in the field strength is less than 1 dB [B31], [B33], [B100], [B97] if the maximum probe dimension is less than $b/3$, where $b$ is the distance from the top wall to the septum (center plate conductor).
Cells can be made in various sizes to suit particular needs and to cover specific frequency ranges. However, since the width \( h \) (surface parallel to the surface of the septum or center plate conductor) should be less than a one half-wavelength to avoid higher order modes in the cell, the upper useful frequency of a TEM cell is approximately 500 MHz.

For proper use of TEM cells, several factors should be considered, as follows:

— The electrical characteristics of the cell
— Higher order modes
— Relative size of the probe being calibrated with respect to the plate separation
— Stability and calibration of the voltmeter, directional couplers, and power meters used in conjunction with the cell to produce field strengths with an absolute, known value

Several of these issues have been considered in more detail by the work in [B51] and [B98].

![Figure B.1—Typical transverse electromagnetic (TEM) cell](image)

**B.1.1 Electrical characteristics**

The rectangular TEM cells available commercially are designed to have a characteristic impedance of approximately 50 \( \Omega \). This value, in ohms, can be calculated from the equation

\[
Z_o = \frac{9.42}{\frac{w}{b} + \frac{2}{\pi} \text{cnh} \left( \frac{\pi h}{2b} \right)}
\]  

(4)
where the dimensions $w$, $b$, and $g$ are given in Figure B.1 [B95].

The fields at the test point, i.e., the geometrical center between the septum (center plate) and the bottom (top), can be calculated from:

$$E = \frac{V}{b} = \frac{\sqrt{\frac{P_{in}}{\sigma}}}{b}$$

$$H = \frac{E}{377}$$

(5)  

(6)

where

$V$ is the voltage at the input or output port of the cell

$Z_o$ is the real part of the characteristic impedance of the cell and $b$ is the distance from the upper wall to the center plate. See B.4.2 for determination of $P_{net}$.

The equivalent plane wave power density ($W$), in watts per square meter, can be calculated from

$$W = \frac{E^2}{377}$$

or

$$W = 377H^2$$

These field values apply only at the test point for a well-matched cell and significant variation will be seen closer to or farther from the septum (center plate).

B.1.2 Higher-order modes and standing waves

The maximum operating frequency of a cell is determined by calculating the cutoff frequencies for the higher order modes. The TE$_{01}$ cutoff frequency $f_c$ is given by the relationship [B139]

$$f_c = \frac{75}{a} \left[ 1 + \frac{4a}{\pi b} \ln \left( \frac{8a}{\pi g} \right) \right]$$

(9)

where $f_c$ is expressed in MHz and $a$, $b$, and $g$ are the cell dimensions in meters. The TEM cell shall be used below this frequency to assure proper operation for probe and sensor calibration.

Some difficulties may be presented by the TE$_{01}$ mode. However, if the frequency of operation is limited to half the TE$_{01}$, cutoff frequency problems should not occur, and uniform fields should be obtained if the cell is properly designed. Additional analyses on higher order modes have been performed by Hill [B51]. However, slight errors in design or construction may sometimes lead to impedance discontinuities in the cell, particularly in the taper regions. These mismatches can produce standing waves, which generate errors in the values of the fields at the calibration point. To assure proper cell operation, field maps at each desired frequency of operation should be performed in a plane above the septum, halfway between the septum and outer wall of the cell. Maps can be made by Field distribution contour plots can be produced using readings from E-field and H-field probes with having small sensors. When using the TEM cell, forward and reflected power measurements should be made at the input port. Constant power values assure consistent TEM cell calibration. The errors due to standing waves from probe insertion can be estimated by calculating the ratio of the field at the test point to the (empty) average field above the septum, the average being taken from one end of the cell to the other along the centerline.

B.1.3 Probe sensor size with respect to plate separation

If the probe or sensor being calibrated occupies 1/3 or less of the distance $b$ (from septum to outer wall of the cell), field perturbation error is less than 10% for the $E$-field and can be corrected to within 1% using methods described in [B32]. However, as when the probe or sensor length is increased, the probe response is increased over that expected from the calculations. This field enhancement is due to loading (capacitive coupling, etc.) of the chamber TEM cell, and, since there is no accurate way to correct for this error, one
should limit the space used to less than \( b/3 \), effectively eliminating the problem. This limits the useful range of a TEM cell to frequencies below 500 MHz for probes with sensors having a diameter-length of 5 cm or less.

### B.1.4 Power measurement stability

The accuracy of probe calibrations using a TEM cell is directly related to the accurate determination of the cell voltage or the power flow through the cell. There are basically two ways to measure power flow through the cell. The first uses directional couplers to measure forward and reflected power, thereby determining the net power delivered to the cell. This method ensures that the accuracy of the field strength is associated with the power meter and coupler calibrations that usually have less than 1% uncertainty. The other method involves use of a high-power attenuator that is attached to the load end of the chamber, and a power meter that is attached to the attenuator to measure the power flow through the chamber. The uncertainty of this measurement (approximately 1%) is associated with the attenuator and power meter calibrations. As long as all components remain constant, this is an accurate method for cell calibration. However, since changes in the cell power or power measuring instruments cannot be detected with a single power measurement at the TEM cell output, this is not a preferred method.

### B.1.5 TEM cell operated with a termination impedance different from 50 \( \Omega \)

TEM cells with termination impedances different from other than 50 \( \Omega \) are not applicable to the methods of this standard.

### B.1.6 Absorber-loaded TEM cells

Absorber-loaded TEM cells can be used only if the transfer standard method is used.

### B.2 Magnetic field generation using Helmholtz coils, 9 kHz to 10 MHz

#### B.2.1 Introduction

The size of the coils and field strength required impact the maximum frequency of calibration and the size of obstruction-free laboratory space needed to assure minimal environmental interaction.

In field probe and sensor calibration it is important to obtain field uniformity. In B.2.2 and B.2.5, the equations are given for use in determining the size and shape of regions of specified field uniformity in standard Helmholtz coil sets. Regions of commonly used values of uniformity are tabulated, and graphical data and formulas are given which allow the arbitrary selection of uniformity, within reason, and produce dimensions of the uniform region.

In a pair of Helmholtz coils, the accuracy of the magnetic fields produced within them is primarily affected by the accuracy with which they are constructed and the accuracy with which the current driving them is known. Secondly, the accuracy is also affected by the equality and uniformity of the driving currents in the two coils. These secondary effects usually arise because of the frequency of operation and the nearness of large metallic (magnetic) surfaces.

A set of Helmholtz coils consists of two circular coils of equal diameter and equal number of turns parallel to each other along an axis through the center of the coils, separated by a distance equal to the common radius of the coils. For multiple turn coils, the diameter of the winding on each coil is much smaller than the diameter of the coil. The two coils are connected in series aiding in order to produce a nearly uniform magnetic field in a region surrounding the center point of the axis between the two coils. This arrangement is shown in Figure B.2. (The coils can be connected in parallel aiding, but the current in the coils must be kept equal.)
B.2.2 Axial field-strength accuracy

Constructional features such as the radii of the coils and their spacing have a direct effect as can be seen from Equation (10) \[B94\] of the axial magnetic field strength, \(H_x\) in A/m, vs. coil size, spacing, number of turns, and current. This equation gives the field strength at a point on the common axis of the two coils, \(P_x\), on the X-axis in Figure 8.2.

\[
H_x = \frac{N_1 l r_1^2}{2(r_1^2 + a_1^2)^{3/2}} \left( r_1 - r_2 \right) \frac{N_2 l r_2^2}{2(r_2^2 + a_2^2)^{3/2}}
\]

(10)

According to the definition of Helmholtz coils, \(r_1 = r_2 = r\), \(N_1 = N_2 = N\) and \(2a_1 = 2a_2 = s = r\)

Where

\(N\)  is the number of turns on each coil
\(r\)  is the radius of each coil, in meters
\(x\)  is the axial position of the magnetic field, in meters from the center of the coil set
\(I\)  is the current in the coils, in amperes

For the special position at the center of the coil set where \(x = 0\), the magnetic field is given by Equation (11).

\[
H_c = \frac{NI}{r(1.25)^{3/2}} = \frac{0.7155NI}{r}
\]

(11)

The approximation using the four-digit constant (0.7155) is less than 0.006 % low, i.e., the error is less than 60 parts per million. Neglecting this small error, the error in \(H_c\) caused by dimensional, constructional, and current variability errors may be found from Equation (12), which is also found in \[B104\].

\[
\varepsilon = \frac{\Delta H_c}{H_c} = -0.2 \left( \frac{\Delta r}{r_1} + \frac{\Delta r}{r_2} \right) - 0.6 \frac{\Delta s}{s} + \frac{\Delta l}{l} + \frac{\Delta N}{N}
\]

(12)

From this relationship, it can be seen that errors in the coil current and the number of turns are most serious, an error in the coil spacing is less serious, and an error in the coil radius is least serious.

B.2.3 Coil radius and spacing error effects
Table B.1 shows some errors in dimensions which will cause errors of 1%, 2%, and 5% in $H_c$. It is apparent in Equation (12) that equal and opposite errors in the radius of the coils will offset each other and not affect the magnetic field. This is correct for points on the center line of the coils, but for fields radially off of the center line, the field uniformity will no longer be symmetrical either side of the center of the coil set (discussed later in this Annex). The important issue is that the coils can be measured with a ruler, and an error as large as 2% in coil radius or 1.6% in coil spacing will be very obvious for coils of practical dimensions. This is one of the reasons that Helmholtz coils have for years had almost the status of primary standards. When measuring the radius of the coils, measure the diameter from the center of the winding through the center of the coil to the center of the winding at the other end of the diameter and divide by two.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>$\varepsilon = 1%$</th>
<th>$\varepsilon = 2%$</th>
<th>$\varepsilon = 5%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1$</td>
<td>5 %</td>
<td>10 %</td>
<td>25 %</td>
</tr>
<tr>
<td>$r_2$</td>
<td>5 %</td>
<td>10 %</td>
<td>25 %</td>
</tr>
<tr>
<td>$r_1 + r_2$</td>
<td>2.5 %</td>
<td>5 %</td>
<td>12.5 %</td>
</tr>
<tr>
<td>$s$</td>
<td>1.66 %</td>
<td>3.33 %</td>
<td>8.33 %</td>
</tr>
</tbody>
</table>

B.2.4 Coil current and turns errors

Errors in coil turns and coil current are more serious, not only because they directly affect the magnetic field on a one-to-one basis, but because they are harder to measure accurately. There can also be errors brought about by unequal coil currents and an unequal number of coil turns which require special methods to avoid.

Coil current errors are dependent on the accuracy and resolution (precision) of the current measuring device or current meter. There are current meters available which have accuracies better than 0.4% and resolutions better than 0.00005%, but there are also many available that are much worse.

Coil turns errors may be determined directly or indirectly. If there are more than two or three turns on each coil, it is difficult to count them and indirect measurements may have be made to determine how much wire is on the coil. The measurement errors can add up to large amounts in these indirect measurements. It is therefore best to assure that the coil manufacturer has counted the turns correctly during construction of the coils. It is important to know that there are an integral number of turns on each coil.

Using an integer number of turns allows a choice of two methods to determine the number of turns. One, a coil resistance measurement will easily determine how many coil turns there are since the coil resistance is proportional to the number of turns. While a resistance measurement might not be sufficiently accurate to determine if there are a certain number of whole turns on the coil, such a measurement will tell how many turns are there if one has a priori knowledge that there are an integral or whole number of turns on the coil; i.e., the leads come out of the coil at the same point on the circumference. Two, a current probe measurement of the product $NI$ will easily give the number of turns by comparison with the input current to the coil, if it is known that there are an integral number of turns on the coil.

The last term in Equation (12), the turns error, may be modified to account for errors in the number of turns on each of the individual coils. Replace $\Delta N/N$ with $0.5(\Delta N_1/N + \Delta N_2/N)$, where $N$ is the design number of turns. This shows that the error in the axial magnetic field is half that of the turns error in each of the coils. Again, if one coil is too small and the other too large by the same error, the center point magnetic field will not be affected, but the symmetry of the uniform field volume will be distorted.

B.2.5 Calculating radial field strength

Equation (13) gives the radial magnetic field strength, $H_r$, at a point off of the coil-axis, e.g., $P$, as shown in Figure B.2. When $y/r$ is zero, this equation gives results identical to Equation (11), and when $x/r$ is also...
zero, it gives results identical to \( E \)quation (11). This equation may be used to compute the magnetic field strength anywhere in the space between the coils and its results are plotted in Figure B.3. Figure B.3 is a normalized plot of field strength relative to center, \( \Delta H/H_c \), versus the axial distance from center, \( x/r \), for several values of radial distance from center, \( y/r \). NOTE—Equations (13) through (17) are not valid when \( y = r \) and \( x = \pm r/2 \).

\[
H_P = H_{P1} + H_{P2}
\]

\( H_{P1} \) is the field contribution from coil 1 and \( H_{P2} \) is the field contribution from coil 2.

\[
H_{P1} = \frac{NI}{2\pi r} D[ f(\rho_1) + g(\rho_1)E ]
\]

\[
H_{P2} = \frac{NI}{2\pi r} F[ f(\rho_2) + g(\rho_2)G ]
\]

\[
D = \frac{1}{\sqrt{1 - \left(\frac{y}{r}\right)^2 + K_1^2}}
\]

\[
E = \frac{1 - \left(\frac{y}{r}\right)^2 - \left(\frac{x - \frac{1}{2}}{r}\right)^2}{\left(1 - \left(\frac{y}{r}\right)^2\right) + K_2^2}
\]

\[
F = \frac{1}{\sqrt{1 + \left(\frac{y}{r}\right)^2 + K_2^2}}
\]

\[
G = \frac{1 - \left(\frac{y}{r}\right)^2 - \left(\frac{x + \frac{1}{2}}{r}\right)^2}{\left(1 - \left(\frac{y}{r}\right)^2\right) + K_2^2}
\]

where

\[
f(\rho_1) = \frac{\pi}{2} \int_0^\pi \frac{d\theta}{\sqrt{1 - \rho_1^2 \sin^2 \theta}}
\]

\[
g(\rho_2) = \frac{\pi}{2} \int_0^\pi \frac{d\theta}{\sqrt{1 - \rho_2^2 \sin^2 \theta}}
\]

with

\[
\rho_c = \frac{4\left(\frac{y}{r}\right)}{\left(1 + \left(\frac{y}{r}\right)^2 + K_1^2\right)}
\]

Note that \( f_1 \) and \( g_2 \) are complete elliptic integrals of the 1st and 2nd kind, respectively of modulus \( r_c \).

The subscript \( i \) is 1 for coil #1 and 2 for coil #2

\[
K_1 = \frac{x}{r} + \frac{1}{2}
\]
The normalized $x$ and $y$ values for field uniformity of 1%, 2%, 5% and 10%.

Table B.3—Normalized radii for several values of field uniformity ($\Delta H/H_c$)

<table>
<thead>
<tr>
<th>Uniformity</th>
<th>$\pm x/r$</th>
<th>$\pm y/r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>2%</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>5%</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>10%</td>
<td>0.6</td>
<td>0.5</td>
</tr>
</tbody>
</table>

From Table B.3, the size of coils needed for a particular maximum field-strength uncertainty based on the size of the field probe or sensor being calibrated can be determined. Each volume is ellipsoidal or cylindrical, approximately, centered on the center point of the Helmholtz coil set, and $x/r$ and $y/r$ are the normalized radii of the ellipsoid. These radii represent half of the maximum dimensions of the field probe or sensor being calibrated relative to the radius of the coils. To find the radii of Helmholtz coils needed for a field probe or sensor being calibrated of a given size, divide the dimensions of the field probe or sensor being calibrated by twice the values in Table B.3. For example, if a magnetic field sensor (field probe or sensor being calibrated) is made up of three orthogonal loops each 20 cm in diameter, and it is desired to keep each loop in the 1% uncertainty or field uniformity volume, the minimum radius of the Helmholtz coils must be $r = 20/(2 \times 0.3) = 33.33$ cm. The diameter of both coils should be 0.67 m or greater.

B.2.7 Maximum frequency of operation

To assure that the magnetic fields within the Helmholtz coil set remain as uniform as possible, the upper frequency of use should be limited such that the current around the circumference of both coils stays constant, and the electric and magnetic fields induced by the intended alternating magnetic field are small enough to be neglected [B104]. A further limit is that the frequency of operation should be well below the self-resonance frequency of the coils. A practical limiting frequency is the frequency at which the impedance of the coils is so high that they are difficult to drive. This last limit is the lowest in frequency and is the one that usually prevails. The hierarchy of these limits are shown in Table B.4 and discussed below.

The frequency at which the currents around the circumference of the coils stays remains constant is the highest of the possible limiting frequencies. At this frequency the length of the wire in each of the coils is no longer than 0.15$\lambda$ or 0.10$\lambda$. Since it is the highest of the limiting frequencies, it is of little practical importance.
Table B.4—Upper frequency limit

<table>
<thead>
<tr>
<th></th>
<th>Length of wire in coils</th>
<th>Highest frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Secondary field effects</td>
<td>Lower than 1</td>
</tr>
<tr>
<td>3</td>
<td>Self resonance</td>
<td>Lower than 2</td>
</tr>
<tr>
<td>4</td>
<td>Falloff of drive current</td>
<td>Lowest frequency</td>
</tr>
</tbody>
</table>

From Maxwell’s equations, an alternating magnetic field generates an alternating electric field, which in turn, generates another alternating magnetic field, etc. Thus when an ac magnetic field is intentionally created by a pair of Helmholtz coils, it generates a series of electric and magnetic fields in the same test volume where the uniform magnetic fields are desired. Also, since the Helmholtz coils do not usually have an electric shield, they directly generate an electric field which also generates a secondary magnetic field, etc. The magnitude of these effects increases with increasing frequency. The frequency at which these effects cannot be neglected is lower than the highest limiting frequency discussed above, but much higher than the self-resonance frequency of the coils [B104].

The self-resonance frequency of the coils is given by the familiar equation, \( f_o = \frac{1}{2\pi \sqrt{LC}} \). The inductance \( L \) of the coils is easily calculated, but \( C \) is the stray capacitance of the coils and is not easily calculated. It could be modeled by the method of moments. This frequency is much lower than the other two limiting frequencies, and it is a limit primarily because the coils are extremely difficult to drive at this frequency since it is a parallel resonance.

A practical maximum frequency is reached before the coils begin to approach resonance. About two orders of magnitude below the self-resonance frequency of the coils is the frequency where for a given generator power, the drive current begins to fall off. The impedance (mostly reactance) of the coils increases with increasing frequency so that more and more generator power is required to maintain the nominal magnetic field. The frequency at which the generator power must be doubled (3 dB) to maintain the desired coil current is often referred to as the bandwidth or corner frequency of the Helmholtz coil set. It is probably reasonable to set the practical upper frequency no higher than the frequency where the generator power would have to be 10 times its level at low frequencies. The term generator used here includes any power amplifier needed to produce the required coil current, so that a factor of 10 increase in generator power may be too extravagant, i.e., the cost of the higher-powered amplifier may be prohibitive. The effect is given in Equation (18).

\[
f_U = \frac{R_S + R_c}{2\pi L_T} \sqrt{\frac{P_U}{P_o} - 1}
\]

\[
L_T = 2N^2 \left\{ a + u \left[ 1 + \left( \frac{8r}{b} \right) - 2 \right] \right\}
\]

where

- \( a \) is the mutual inductance factor, \( 0.494 \times 10^{-6} \) for Helmholtz coils [B104]
- \( b \) is the effective radius of the coil winding, m (see Figure B.4) [B120]
- \( R_S \) is the generator source impedance, \( \Omega \)
- \( R_c \) is the total resistance of both coils, \( \Omega \)
- \( P_U/P_o \) is the ratio of the generator power at the upper frequency to the generator power at low frequencies.
B.2.8 Extending the upper frequency limit

There are situations in which it is necessary to feed the coils in parallel. This occurs at higher frequencies where the impedance of the coil is large enough to make it difficult to drive the necessary current through the coils when they are connected in series aiding. The upper frequency can be extended by a factor of four by connecting the coils in parallel-aiding. Use this parallel-aiding connection only when absolutely necessary.

When the coils are connected in parallel-aiding, the two coil currents must be kept equal and in phase. To do this, they must come from the same generator through phase-matched paths and be independently adjustable. To evaluate the errors caused by this connection, replace the last two terms in Equation (12) with a new last term, as shown in Equation (20), in which \( N \) is the design value and \( I \) is the intended current.

\[
\varepsilon = \frac{\Delta H_c}{H_c} = -0.2 \left( \frac{\Delta r_1}{r} + \frac{\Delta r_2}{r} \right) - 0.6 \frac{\Delta \lambda}{s} + 0.5 \left( \frac{\Delta N_1 I_1}{NI} + \frac{\Delta N_2 I_2}{NI} \right) \tag{20}
\]

This shows that the products \( NI \) are what must be controlled and kept as accurate and as equal as is possible. If a current probe is connected around each coil, the value of \( NI \) in both coils can be set equally and accurately within the resolution and accuracy of the current probe and voltmeter combination used. The last term of Equation (13) now becomes \((\Delta I_{cp}/I + \Delta I_{cpr}/I)\), where \( \Delta I_{cp}/I \) is the accuracy of the probe and voltmeter, \( \Delta I_{cpr}/I \) is their resolution, and the coefficient 0.5 becomes unity. If a precision current meter is used to set the current in one coil and the current probe-voltmeter technique is used to bring \( NI \) to equality in both coils, the last term of Equation (14) becomes \((\Delta I/|I| + 0.5\Delta I_{cp}/|I|)\), where \( \Delta I/|I| \) is the error in the current meter. For example, if the current accuracy is 0.4% and the resolution of the current probe-voltmeter is 0.01%, then the total error in \( H_x \) will be 0.405%. The inequality of \( NI \) in both coils is the resolution of the current probe-voltmeter. This technique can produce a more symmetrical uniform field volume than individually adjusting the coil currents when the coils must be fed in parallel, and is the preferred approach.

If only a single calibration frequency is used, the coils that are connected in series-aiding can be series resonated by one external coil-capacitor network to make driving easier. The combined length of wire in the two Helmholtz coils (not including the external resonant circuit) must remain below self-resonance, however.

B.2.9 Effects of loading

A large field probe or sensor being calibrated that is made of magnetic material may load the coils and concentrate the fields in its vicinity. If inserting the field probe or sensor being calibrated into the test space within the Helmholtz coil set causes the coil current to change by more than a few percent, it should be suspected that the field is distorted and may not be accurate even after returning the coil current to the correct value. The coil current should always be set with the system empty and then reset to the original
value after the field probe or sensor being calibrated is inserted. If field distortion is suspected, a larger set of Helmholtz coils should be used.

Using the Helmholtz coil set inside of a shielded enclosure that is too small will affect the accuracy of the fields. If a shielded enclosure is used, its smallest dimension must be more than 6.7r to prevent loading of the system and distortion of the fields. This dimension may also be used to determine how far away from the Helmholtz coils large metallic objects should be.

**B.2.10 Summary**

The use of Helmholtz coils for probe or sensor calibration is summarized as follows [B19]:

- Helmholtz coils may be used to volumes with dimensions of 0.6r for highly accurate probe or sensor calibration.
- Helmholtz coils should be used in the series-aiding connection, but may be used in the parallel-aiding connection if necessary—with extra current controls and precautions.
- Balance the products NI in the two coils for maximum accuracy.
- Consider Helmholtz coils a primary standard—they can be calibrated by ruler.

**B.3 Open-ended waveguide source in anechoic chamber, 200—450 MHz**

Open-ended waveguides are perhaps the smallest practical source antennas. They are readily available, do not have serious mismatch problems, and yet have sufficient directive gain to concentrate the energy in the calibration region and facilitate the suppression of scattered energy in the test chamber. Further, one can easily operate at distances greater than four \( \frac{4a}{\lambda} \). However, an open-ended waveguide antenna shall consist of a section of waveguide whose aperture end extends several wavelengths from any flanges or bends. Also, the aperture (radiating) end should be cleanly cut in the plane perpendicular to the axis of propagation of the guide. For common open-ended waveguide apertures with a two-to-one aspect ratio, the far-field gain is approximated by the equation [B76]

\[
g = 21.0 f a 
\]

where:

- \( f \) is the frequency in GHz
- \( a \) is the width (larger dimension) of the waveguide aperture in meters

When it is necessary to calibrate a large number of nominally identical probes or sensors, the extrapolation method described in [B108] is useful when applied as follows. Let \( B_d \) be the meter indication with the probe at an arbitrary near-field distance \( d \) and \( B_o \), the indication with the probe or sensor at a large distance \( d_o \), where far-field conditions hold. The relations can be written as

\[
B_o = K W_o
\]

\[
B_d = K W_d
\]

where

- \( W_o \) is the far-field power density
- \( W_d \) is the equivalent plane-wave power density in the near field
- \( K \) is a proportionality factor that relates the meter indication to the incident power density

In the extrapolation technique, \( B_o \) is measured over a range of \( d \)-distance \( d \), and a power series is fitted to the product \( B_d d^2 \) over the measurement interval. This series is then used to determine \( B_d d_o^2 \) by extrapolation. The following ratio can then be obtained.
\[
\frac{B_d d^2}{B_o d_o^2} = F_d
\]  

Equation (24)

\( F_d \) (the near-field correction factor) can also be determined without recourse to the extrapolation method if a long enough range is available to measure \( B_d d^2 \) directly. Combining the above equations yields

\[
W_d = F_d W_o \left( \frac{d_o}{d} \right)^2 = \frac{F_d P_{net} g}{4 \pi d}
\]  

Equation (25)

**NOTE**—\( F_d \) is a nonlinear function of \( d \) and is valid only at the point at which it was measured.

since

\[
W_o = \frac{P_{net} g}{4 \pi d^2}
\]  

Equation (26)

\( P_{net} \) can be measured, and \( g \) (the far-field gain of the transmitting antenna) can be obtained by extrapolation method or by other methods previously referenced. The near-field correction factor \( F_d \) is a function of \( d \), and should be determined for every combination of radiator and probe/sensor type. However, once \( F_d \) has been obtained for a given probe or sensor, it can be used to calibrate other probes of the same type with little additional error.

**NOTE**—The near-field gain calculations for horns antennas do not yield accurate results for open-ended waveguides, so the near-field gain should be measured. An overall uncertainty of 1.0 dB or less can be achieved if sufficient care is taken [B18], [B53]. See B.4.2 for details on measuring power to the transmitting device.

### B.4 Pyramidal horn antenna source in an anechoic chamber, 450 MHz—40 GHz

#### B.4.1 Standard transmitting antenna equations.

A transmitting antenna in free space that radiates \( P \) watts and has a gain \( g \) in a given direction will radiate \( Pg/4\pi \) watts per steradian at a distance that is large compared to the antenna aperture. The power density in W/m² at a distance \( d \) from the antenna will be \( Pg/4\pi d^2 \). In terms of the field strength existing at the same distance, the power density is \( E^2/\eta \). By equating these two expressions, the free-space field may be determined from the relationship:

\[
E = \sqrt{\frac{\eta P g}{4 \pi d^2}}
\]  

Equation (27)

where

- \( E \) is free-space RMS electric field strength, in V/m
- \( P \) is input power to the transmitting antenna, in W
- \( G \) is gain of the transmitting antenna in the direction toward the receiving point relative to an isotropic radiator
- \( D \) is distance from the transmitting antenna to the receiving point, in meters
- \( \eta \) is intrinsic impedance of propagation medium in ohms

For calibration purposes, an anechoic chamber free of reflecting objects shall be used.

#### B.4.2 Measurement of power delivered to a transmitting device

Figure B.5 shows a typical setup for measuring net power to a transmitting antenna. The four-port dual-directional coupler allows measurement of the power incident upon and reflected from the antenna.
Figure B.5—System for measuring RF power delivered to an antenna

The ratio of power emerging from port 4 (i.e., $P_{\text{inc}}$) to the power $P_1$ read by the power meter on port 1 is the incident-power coupling factor $C_{\text{inc}}$. The reflected-power coupling factor $C_{\text{refl}}$ is the ratio of power entering port 4 (i.e., $P_{\text{refl}}$) to the power $P_2$ read by the power meter on port 2. (Measuring coupling factors with respect to port 4 eliminates the need for a separate measurement of coupler insertion loss.)

Manufacturers furnish nominal coupling factors over the frequency range of the coupler. For greatest accuracy in obtaining $P_{\text{net}}$, however, both coupling factors should be known at each measurement frequency. Then, at a given frequency

$$P_{\text{net}} = C_{\text{inc}}P_1 - C_{\text{refl}}P_2$$

Equation (28) is valid for use with directional couplers having high directivity (at least 25—30 dB), but may give inaccurate values for $P_{\text{net}}$ if the coupler has low directivity and if the port-4 load is not well matched to the coupler or transmission line impedance. An analysis of the directional coupler as a four-port junction has been done in terms of the reflection coefficients and scattering parameters of the system, see [B74][B74]. The net power delivered to the transmitting antenna is given by

$$P_{\text{net}} = P_{\text{inc}} - P_{\text{ref}}$$

$$P_{\text{net}} = \frac{P_1}{1 - |\Gamma_1|^2} \frac{|S_{34}|^2}{|S_{13}|^2} |g(S,\Gamma)|^2$$

$$P_{\text{net}} = \frac{P_2}{1 - |\Gamma_2|^2} \frac{1}{|S_{24}|^2} |h(S,\Gamma)|^2$$

The symbols $\Gamma_1$ and $\Gamma_2$, represent the reflection coefficients observed looking into power meters 1 and 2. $S_{ij}$ is the scattering parameter defined as the ratio of the complex wave amplitude emerging from port i to that incident upon port j, and $g(S,\Gamma)$ and $h(S,\Gamma)$ are functions of the system $S$-parameters and the reflection coefficients of ports 1, 2, and 4. For an ideal coupler, i.e., one having zero reflection coefficient for all input ports and infinite directivity ($S_{11} = S_{22} = S_{33} = S_{44} = S_{23} = S_{32} = S_{41} = S_{14} = 0$), with matched power meters at ports 1 and 2 ($\Gamma_1 = \Gamma_2 = 0$), the terms $g(S,\Gamma) = h(S,\Gamma) = 1$. Unless the magnitudes and phases of the system $S$-parameters and the reflection coefficients of a real system are well determined, $g(S,\Gamma)$ and $h(S,\Gamma)$ are not calculable. The deviation of $g(S,\Gamma)$ and $h(S,\Gamma)$ from unity is, therefore, taken to be part of the uncertainty in the determination of the net power delivered to the standard antenna. Although the degree of deviation from unity is a function of the system $S$ and $\Gamma$ parameters, it is found to be, in general, less than 1%—see [B74][B74].

To compute the net power using Equation (29), the terms $S_{ij}/S_{11}$ and $1/S_{11}$ need to be determined. Although the magnitudes of $S_{11}, S_{22}$, and $S_{33}$ could be measured with a network analyzer, the system described here can...
be made self-calibrating by utilizing a standard flat-plate short and a matched termination. When a short (\(\Gamma_4 = -1\)) is placed at port 4, the ratio of power measurements \(P_2\) and \(P_1\) gives
\[
\frac{P_2}{P_1} = \left| \frac{S_{24}S_{34}}{S_{13}} \right|^2 \frac{1 - \left| \Gamma_4 \right|^2}{1 - \left| \Gamma_1 \right|^2} (1 + |\Delta_1|^2)
\]
(32)
where \(\Delta_1(\mathbf{S}, \Gamma)\) is a complex quantity much less than unity (see [B95]). The second step in evaluating the \(S\)-parameter coefficients in Equation (29) is to move the power meter from port 2 to port 4 and terminate port 2 in 50 \(\Omega\). The ratio of the two power measurements \(P_1\) and \(P_4\) is
\[
\frac{P_1}{P_4} = \left| \frac{S_{13}}{S_{34}} \right|^2 \frac{1 - \left| \Gamma_1 \right|^2}{1 - \left| \Gamma_4 \right|^2} (1 + |\Delta_2|^2)
\]
(33)
where \(\Delta_2\) is another complex quantity much less than unity.

From the four power measurements and values for the power meter reflection coefficients \(\Gamma_1, \Gamma_2,\) and \(\Gamma_4\), the quantities \(|S_{34}/S_{13}|^2\) and \(|S_{34}|^2\) may be computed from Equations (30) and (31). The terms \(\Delta_1\) and \(\Delta_2\) involve products of the system S-parameters and reflection coefficients \(\Gamma\) whose phases are not known. Therefore, the magnitudes of \(\Delta_1\) and \(\Delta_2\) cannot be determined, and the deviation of \(\Delta_1\) and \(\Delta_2\) from zero is unknown. Moreover, the uncertainties in the power measurements and in the values for the reflection coefficients also contribute to the uncertainty in the determination of \(|S_{34}/S_{13}|\) and \(|S_{34}|^2\). The detailed discussion on this topic is given in [B76].

### B.4.3 Standard--field equations for an anechoic chamber

Electromagnetic fields in an anechoic chamber are usually established with standard transmitting antennas. Equation (27) is used to calculate the electric field on the axis (boresight) of the antenna. The quantities to be determined are net power \(P\), distance \(d\), and antenna gain \(g\), relative to an isotropic antenna. The net power delivered to the antenna is measured as described in B.4.2, and \(d\) is measured by any suitably accurate procedure. Evaluating the radiated electric field then reduces to determining the transmitting antenna gain at each measurement frequency and distance.

In deriving the far-field gain of a pyramidal horn (Figure B.6) by the Kirchhoff method, Schelkunoff accounted for the effect of the horn flare by introducing a quadratic phase error in the dominant-mode field along the aperture coordinates, see [B126]. Geometrical optics and single diffraction by the aperture edges yield essentially the Kirchhoff results. The proximity effect in the near field (i.e., an on-axis point is not equidistant from points in the aperture plane) can also be approximated by a quadratic phase error in the aperture field. Taking into account the preceding considerations, the near-field gain \(g\) of a pyramidal horn radiating at a wavelength \(\lambda\) (in meters) is given by [B70]
\[
g = \frac{32\pi f^2}{\lambda^2} R_h R_H = 113.3 f^2 ab R_h R_H
\]
(34)
where \(f\) is in GHz.
The terms $R_E$ and $R_H$ are often written in terms of Fresnel integrals [B69] and are functions of the horn dimensions and the on-axis distance from aperture plane to field point. The numeric gain may be more easily obtained from tabulated values for $R_E$ and $R_H$ in dB [B70] to which polynomial expressions have been fitted [B83].

\[
R_E = -(0.1\beta^2)(2.31 + 0.053\beta)
\]
\[
R_H = -(0.01a)(1 + 10.19a + 0.51a^2 - 0.097a^3)
\]  
(35)

(36)

where

\[
a = \frac{a^2f}{0.3} \left( \frac{1}{I_H} + \frac{1}{d} \right)
\]

\[
\beta = \frac{b^2f}{0.3} \left( \frac{1}{I_E} + \frac{1}{d} \right)
\]

(37A)

(38B)

and

- $a$, $b$, $I_E$, $I_H$ are horn dimensions, in meters
- $F$ is frequency in GHz
- $D$ is on-axis distance from horn aperture to field point in meters

The terms $R_E$ and $R_H$ in Equation (34) are gain reduction factors that are positive and less than unity. Though their values in decibels are negative, the tabulation in [B70] gives these decibel values as positive. Therefore, a minus sign (not present in [B81] [B82]) is included in Equation (36) to make Equation (36) consistent with equation (32).

From equation (32) for the gain $g$, the horn gain $G$, in dBi, is

\[
G = 10\log(g) = 20.54 + 10\log(ab) + 20\log(f) + R_E + R_H
\]

(39)

The numeric gain $g$ is then

\[
g = 10^{g/10}
\]

(40)

If the test setup uses coaxial components such as directional couplers and waveguide-to-coax transitions, then the horn antenna gain must include the loss of the waveguide-to-coax transition.

Equations (34) to (39) were derived using an aperture integration technique, by assuming that no
reflection occurs at the throat or aperture of the horn, and assuming the field incident on the aperture is a TE_{10} waveguide mode but with a quadratic phase distribution across the aperture. As such, effects such as multiple reflections from the horn edge, and higher-order modes at the aperture have not been taken into account. Other approximations were applied to obtain the closed form results in these equations. Depending on the frequency and horn design, the error is generally ±0.5 dB, but can be as large as ±1 dB. If Equations (34)-(39) are used to establish the standard field, this error should be included in the calibration uncertainty. For better accuracy, a numerical method using full-wave integration can be used [ref][B73].

An alternate method for power density calibration is specified in IEEE Std C95.3-2002. It utilizes a truncated horn antenna, quasi-near-field gain measurements, and scalar “power equations” to determine plane wave power density with low uncertainties in an anechoic chamber [B6].

### B.5 Waveguide chamber, 100 MHz to 2.6 GHz

A rectangular waveguide chamber may be used to calibrate field probes and sensors specifically used for microwave leakage field detection (MPE).

The fields inside a rectangular waveguide can be calculated and in some cases are sufficiently uniform to be considered for calibration purposes. The main advantage of such a system is that considerably less power and space are required. One disadvantage is that the maximum transverse dimension of a rectangular waveguide should be less than the free-space wavelength at the highest calibration frequency in order to avoid higher-order modes that result in complicated field distributions. Hence, the method is generally used only for frequencies below 2.6 GHz (WR430), since the device being calibrated should be small compared with the guide dimensions. The distribution of the known field in the waveguide is an approximation to leakage fields propagated from a leak in a microwave oven door. The field in the latter case would decay rapidly with distance from the radiator, and the probe sensor would experience the major effect of the field, i.e., the handle and cable are illuminated by a greatly decreased highly decayed field. Therefore, waveguide calibrations may provide a lower uncertainty in the calibration of leakage probes than calibration in a plane-wave field where the entire probe is more uniformly illuminated. A careful error analysis of this problem has not been completed, but it appears that if the maximum probe dimension is less than one-third the smallest waveguide dimension, the total uncertainty will not exceed ±1 dB [B1][B3], [B140].

Figure B.7 shows how a section of rectangular waveguide can be used for calibrations. A reflection-free load termination is connected to the output end to prevent standing waves that would cause serious errors in the calibration. The probe to be calibrated is usually inserted into the waveguide through a hole in the side wall (as in Figure B.7) and positioned in the center of the guide where the field is most nearly uniform. (Entry Insertion through the top wall is not recommended because spurious pickup by the leads that are then aligned with the E-field is greater or potential undesired radiation might occur). The access hole should be as small as possible to minimize perturbation of the field distribution. Equations for calculating the field distribution from $P_{net}$ (the net power delivered to the section) and the guide dimensions can be found in [B52]-[B50], [B82]-[B82]. The “equivalent power density” can be determined in terms of $E$ (not $E \times H$) at the center of a rectangular guide in which the width, $a$, is twice the height ($a$ is the wider dimension) from

$$W = \frac{4P_{net}}{a^2} \left[1 - \left(\frac{\lambda}{2a}\right)^2\right]^{-1/2}$$

See B.4.2 for details on measuring power to the transmitting device.
B.6 Gigahertz TEM (GTEM) cell, 9 kHz to 1 GHz

Another transmission line structure for calibrating electromagnetic field probes is known as the GTEM cell, shown in Figure B.8 [B48], [B58], [B80]. The GTEM cell consists of a tapered (pyramidal) asymmetrical rectangular coaxial transmission line, similar to a lengthened input section of a TEM cell. Cross-sectional dimensions are selected to maintain a constant $50 \, \Omega$ characteristic impedance along the length. Like the basic circular coaxial transmission lines and regular TEM cells, the wave impedance between the outer and inner conductors is approximately $377 \, \Omega$. A GTEM can be constructed to have a much larger working volume than a TEM cell. There are no major geometrical discontinuities, as there are in a standard TEM cell, which has angle changes from the input/output tapers to the middle straight section, so moding may not be seen and therefore higher-order mode excitations are not evident in GTEM VSWR measurements below 20 GHz. The septum (or center conductor plate) is terminated in a series and parallel $50 \, \Omega$ resistor array, arranged to provide a $50 \, \Omega$ circuit impedance and which dissipates fields and currents up to at least the low MHz frequencies (depending on GTEM size). Pyramidal absorber covering the back wall dissipates the approximately plane wave fields at all higher frequencies. Other examples of GTEM field calculations and use for calibration purposes are given in [B67], [B68], [B77], [B92], [B115], [B125], [B135].

The GTEM characteristic impedance and quasi-static field can be calculated approximately using asymmetric TEM cell theory [B132], [B138]. For most GTEM sizes, the quasi-static field calculations are most accurate up to a few hundred MHz. At higher frequencies, the measured field may vary up to about $\pm 4 \, \text{dB}$ [B49]. At present, a rigorous method of GTEM field calculation for all frequencies is not available. Although some analytical methods for approximate GTEM field calculation have been presented, e.g., [B77], most are relatively complex and have not been widely used for routine field calculations. For these reasons, it is recommended to use the transfer standard method when calibrating probes in a GTEM. Refer to B.4.2 for details on measuring power to the transmitting device.
B.7 Parallel plate transmission line

One such transmission line structure for calibrating electromagnetic field probes is the parallel-plate transmission line shown in Figure B.9.

![Figure B.9—Parallel plate transmission line]

This structure consists of two parallel flat plates for which the field distribution is assumed to be a plane wave and is almost uniform over certain regions between them. The two plates can be of the same width or one of the plates can be much wider than the other, approximating infinite width. The field distributions are exactly calculable by means of conformal transformations, and results are given in references [B11], [B13], [B14], [B16], [B22], [B25], [B26], [B30], [B45], [B50], [B55], [B85], [B84], [B87], [B91], [B101], [B99], [B100], [B101], [B121], [B148], [B142]. These calculations are based upon the infinitely long, two-dimensional, cross-section of the plates.

At both ends of the parallel-plate transmission line there must be input and output sections. The output must have a load that terminates the transmission line in its characteristic impedance in order to prevent reflections and standing waves from occurring on the line. This termination may be either distributed across the width and separation of the plates [B9], [B10], [B85], [B122], [B123], [B124], [B141], or by a tapered transmission line section to a coaxial output used. The distributed termination is preferred because multimode field diffraction problems associated with bends in the conductor plates [B13], [B50] are avoided.

The input to the transmission line is usually a coaxial line from a source generator, so an input transition
from the coaxial line to a two-plate line and a tapered “conical” transmission line from the transition to the parallel plates are required, as shown in Figure B.10.

![Figure B.10—Parallel plate transmission line with conical input and output sections](image)

The fields in the input tapered section have a spherical wave front because of the (nearly-)point source at the input transition. When this spherical wave front reaches the parallel plate section, it is converted to a TEM plane wave. After this conversion occurs, the wave is no longer spherical. The TEM wave will propagate down the transmission line until the termination is reached. If the impedance matching is good at the bend to the termination tapered section and the termination itself, minimal distortion to the TEM wave will occur. Field diffraction can occur at higher frequencies at this bend [B13], [B50] which can cause scattered fields that can bounce back and forth in the device. Having a long tapered output section will reduce these effects.

The distance within the parallel plate section required for the spherical to TEM conversion is a function of the length of the conical section and the height \(h\) of the parallel plate spacing. The longer the conical section and/or the smaller the plate spacing, the shorter the conversion distance. Both of the parameters determine the angle \(\Theta\) that the conical section plate makes with the ground plane. The conversion distance \(L\) is given by

\[
L = h \left( \csc \Theta - \cot \Theta \right)
\]

where \(h\) is the parallel plate spacing. [B149][B13],[B50].

A similar effect occurs for the output tapered section. The smaller the angle between the parallel plate section and the output taper section (i.e. the longer the taper and/or the smaller the spacing between the parallel plates), the smaller the field diffraction at the bend will be. This in turn will result in smaller field distortion. The fields in the input tapered section have spherical wave fronts because of the [near] point source at the input transition. When these spherical wave fronts reach the parallel plate section, two things happen, neither of which allows for smooth transition to plane waves. First, the incident wave fronts continue to be spherical, propagating in straight lines until they strike one of the plates or until they exit the sides of the line. Second, field diffraction occurs at the bends in the conductor plates [B7, B24], generating higher modes. Both phenomena produce scattered fields that bounce back and forth between the plates as they propagate down the line.

If a tapered termination section is used, another phenomenon occurs that significantly perturbs the fields within the line. Some of the wave fronts bounce around within the taper and never reach the termination adapter, but instead are eventually reflected back into the parallel plate section, similarly to paths traced by ray optics. Those of these that reach the input taper have the same thing happen again, so that waves rattle around between the input and output sections, eventually being lost out the sides of the line or attenuated by the finite conductivity of the plates. They never reach the input or output coaxial adapters, and thus do not show up on time domain reflectometer or parameter measurements at these points. The line can thus show very good input and output impedance matches, but still have significant standing waves within it. Indeed, spectral nulls of 20—30 dB have been measured, which change location along the line with frequency. Great care must therefore be taken when using this type of transmission line and many measurements taken...
in order to characterize its performance.

### B.8 Conical transmission line

Some of the problems associated with the parallel-plate transmission line discussed above can be avoided by making a transmission line that consists only of the input taper section, known as a conical transmission line [B9], [B10], [B85], [B122], [B123], [B124], [B141] with a distributed termination [B8], [B12], [B81], [B143], [B144] as shown in Figure B.11.

![Conical transmission line with distributed terminations](image)

Figure B.11—Conical transmission line with distributed terminations

Launch of this device is identical to that of the parallel plate with tapered input (i.e., spherical). The field uniformity near the centerline of one of the plates approaches that of a plane wave. The terminator can be constructed as a set of resistive strings that add in parallel to terminate the characteristic impedance of the line at low frequencies. The sparseness of the termination strings allows the very high frequencies to pass through without reflection. The intermediate frequency reflections can be minimized by optimizing the inductance of the strings. Such calibration fixtures have been made for probe calibrations with step rise times of 40 ps (10 GHz) [B129],[B130],[B131],[B134].

### B.9 Cone and ground plane

One approach to time-domain sensor calibration is to construct a field generator that produces an accurately known incident field. One such structure is the cone and ground plane structure shown in Figure B.12. This type of structure has been used by Phillips Laboratory at Kirtland Air Force Base in the past and is currently being used by NIST [B89] for a wide variety of primary standard sensors and antenna calibrations. As can be seen, the structure consists of a rectangular ground plane and a cone of solid half angle $\theta/2$ that is driven from below by a high-speed pulse generator.

The geometry of this structure permits the computation of the generated field using simple, closed-form analytical expressions that are dependent only on the structural geometry. The characteristic impedance ($Z_c$) of this structure is given by

$$Z_c = 60 \ln \left[ \sec \left( \frac{\theta}{2} \right) \right]$$

(42)

If the impulse generator and the associated driven transmission line have a characteristic impedance $Z_d$, an outward traveling spherical wavefront is generated with an electric field...
Where $V(t)$ is the time-domain drive voltage at the base of the cone. If $r_{cone}$ is the length of the cone and $r_{gp}$ is the minimum distance from the base of the cone to the nearest point(s) on the edge of the ground plane, Equation (40) is bounded by a minimum radius at the base of the cone and a maximum radius defined by the smaller of these two distances $r_{cone}$ and $r_{gp}$. These distances dictate the time window for which Equation (40) is valid.

$$0 \leq t \leq \frac{2c}{\min[r_{cone}, r_{gp}]}$$

where $c = 3 \times 10^8$ m/s. Before any reflections occur from either the end of the cone or the edge of the ground plane, Equation (40) indicates that the cone generates an axially symmetric $\theta$-directed electric field that is constant at a fixed radius $r$ and angle $\theta$.

There are no absolute rules for selecting the dimensions of the cone and ground plane. The choice will be dictated by the following considerations:

- The physical dimensions of the sensor to be calibrated. The sensor under test must fit within the volume for which Equation (40) is valid. For small sensors this will not be an issue. However, for TEM horn sensors, the physical length increases as the low frequency limit is decreased [B110] and the length of the sensor might very well extend beyond the region of validity for the ground plane cone system.

- The sensor impulse response must decay to a sufficiently small value before the first reflections from either the ground plane or the end of the cone.
Field sensor and field probe factors affecting calibration

A number of factors associated with the instrumentation and interconnecting cables (i.e., external to the field probe or field sensor) may affect the results of a measurement or calibration. This section is intended to inform the reader of the most common effects so that these may be taken into consideration when performing a measurement or calibration.

C.1 Cables

Coaxial and other RF cables used in a test setup are prone to signal losses, particularly at high frequencies. It is necessary to measure and account for these losses in any calibration or measurement where signals are being transmitted.

The influence of a conducting cable, such as from a sensing element to a transmitter or meter in an electromagnetic field probe, is twofold. The first effect is the perturbation of the field environment by the conducting cable, which shorts out the local electric field along the cable and creates a large field enhancement at its ends. The second effect is the currents that are driven onto the conductor in the process of the first effect, which drive large charges onto the sensing elements by the continuity equation (the field enhancement) and cause large false readings.

These currents, when they travel along the exterior of the cable, form a transmission line with conductors, near or far, of the “outside world.” This transmission line has a characteristic impedance, known as a “back impedance,” which is usually between 100—300 Ω. In addition to the two effects discussed in the preceding paragraph, this impedance can often perturb a measurement because it can be in parallel to the terminal impedance at one end of the cable.

The currents along the cable will be reduced if the back impedance can be increased. This can be done easily and inexpensively by placing ferrite beads on the outside of the cable. These beads act as radio frequency chokes to present a high impedance to the current flow. They are usually in the form of toroidal ferrite castings, either solid (uncut) or longitudinally cut so that they can be retrofitted to existing cables.

The ferrite materials add a complex impedance (real plus imaginary) to the back impedance. The imaginary part is the inductance of the ferrite that results from the real part of the permeability. The real part of the
impedance comes from the imaginary part of the permeability, which is associated with losses in the material. At high frequencies, above about 10 MHz, the impedance from the ferrite is primarily real (lossy), and reaches a constant value with frequency above about 100 MHz.

Two types of ferrite materials are routinely used for this purpose, one based on a manganese-zinc material and the other on a nickel-zinc material. The manganese-zinc material presents a larger impedance below 10 MHz. For a ratio of the outer diameter to the inner diameter of the toroid of two, the value of real impedance increases from about 15 Ω/cm of bead length at 1 MHz to about 60 Ω/cm of bead length at 5 MHz. Above 5 MHz, it decreases to a final value of about 30 Ω/cm of bead length above 100 MHz. This ferrite is reasonably conductive, on the order of $10^1$—$10^2$ Ω-cm volumetric resistivity, and often must be insulated from conductors.

The nickel-zinc material resistivity increases from about 30 Ω-cm of bead length at 10 MHz to about 70 Ω-cm of bead length above 100 MHz. The above values are approximate and vary with manufacturer and product. They are also for the uncut toroids. This material is essentially an insulator, with a very high volumetric resistivity of $10^5$—$10^9$ Ω·cm.

The use of ferrites can increase the back impedance into the kilohm region (at high frequencies) with just a few centimeters of beads on a cable. This will considerably reduce the field perturbation and sensor errors. Coaxial and other RF cables may interact with the field used in the calibration in the form of undesired signal pickup. Measures should be taken to ensure that undesired signals are minimized. Specifically, any instrumentation cables exposed to the field should be routed along the equipotential field lines in order to minimize coupling of the field to the cable. Care should also be taken with signal cables external to the field. Avoid routing near power cables or near other noisy cables or sources.

C.2 Other Parameters

C.2.1 Readout device sampling effects

Errors can occur when using digital sampling instruments, particularly when modulated signals are being measured. Aliasing of harmonics above the Nyquist frequency of the instrument can cause erroneous signals to appear to be present. The manufacturer’s instructions should be well understood and followed when using this type of instrument.

C.2.1 Spurious response to unintended field components

$E$-field probes should respond to an $E$-field without any spurious $H$-field pickup, and $H$-field probes should respond to an $H$-field without any spurious $E$-field pickup. For $H$-field probes, rejection of spurious $E$-field pickup can be evaluated using a field with a high $E$ to $H$ ratio, such as exists in a TEM cell [B96]. For $E$-field probes, rejection of spurious $H$-field pickup can be evaluated using a field with a high $H$ to $E$ ratio, such as exists near a loop antenna.

C.3 Special considerations for multi-source multi-frequency probe response and calibrations

See ... [B78], [B116], [B133].

C.4 Field perturbation, capacitive coupling (boundary) effects

See ... [B2], See ... [B23], See ... [B66], [B27], [B35], [B105], [B137]. See ... [B111].
Annex D

MOVED TO CLAUSE 8 WITH SLIGHT RE-WORDING

(informative)

**Types of measurements**

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

Many of the sensors that require calibration are broadband. This may mean anything from an octave in frequency to several decades of useful bandwidth. This implies, for reasons of hardware and personnel utilization optimization (cost), that the calibration process utilize equipment that can automatically cover a multitude of frequencies, rather than a single frequency at a time.

This broadband requirement precludes the use of standard half-wave dipoles as the primary standards. These can, however, be used as single-frequency calibration checks on the broadband reference standard sensors and on the field sensors.
Annex E

MOVED TO CLAUSE 8 WITH SLIGHT RE-WORDING

(informative)

Time-domain versus frequency-domain measurements

At low frequencies, below a few tens of MHz, the calibration procedures should be performed in the frequency domain. At these frequencies, calibration fixtures can be constructed with reasonably low SWR, and instrumentation is readily available to most facilities for the measurements [B42].

At higher frequencies, the calibration may be performed in the time domain, using transient measurement techniques. The reason for this is that test cells have significant reflections at these frequencies, which are difficult to remove from CW measurements. In the time domain, the reflections can be removed from the data by windowing the data, and only analyzing that portion that contains the sensor response, cutting out those portions that contain reflections. Obviously, the cell must be of sufficient dimensions that the clear time between the incident field and the first terminator reflection is greater than the probe response time.

The time (transient) domain field sensor/field probe design shall allow it to respond to pulses.
Annex F
(informative)

Deconvolution

The calibration accuracy of a given time domain field sensor (field probe) can be greatly improved by using the deconvolution technique. Deconvolution allows the removal of the effects of the measurement system (instrumentation plus simulator) from the field sensor (field probe) calibration data \[B17\], \[B118\], \[B119\], \[B130\], \[B131\], producing very accurate results.

In order to perform a deconvolution, two separate measurements must be performed: 1) a time domain waveform for a reference field sensor (field probe) with known characteristics is first obtained, and then 2) a second waveform is acquired for the field sensor (field probe) under test. The measurement process is depicted in Figure F.1. After the waveforms are captured and digitized, they are Fourier-transformed into the frequency domain, typically by means of a fast Fourier transform (FFT), a chirp z-transform, or another available transform algorithm. The deconvolution procedure is then performed in the frequency domain by taking the ratio of the transformed data for the field sensor (field probe) under test to that of the transformed reference field sensor (field probe) data. The transformed data obtained for each of the field sensors (field probes) is a product of the transfer function of the generator, connecting cable, simulator, and the sampling oscilloscope. Taking the ratio of the two data sets cancels out all the instrumentation and simulator effects. All that remains is the ratio of the responses of the field sensor (field probe) under test to that of the reference field sensor (field probe). Since the reference field sensor (field probe) characteristics are known, the transfer function of the field sensor (field probe) under test can be readily determined by factoring out the known reference field sensor (field probe) characteristics. Figure F.2 depicts the steps that are involved in the basic deconvolution procedure.

![Diagram](image)

Figure F.1—Instrumentation setup

The final desired frequency domain results of the deconvolution procedure is the actual probe transfer function with all of the spurious effects of the instrumentation and simulator removed. The deconvolved field sensor (field probe) transfer function can then be inverse transformed back into the time domain to yield the impulse response of the field sensor (field probe) under test, which is a highly useful result. Figure F.3 depicts one implementation of a deconvolution procedure to obtain the field sensor (field probe) transfer function, as well as a variety of time domain field sensor (field probe) responses.
Figure F.2—Block diagram of the deconvolution procedure

Data Processing

Figure F.3—Time domain deconvolution data processing
Annex G

(informative)

| Burst-peak field measurements |

Field probes and sensors are often used as radiation monitors where the electromagnetic radiation seen by the probe for a time less than what would be required for the display of the true field strength of exposure. A radar transmitter RF hazard (MPE) measurement is an example [B107], [B121], [B127].

Many field probes used for this type of measurement have a certain time constant to in the recorder readout device output and with a the maximum hold mode meter indication is approximately 0.25 s. The probe elements’ time constant comprises the major contribution to this total time constant. Reducing the electronic circuitry response time would not contribute a significant reduction in the overall time constant.

Without stopping the radar rotation, a calculation of what the power density would be from due to illumination of a rotating radar beam if it were stalled can still be made.

Knowledge of the time constant, illumination period, and the maximum-hold mode power density reading is required. Recorder output measurements are not necessary. The “Max Hold” mode meter reading corresponds to the peak of the recorder output signal. A few sweeps of the beam may be required to reach the full peak for short illumination periods.

The illumination period \( t \), in seconds, is equal to the beam width in degrees divided by the sweep rate in revolutions per minute (r/min) all multiplied by 0.167.

\[
t = \frac{\text{beamwidth}}{r/\text{min}}
\]  

(45)

if we define \( K \) as the ratio of the “Max Hold” meter indication to the actual maximum output (i.e., if constantly illuminated).

\[
K = \frac{E_{\text{hold}}}{E_{\text{cw}}} = 1 - e^{-t/T}
\]  

(46)

where

- \( t \) is period of illumination in seconds
- \( T \) is time constant of probe and circuitry
- \( K \) is maximum hold ratio
- \( E_{\text{hold}} \) is maximum indication
- \( E_{\text{cw}} \) is continuous wave indication.

A limitation in the use of this technique is that the period between illumination periods must be at least one time constant \( T \). This illumination would require sweep rates of approximately 200 r/min, a most unlikely situation.

To illustrate the calculation, the following parameters have been selected.

- Beam width of 1.3 degrees
- A sweep rate of 12 r/min

The illumination period is:

\[
t = 0.167 \times \frac{1.3}{12} = 0.018
\]  

(47)
For small values of $t$, the illumination time relative to the probe time constant, the value of $K$ is equal to the illumination time $t$ divided by the probe time constant $T$. The error in making this approximation is 2.5% for an illumination time of 0.01 s and 8% for an illumination time of 0.03 s.

The ratio of indicated to actual maximum power density is

$$\frac{t}{T} = \frac{0.018}{0.291} = 0.062$$

$$K = 1 - e^{-0.062} = 0.060$$

(48A) (49B)

The “Max Hold” indicated readings must be multiplied by $1/K$ or 16.6 to obtain the true maximum power density applicable for constant illumination.

The time averaged power density $P_{avg}$ can be calculated as the product of the burst peak power density and the radar sweep duty factor. The burst peak power density $P_{d burst}$ is defined as the maximum power density at constant illumination. This is the power density in a stalled beam. The sweep duty factor is the product of the illumination time $t$ and the sweep rate in sweeps per second (or the beamwidth in degrees divided by 360°).
Annex H

RE-ORDER/RE-NAME ANNEXES AS FOLLOWS:

CHANGE TO:
Annex A Grades of calibrations
Annex B Field generation setups and calculation methods
Annex C Estimating uncertainty
Annex C Miscellaneous factors affecting probe calibration and use
Annex D Deconvolution
Annex E Time-domain pulse fidelity
Annex F Burst-peak field measurements
Annex G Bibliography

PER IEEE STDS STYLE GUIDE TABLE AND FIGURE NUMBERING SCHEME FOR ANNEXES, AND RECENT EXPERIENCE WITH IEEE STD 1528 EDITS: ALL EQUATIONS IN ANNEXES NEED RE-NUMBERING TO FORMAT E.G., (B.12), WITH NUMBERING RE-STARTING AT X.1 IN EACH SEPARATE ANNEX (X = A, B, C, …). 1309 WG SHOULD DO THIS, NOT ASSUME THAT IEEE EDITOR WILL TAKE OF IT.

(informative)

Examples on determining Estimating uncertainty

H.1 Standard uncertainty

List each component that contributes to the overall measurement calibration uncertainty and its independent9 uncertainty, tolerance, or error. Identify each influence quantity as to its type, either evaluated statistically (type A) or by another method (type B).

The type A evaluation method may be based on any valid statistical method for treating data. Two examples are the method of least squares to estimate a curve and its standard deviation, and finding the standard deviation of the mean of a series of independent data.

Type A (statistical method)

—Variations in readings 0.09 dB (1%, if voltage dependent)

The type B method is based on all relevant information available, such as follows:

a) Previous measurement data
b) Manufacturer’s specifications
c) Data provided from calibration or other reports

9 The examples in this Annex assume that the influence quantities contributing to calibration uncertainty are independent of each other. Consult the GUM or ANSENCISL Z540-2 for instructions on handling correlated influence quantities. (These standards contain identical equations, figures and other technical information, but the GUM is written in Oxford English and Z540-2 is written in American English.)
d) Estimates based on experience

e) Other data

Type A (statistical method). The descriptive statistics of the readings, i.e., the mean value $\mu$ and standard deviation $\sigma$ of the readings are found by a statistical method. The standard uncertainty $u$ is the standard deviation (standard error) of the mean. It is found by:

$$u = \frac{\sigma}{\sqrt{n}}$$

where $n$ is the number of readings.  \hfill (H1A)

For example, if a power meter is connected to a power standard and $n = 8$ independent readings are taken, and the standard deviation of these readings is $\sigma = 0.2546$ dB, the standard uncertainty of the power meter is:

$$u = \frac{0.2546}{\sqrt{8}} = 0.090 \text{ dB}$$

NOTE: If the mean value $\mu$ read on the power meter is different than the level set on the power standard, the difference is a bias or systematic effect. The measured data using the power meter should be corrected by the amount of this bias.

Type B (other methods).—overall measurement uncertainties and independent uncertainties. The tolerances or calibrated uncertainties of all of the instruments used in the calibration are listed with their tolerance or uncertainty. The following tabulation (H.1) shows an example. The values presented are illustrative examples and don’t necessarily represent what a calibration lab may be able to achieve.

Table H.1. Tabulation of Influence Quantities.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Basis</th>
<th>Distribution</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power meter with sensor # 001</td>
<td>Repeated calibration, $n = 8$, Type A, $\sigma = 0.2546$ dB</td>
<td>Normal $k = 1/\sqrt{n}$</td>
<td>0.090 dB</td>
</tr>
<tr>
<td>TEM cell field uniformity</td>
<td>Calculated Dimensional Effects Type B, Tol. 0.12 dB</td>
<td>Rectangular $k = 1/\sqrt{3}$</td>
<td>0.069 dB</td>
</tr>
<tr>
<td>Placement of DUT</td>
<td>Possible Field Variation Type B, 0.09 dB</td>
<td>Rectangular $k = 1/\sqrt{3}$</td>
<td>0.052 dB</td>
</tr>
</tbody>
</table>

| Power meter with sensor # 001*  | 0.21 dB (5%, if power dependent) | 2.89 %       |
| TEM cell field uniformity       | 0.12 dB (3%, if power dependent) | 1.73 %       |
| Placement of DUT                | 0.09 dB (2%, if power dependent) | 1.15 %       |

* Each instrument that is used in the measurement shall be listed individually.

In this example the power meter uncertainty is from a normal distribution, and the DUT placement tolerance and the TEM cell dimensional tolerance are each approximated as a rectangular distribution. The standard deviation of the power meter was already found from repeated calibration measurements, thus the $k$-factor for its standard uncertainty is $1/\sqrt{n}$. The standard uncertainty of each of the other two is equal to its tolerance divided by $\sqrt{3}$, i.e., $k = 1/\sqrt{3}$. In the event that a tolerance or specification is given in percent, it shall be converted to decibels or linear terms. In this example, dB was used so the conversion should be to dB. If the linear term V/m had been used then all tolerances and uncertainties would need to be converted to volts or V/m, as appropriate. Note that in this example the power meter uncertainty, DUT placement uncertainty, and the TEM cell uncertainty are approximated as a rectangular distribution, thus the independent uncertainty is equal to the measurement uncertainty divided by $\sqrt{3}$.

NOTE—The conversion process between uncertainty in percent and in decibels is not symmetric. For example, just converting percent to logarithms, \lg(1+p%) = \lg(1-p%) = |lg(1+p%)|. Usually, the worst-case absolute value is used when converting percent to decibels. Percent should not be used with the normal distribution, because it is not additive (except in the special case where each percentage is from the same base). The normal distribution is correctly used only with additive.
As an example using the power meter uncertainty above, \( |1 - 10^{0.21/10}| = |1 - 10^{0.021}| \).

The relationship between decibels and ratio is
\[
P_{\text{dB}} = 10 \log_{10} (P_{\text{ratio}}) \quad (50A) \\
\text{and} \quad P_{\text{ratio}} = 10^{P_{\text{dB}}/10} \quad (51B)
\]
or for voltage dependent data,
\[
V_{\text{dB}} = 20 \log_{10} (V_{\text{ratio}}) \quad (52A) \\
\text{and} \quad V_{\text{ratio}} = 10^{V_{\text{dB}}/20} \quad (53B)
\]
For example: if \( P_{\text{dB}} = 0.21 \text{ dB} \), then \( P_{\text{ratio}} = 1.05 \), giving an uncertainty (not \( u \)) of 5%, and if \( V_{\text{dB}} = 0.21 \text{ dB} \), then \( V_{\text{ratio}} = 1.025 \), giving a measurement uncertainty of 2.5%.

H.2 Combined standard uncertainty

Combine all components by using the root sum of squares (RSS) method. All values in decibels must be converted to ratio form for this equation.

For example, using the above components and assuming they are uncorrelated, the combined standard uncertainty is:
\[
u_c = \sqrt{\sum (u_i)^2} \quad (54A)
\]
\[
u_c = \sqrt{((0.025)^2) + (0.069)^2 + (0.00115)^2} = 0.037 \quad (55B)
\]
This shows that \( \nu_c = 6.2\% \). In this example, the probe was calibrated in terms of power, or \( E^2 \), the \( \nu_c \) of 3.7% would convert to decibels as \( 10 \log (1.037) \). Thus, \( \nu_c = 0.16 \text{ dB} \). For voltage probe calibration the conversion would be \( 20 \log (\text{quantity}) \). If the errors are correlated, see ISO/TAG 4/WG or NCSL-PRI for further instructions.

The combined standard uncertainty is the standard uncertainty of a result when it is obtained from the values of several other independent quantities. It is equal to the positive square root of the sum of the weighted variances and covariances of the other quantities. This is a statement of the law of propagation of uncertainty, and uses the root sum of the squares (RSS) method. A general formula is:
\[
u_c = \left( \sum_{i=1}^{n} (c_i u_i)^2 \right)^{1/2} \quad (H4A)
\]
Where: \( c_i \) is the sensitivity coefficient of \( u_i \), and \( u_i \) is the standard uncertainty of an influence quantity. For the quantities usually found in instrumentation calibration, the sensitivity coefficient is unity.

NOTE: This equation is for use only with independent influence quantities. For influence quantities that are not independent, see the GUM or ANSI/NCSL Z540-2 for the method of treatment.

NOTE: Do NOT double-count uncertainty components, e.g., do not include a Type-B influence quantity that has already been included in a Type-A evaluation. (See the GUM or ANSI/NCSL Z540-2.)

NOTE: Do not include bias in the uncertainty if it is known and can be used as a correction.

For example, using the values in the table above:
\[
u_c = \sqrt{0.090^2 + 0.069^2 + 0.052^2} = 0.125 \text{ dB} \quad (H4B)
\]
This shows that \( \nu_c = 0.125 \text{ dB} \). If it is necessary to state the standard uncertainty in percent, then convert \( \nu_c \) to percent by:
\[ u_c = 100 \times \left( 10^{\frac{0.125}{10}} - 1 \right) = 2.9\% , \text{ which is the worst-case dB – \% conversion.} \quad (\text{H5}) \]

NOTE: Since the power meter was calibrated in terms of power, from a power standard, it is necessary to use the divisor of 10 in the denominator of the exponent for the conversion from dB to \%.

H.3 Expanded uncertainty

Multiply the combined standard uncertainty by a coverage factor, called \( k \). The value of \( k \) shall be \( 2 \), which gives a confidence level of approximately 95\%. The expanded uncertainty is:

\[ U = k u_c \quad (\text{H6A}) \]

Using the same values as before, where \( u_c = 3.7\%0.125 \text{ dB} \) (or, \( u_c = 2.9\%0.16 \text{ dB} \)) and \( k = 2 \), gives the expanded uncertainty:

\[ U = 2 \times (3.7\%) = 7.4\%(0.31 \text{ dB}) \quad (\text{H6B}) \]

Again, as the example probe was calibrated in terms of power or \( E \), the conversion to decibels would be done as 10log (quantity).

NOTE: Again, since the power meter was calibrated in terms of power, it is necessary to use the divisor of 10 in the denominator of the exponent for the conversion from dB to \%.

H.4 Reporting uncertainty

The simplest proper way to report calibration uncertainty in the calibration certificate or report is to report the expanded uncertainty and the \( k \)-factor. For example:

\[ U = 0.25 \text{ dB}, \ k = 2 \quad (\text{H7}) \]

This is all that the standards require; however, it is often helpful to the user of the calibration certificate to report also the level of confidence (e.g., confidence is 95 \%), especially if the level of confidence is different than the conventionally used 95 \%.

In a calibration report it is helpful to the user if the uncertainty results are displayed. The simplest approach is to display the uncertainty results in a table (for example, Table H.2) with some additional explanation, if necessary (see below the table).

\[ Table \ H.2. \text{ Calibration Uncertainty of the [Mfg.] Model [####] E-Field Probe.} \]

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Basis</th>
<th>Distribution</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power meter with sensor # 001</td>
<td>Repeated calibration, ( n = 8 ), Type A, ( \sigma = 0.2546 \text{ dB} )</td>
<td>Normal, ( k = 1/\sqrt{n} )</td>
<td>0.090 dB</td>
</tr>
<tr>
<td>TEM cell field uniformity</td>
<td>Calculated Dimensional Effects, Type B, Tol. 0.12 dB</td>
<td>Rectangular, ( k = 1/\sqrt{3} )</td>
<td>0.069 dB</td>
</tr>
<tr>
<td>Placement of DUT</td>
<td>Possible Field Variation, Type B, 0.09 dB</td>
<td>Rectangular, ( k = 1/\sqrt{3} )</td>
<td>0.052 dB</td>
</tr>
<tr>
<td>Combined Standard Uncertainty</td>
<td>Law of Propagation of Uncertainty (RSS)</td>
<td>Normal</td>
<td>0.125 dB</td>
</tr>
<tr>
<td>Expanded Uncertainty</td>
<td>( k_p = 2.11 )</td>
<td>Normal</td>
<td>0.26 dB</td>
</tr>
</tbody>
</table>

\[ Table \ H.5—Table of uncertainties \]

<table>
<thead>
<tr>
<th>Description of uncertainty</th>
<th>Type B measurement Uncertainty</th>
<th>Standard uncertainty ( u_c(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variations in readings</td>
<td>1 (Type A)</td>
<td></td>
</tr>
<tr>
<td>Power meter with sensor # 001</td>
<td>0.21 dB (rectangular)</td>
<td>2.89 (Type B)</td>
</tr>
<tr>
<td>TEM cell field uniformity</td>
<td>0.12 dB (rectangular)</td>
<td>1.73 (Type B)</td>
</tr>
<tr>
<td>Placement of device under test (DUT)</td>
<td>0.09 dB (rectangular)</td>
<td>1.13 (Type B)</td>
</tr>
</tbody>
</table>
Combined standard uncertainty: \( u_c \) = 3.7\%  
Expanded uncertainty: \( U \) = ± 0.31 dB

The further explanation in this case is to tell the user why the uncertainty is expanded by \( k_p = 2.11 \) instead of \( k = 2 \).

Since the power meter was calibrated by repeated measurements, the degrees of freedom of that calibration may result in an under-assessment of the expanded uncertainty. The number of degrees of freedom of the generator calibration is \( v = n - 1 = 7 \). (The number of degrees of freedom of the Type B quantities is taken to be infinite, i.e., \( v = \infty \). See the GUM or Z540-2)

If the following inequality is satisfied, then \( k = 2 \) will provide a probability of 95\% that the expanded uncertainty contains the true value of the measurand,

\[
\frac{u_c}{u_1} \geq 3 \quad \text{(H8)}
\]

However, using the values in Table H.2 the ratio of \( u_c \) to \( u_1 \) is only about 1.4, indicating that \( k = 2 \) will not assure a level of confidence of 95\%. To find the correct \( k \)-factor, one shall find the effective degrees of freedom \( \nu_{eff} \), and compare that with the values from a statistical table. (See Table H.3 below, which was derived from Table b.1 of NIST TN 1297). This is done as follows when only one quantity is found from repeated measurements.

\[
V_{eff} = V \left( \frac{u_c}{u_1} \right)^4 \quad \text{(H9A)}
\]

The effective degrees of freedom are thus:

\[
V_{eff} = V \left( \frac{u_c}{u_1} \right)^4 = 7 \times \left( \frac{0.125}{0.090} \right)^4 = 7 \times 1.389^4 = 7 \times 3.721 = 26.05 \approx 26 \quad \text{(H9B)}
\]

Where: \( V \) is the number of degrees of freedom of \( u_1 \).

From Table H.3, it may be seen that \( k_p \approx 2.11 \), which makes the expanded uncertainty \( U \approx 0.26 \text{ dB} \) for 95\% confidence. This value of \( U \) is insignificantly larger than the value of 0.25 dB that would have been obtained with \( k = 2 \). However, if the degrees of freedom of \( u_1 \) had been only 2, then the effective degrees of freedom would have been approximately 7.5 and \( k_p \) would have been approximately 2.4. This would have resulted in the expanded uncertainty becoming 0.3 dB for a 95\% level of confidence.

### Table H.3. Values of \( k_p \) vs. \( \nu_{eff} \) for 95% Confidence (NIST TN 1297).

<table>
<thead>
<tr>
<th>( \nu_{eff} )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>( \infty )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_p )</td>
<td>13.97</td>
<td>4.53</td>
<td>3.31</td>
<td>2.87</td>
<td>2.65</td>
<td>2.52</td>
<td>2.43</td>
<td>2.37</td>
<td>2.28</td>
<td>2.13</td>
<td>2.05</td>
<td>2.00</td>
</tr>
</tbody>
</table>

The complete equation\(^{10}\) for the effective degrees of freedom is as follows:

\[
V_{eff} = \frac{u_c^4(y)}{\sum_{i=1}^{N} \frac{u_1^4(y)}{V_i}} \quad \text{, } N \text{ is the number of influence quantities.} \quad \text{(H10)}
\]

Many worked-out examples of measurement uncertainty estimates may be found in LAB34 [B150], published by the United Kingdom Accreditation Service (UKAS) in England. It has been produced to help test and calibration laboratories comply with ISO Guide and ISO/IEC 17025. Other discussions and examples of probe calibration uncertainty analyses and issues are given for example in [B4], [B6], [B38], [B42], [B46], [B106], [B112], [B125], [B135].

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\(^{10}\)This is known as the Welch-Satterthwaite equation (See [B151], [B75], [B79], pp. 215-216).
An additional uncertainty budget example is as follows.

**Table H.6** Example of uncertainties commonly achievable in laboratories for generating a standard field for a calibration using a TEM cell

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Relative standard uncertainty</th>
<th>Distribution</th>
<th>Sensitivity Coefficient</th>
<th>Estimated contribution to standard uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ (correction factor representing the deviation of the TEM cell from ideal behaviour = TEM cell field uniformity)</td>
<td>0.029</td>
<td>rectangular</td>
<td>1</td>
<td>0.029</td>
</tr>
<tr>
<td>d (distance septum/walls of the cell)</td>
<td>0.004</td>
<td>rectangular</td>
<td>1</td>
<td>0.004</td>
</tr>
<tr>
<td>P_{cell} (net power available IN the cell)</td>
<td>0.056</td>
<td>normal</td>
<td>0.5</td>
<td>0.028</td>
</tr>
<tr>
<td>Z_0 (real part of the TEM cell characteristic impedance measured on an ideal plane normal to the septum at the middle of the cell)</td>
<td>0.029</td>
<td>rectangular</td>
<td>0.5</td>
<td>0.0145</td>
</tr>
<tr>
<td>E_{meas} (mean value of the probe readings = repeatability of readings)</td>
<td>$\frac{u(E_{\text{meas}})}{E_{\text{meas}}}$</td>
<td>normal</td>
<td>1</td>
<td>$\frac{u(E_{\text{meas}})}{E_{\text{meas}}}$</td>
</tr>
</tbody>
</table>

Assuming the uncertainty associated to the repeatability of measurements is negligible, the combined standard uncertainty is 0.043

Assuming the uncertainty associated to the repeatability of measurements is negligible, the extended uncertainty (95% confidence) in generating the standard field is 8.6% (best capability)

(1) Best probes better than 1%; lower performances probes around 3% or higher.
An additional uncertainty budget example is as follows.

**Uncertainty Budget for Isotropic Probes using a Standard Field Method from 1 to 40 Ghz using Standard Gain Horns/Open Ended Waveguides**

<table>
<thead>
<tr>
<th>Sources of Uncertainty</th>
<th>Value in dB</th>
<th>Distribution</th>
<th>Divisor</th>
<th>Sensitivity Coefficient (Ci)</th>
<th>Result (Ci x Ui)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Repeatability (Std)</td>
<td>+/- 0.2</td>
<td>Normal</td>
<td>1</td>
<td>1</td>
<td>0.200</td>
</tr>
<tr>
<td>2. Mismatch at Coupler to Std Gain Horn Connection</td>
<td>+/- 0.155</td>
<td>U-Shaped</td>
<td>1.414</td>
<td>1</td>
<td>0.110</td>
</tr>
<tr>
<td>2A. Mismatch Error at FWD Pwr Sensor</td>
<td>+/- 0.155</td>
<td>U-Shaped</td>
<td>1.414</td>
<td>1</td>
<td>0.110</td>
</tr>
<tr>
<td>2B. Mismatch Error at RFL Pwr Sensor</td>
<td>+/- 0.155</td>
<td>U-Shaped</td>
<td>1.414</td>
<td>1</td>
<td>0.110</td>
</tr>
<tr>
<td>2C. Mismatch Error at Input of Dir. Coupler</td>
<td>+/- 0.155</td>
<td>U-Shaped</td>
<td>1.414</td>
<td>1</td>
<td>0.110</td>
</tr>
<tr>
<td>3: Spacing Error</td>
<td>+/- 0.02</td>
<td>Rectangular</td>
<td>1.732</td>
<td>1</td>
<td>0.012</td>
</tr>
<tr>
<td>4. Alignment Error</td>
<td>+/- 0.2</td>
<td>Rectangular</td>
<td>1.732</td>
<td>1</td>
<td>0.115</td>
</tr>
<tr>
<td>5. Power Sensor Error</td>
<td>+/- 0.14</td>
<td>Rectangular</td>
<td>1.732</td>
<td>1</td>
<td>0.081</td>
</tr>
<tr>
<td>5A. Power Meter Error</td>
<td>+/- 0.05</td>
<td>Rectangular</td>
<td>1.732</td>
<td>1</td>
<td>0.029</td>
</tr>
<tr>
<td>6. Dir. Coupler Error</td>
<td>+/- 0.14</td>
<td>Rectangular</td>
<td>1.732</td>
<td>1</td>
<td>0.081</td>
</tr>
<tr>
<td>7. Residual Ground Reflection Error</td>
<td>+/- 0.1</td>
<td>Rectangular</td>
<td>1.732</td>
<td>1</td>
<td>0.058</td>
</tr>
<tr>
<td>8. Thermal Error for coax cables.</td>
<td>+/- 0.15</td>
<td>Rectangular</td>
<td>1.732</td>
<td>1</td>
<td>0.087</td>
</tr>
<tr>
<td>9. Coax Cable Flex Error.</td>
<td>+/- 0.15</td>
<td>Rectangular</td>
<td>1.732</td>
<td>1</td>
<td>0.087</td>
</tr>
<tr>
<td>10. Multiple Reflection Error.</td>
<td>+/- 0.1</td>
<td>Rectangular</td>
<td>1.732</td>
<td>1</td>
<td>0.058</td>
</tr>
<tr>
<td>11: Instrument Error</td>
<td>+/- 0.15</td>
<td>Rectangular</td>
<td>1.732</td>
<td>1</td>
<td>0.087</td>
</tr>
<tr>
<td>12: Standard Gain Horn Error</td>
<td>+/- 0.5</td>
<td>Rectangular</td>
<td>1.732</td>
<td>1</td>
<td>0.289</td>
</tr>
<tr>
<td>Combined standard uncertainty +/- Uc(y)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.477</td>
</tr>
<tr>
<td>Expanded uncertainty U = +/- 2 Uc(y)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.955</td>
</tr>
</tbody>
</table>
Normal distribution was assigned to uncertainties derived from multiple contributions. The standard uncertainty of a contribution with assumed normal distribution is found by dividing the expanded uncertainty by the coverage factor k, appropriate to the stated level of confidence. Strictly speaking for a level of confidence of 95%, \( K = 1.96 \), this document uses a value of \( k=2 \).

Rectangular distribution means that there is equal probability of the true value lying anywhere between the prescribed limits. A rectangular distribution was assigned where a manufacturer's specification was not available.

1. Repeatability: This value was determined from a set of a minimum of 20 measurements with the maximum deviation recorded here.

2. Mismatch Errors: A VSWR average is 1.5:1 which gives a Voltage reflection coefficient of 0.2. The connecting attenuators and power sensors have a VSWR of 1.2:1 which gives a Voltage reflection coefficient of 0.09. So the uncertainty limit will be \( 20 \times \log (1+/- r1rg) = +/- 0.155 \) dB.

3. Spacing Error: This value was obtained based on a spacing error of +/- 2 cm.

4. Alignment Error: This error is based on changing the alignment by +/- 5 Degrees.

5. Power Sensor Error: This error is based on the worst case error for the power sensor. 5A is based on the power meter error. Power meter used is a HP438A

6. Directional Coupler Error: This error is based on the error associated with the directional coupler on its insertion loss.

7. Residual Ground Reflection Error: This error is estimated based on the residual ground reflection when using a dual 45 degree angle absorbing fence for this calibration.

8. Thermal Error for Coax Cables: This error has been estimated to be 0.15 dB.

9. Coax Cable Flex Error: This error has been estimated to be 0.15 dB.

10. Multiple Reflection Error: This error has been estimated to be 0.3 dB from discussions with NIST personnel at Boulder. This is reflections from the probe head, etc.

11. Instrument Error: This error is based on the linearity of the particular probe being calibrated.

12. Std. Gain Horn Error: This error is based on the mfr. Error for the std gain horns. Minimum is consider 0.5 dB but can be as high as 1.0 dB.
Annex I

(informative)

Time-domain pulse fidelity

Pulse fidelity is defined as how well the output waveform from a sensor matches the shape of the incident field. Figure I.1 shows the parameters of interest that might be included into the pulse fidelity. These parameters taken as a group define the pulse fidelity.

![Figure I.1—Waveform parameter for definition of pulse fidelity](image)

The difference in sensitivity of the sensor from its designed value is the amplitude error, the deviation of the amplitude of the output signal from what it should be. This deviation can be expressed as a percent or as a decibel value.

The rise time of the sensor (first transition duration) is usually expressed as the time between the 10% (proximal) point of the rise and the 90% (distal) point. These points are often taken as the percentage points to the maximum point of the waveform, but with the concept of pulse fidelity they should be taken as the percentages of the level part of the output (pulse amplitude) as shown.

The overshoot is the difference of the peak value from the pulse amplitude. Some overshoot is necessary in order to realize fast rise times, but it should not be excessive. The overshoot can be expressed as a percentage of the pulse amplitude.

Ringing is the damped oscillation that occurs when a sensor response is underdamped. Overshoot and ringing occur simultaneously, being properties of the inherent and stray reactances of the sensor output. Generally, this type of response is due to the inductance and capacitance between the sensing element and the [resistive] impedance of the output cable. A large resonance will thus give both a large overshoot and long ringing (high-Q); small resonances give small overshoot and ringing that is quickly damped (low-Q).

The response that seems to give the best pulse fidelity is that of a maximally flat circuit that has less than 5% overshoot and minimal ringing, as seen in Figure I.2. This has a significantly faster rise time than a critically damped response, which in turn is significantly faster than the exponential response from a single pole.
Figure I.2—Waveform parameters for maximally flat sensor response
Annex J

Bibliography

These publications are for information only and are not essential for application of this standard.

Per IEEE Style Guide: de-capitalize some titles within quote marks => at least for journals per 19.2 and per IEEE Trans. Style; maybe also for SSN, NIST TN, etc per 19.4.2

Replaced semi-colons by commas in author lists; em dash by hyphen


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11 *Sensor and Simulation Notes* are a publication series sponsored by the US Air Force Research Laboratory. Copies can be requested from: Air Force Research Laboratory, Office of Public Affairs, 3550 Aberdeen Avenue S.E., Kirtland AFB, NM 87117-5776, (http://www.deafb.af.mil/). Many documents from the *Notes* series are available at the Internet site: (http://iget104.et.uni-magdeburg.de/cgi-bin/note/browse.html) *SSN* is the abbreviation for “SENSOR AND SIMULATION NOTE,” a series of publications by the Phillips Laboratory (formerly the Air Force Weapons Laboratory [AFWL]). Listings of these can be found in the *IEEE Antennas and Propagation Magazine*. Copies can be requested from the author, the Defense Documentation Center, Cameron Station, VA 22314, or from the editor, Dr. Carl E. Baum, Phillips Laboratory (WSR), Kirtland Air Force Base, NM 87117.
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13 ETSI publications are available from the European Telecommunications Standards Institute, 650 Route des Luices, F-06921 Sophia Antipolis Cedex, France (http://www.etsi.org/).


Waveguides.  


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14 IEC publications are available from the International Electrotechnical Commission, IEC Central Office, 3, rue de la Varembe, P.O. Box 131, CH-1211 Genève 20, Switzerland (http://www.iec.ch).

15 ISO publications are available from the ISO Central Secretariat, Case Postale 56, 1 rue de la Varembe, CH-1211 Genève 20, Switzerland (http://www.iso.ch).


17 VDI publications are available from VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik (GMA), Postfach 10 11 39, 40002 Düsseldorf, Germany (http://dev.vdi-online.de/vdi/vrp/richtlinien/index.php).
