TECHNICAL REPORT

ISO/TR 10305-2

First edition
2003-02-15

Road vehicles — Calibration of electromagnetic field strength measuring devices —

Part 2: IEEE standard for calibration of electromagnetic field sensors and probes, excluding antennas, from 9 kHz to 40 GHz

Vehicules routiers — Étalonnage des appareils de mesure de l'intensité d'un champ électromagnétique —

Partie 2: Méthode normalisée de l'IEEE pour l'étalonnage des capteurs et des sondes de champ électromagnétique, à l'exclusion des antennes, entre 9 kHz et 40 GHz

Reference number
ISO/TR 10305-2:2003(E)

Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

In exceptional circumstances, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example), it may decide by a simple majority vote of its participating members to publish a Technical Report. A Technical Report is entirely informative in nature and does not have to be reviewed until the data it provides are considered to be no longer valid or useful.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 10305-2 was prepared by the US Institute of Electrical and Electronics Engineers (IEEE) (as IEEE 1309-1996) and was adopted without modification by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 3, *Electrical and electronic equipment*.

This first edition of ISO/TR 10305-2, together with that of ISO/TR 10305-1, cancels and replaces the first edition of ISO/TR 10305, which has been technically revised.

ISO/TR 10305 consists of the following parts, under the general title *Road vehicles — Calibration of electromagnetic field strength measuring devices*:

— *Part 1: Devices for measurement of electromagnetic fields at frequencies > 0 Hz*

— *Part 2: IEEE standard for calibration of electromagnetic field sensors and probes, excluding antennas, from 9 kHz to 40 GHz*

Introduction

The necessity for EMC (electromagnetic compatibility) testing of road vehicles and their components has led to the publication of a number of standardized test procedures. The need, too, for a standardized method for the calibration of field strength measuring devices was seen by the responsible ISO subcommittee. As no such International Standard was at the time available from either ISO or IEC, ISO/TR 10305 was published in 1992, based on the amended 1975 edition of the US National Bureau of Standards (now the National Institute of Standards and Technology, NIST) report, NBSIR 75-804.

That document having been considered incomplete, two new calibration methods were independently developed by DIN, the German Institute for Standardization, and by IEEE, the US Institute of Electrical and Electronics Engineers. It was decided to publish the methods as the two parts of a Technical Report replacing ISO/TR 10305:1992. Part 1 is an English translation of part 26 of DIN VDE 0847 and part 2 is the adoption, without modification, of IEEE std 1309-1996. Each of the two parts should be considered as independent of the other, no effort having been made to combine them.

The user of either method is kindly requested to report on the experience to ISO/TC 22/SC 3.

In the event of IEC publishing a general calibration procedure as an International Standard, ISO/TR 10305 could be withdrawn, as there is no anticipated need for special calibration methods for use in the automotive industry.

Road vehicles — Calibration of electromagnetic field strength measuring devices —

Part 2: IEEE standard for calibration of electromagnetic field sensors and probes, excluding antennas, from 9 kHz to 40 GHz

1 Scope

This part of ISO/TR 10305 specifies techniques for calibrating electromagnetic field sensors and probes, excluding antennas, used in automotive testing for the measurement of magnetic fields at frequencies from 9 kHz to 40 GHz. In the automotive field, these field strength measuring devices are used for measurements specified in the various parts of ISO 11451 and ISO 11452.

The scope and field of application are further detailed in clause 1 (see page 9) of the enclosed IEEE standard.

2 Requirements

For the purposes of international standardization, the following provisions shall apply to the specific clauses and paragraphs of IEEE std 1309-1996.

Pages i to iv (reproduced here as pages 3 to 6)

This is information relevant to the IEEE publication only.

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Add the following information to Annex J.

[1] ISO 11451 (all parts), *Road vehicles — Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy*

[2] ISO 11452 (all parts), *Road vehicles — Component test methods for electrical disturbances from narrowband radiated electromagnetic energy*

[3] DIN VDE 0847, *Methods of measurement for the electromagnetic compatibility — Part 26: Calibration of field measuring receivers for EMC and personal safety applications for frequencies > 0 Hz*

[4] NBSIR 75-804, *Generation of Standard EM fields for Calibration of Power Density Meters 20 kHz to 1 000 MHz*

3 Revision of publication IEEE 1309-1996

It has been agreed with IEEE that ISO/TC 22, *Road vehicles*, Subcommittee SC 3, *Electrical and electronic equipment*, will be consulted in the event of any revision or amendment of IEEE std 1309-1996. To this end, ANSI, the American National Standards Institute, will act as liaison between IEEE and ISO.

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

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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.

The following is a list of committee members and significant contributors.

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Contents

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

1. Overview

1.1 Scope

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

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

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

Most electromagnetic field measurements are made in the frequency domain, either at a single frequency or at a number of frequencies. The ever-increasing susceptibility of electronic circuits has awakened interest in transient electromagnetic phenomena such as electrostatic discharge (ESD), electromagnetic pulse (EMP), and system-generated transients, such as automotive ignition noise. The measurement of these transient fields requires electromagnetic field probes and sensors that can faithfully replicate the transient waveshapes, 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]Information on references can be found in clause 2.

1.2 Purpose

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

1.3 Background

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

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

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

1.4 Grades of calibration

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

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

1.5 Generic Probe Types

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

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

Table 1—Generic EM field probes and sensors

Free field	Ground plane field
E-Field (dipole)	*E*-Field (monopole)
H-Field (loop)	*H*-Field (half-loop)
D-dot	*D*-dot
B-dot	*B*-dot

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

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

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CAUTION

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

2. References

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

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

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

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

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

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

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

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

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

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

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

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

National Conference of Standards Laboratories (NCSL) RP-12, Recommended Practice for Determining and Reporting Measurement Uncertainties, 1 Feb. 1994.[6]

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

3. Definitions

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4. Measurement methods

4.1 Methods

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

Table 2—Three calibration methods

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

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

4.2 Field sensor or field probe orientation during frequency domain calibration

4.2.1 Directional and positional effects

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

4.2.2 Calibration data collection

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

4.2.2.1 Maximum interception alignment

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

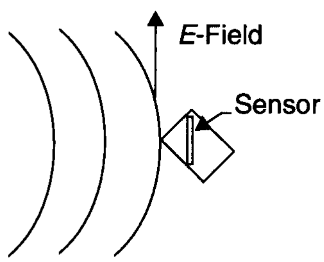


Figure 1—Maximum interception alignment

4.2.2.2 Physical major axis

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

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

4.2.2.3 Physical minor axis

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

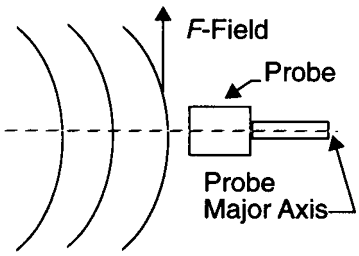


Figure 2—Physical major axis alignment

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

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

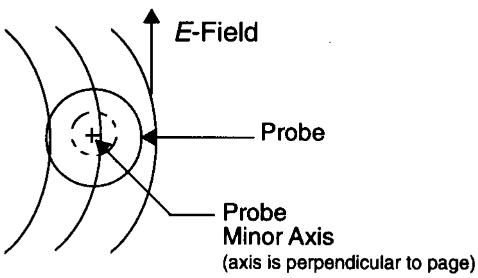


Figure 3—Physical minor axis alignment

4.3 Field probe or field sensor orientation during time domain calibration

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

a) Usually information is sought about one or more vector components of the following four field quantities: the electric field intensity *E*, the electric flux density *D*, the magnetic flux density *B*, and the magnetic intensity field *H* [B29]. Different sensors have been developed and optimized to measure the various field quantities [B9]. In most sensor applications, information about a particular electromagnetic field component (its time derivative or some other linear operation(s) with respect to time) is of interest. Only in rare instances is information needed about all of the field components for a given measurement.

b) For a field sensor calibration to be of maximum value, the calibration of a sensor should be performed in a manner that most closely simulates the way that it will be deployed in the actual measurement. All of these factors could significantly affect the measurement results obtained. Thus one should carefully address the role of the sensor orientation in space, means of mounting the sensor, cable connections (if any) to the sensor, as well as the orientation of the sensor when performing the calibration.

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

5. Standard field generation methods

5.1 Frequency domain field generation

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

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

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

NOTES

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

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

3—The Gigahertz 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.

5.2 Time domain field generation

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

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

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

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

6. Determining uncertainty

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

6.1 Standard uncertainty

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

6.2 Combined standard uncertainty

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

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

6.3 Expanded uncertainty

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

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

6.4 Reporting uncertainty

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

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

a) A list of all components of standard uncertainty, together with their degrees of freedom where appropriate, and the resulting value of u_c. The components should be identified according to the method used to estimate their numerical values as follows:

   1) those that are evaluated by statistical methods
   2) those that are evaluated by other methods

b) A reference to or a detailed description of how each component of standard uncertainty is evaluated.

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

7. Characteristics to be measured

7.1 Frequency domain calibration

7.1.1 Dynamic range (amplitude)

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

7.1.2 Frequency response

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

7.1.3 Isotropy

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

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

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

or

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

if S is the measured amplitude in field strength units.

7.1.4 Response time (optional)

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

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

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

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

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

7.1.5 Time constant (optional)

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

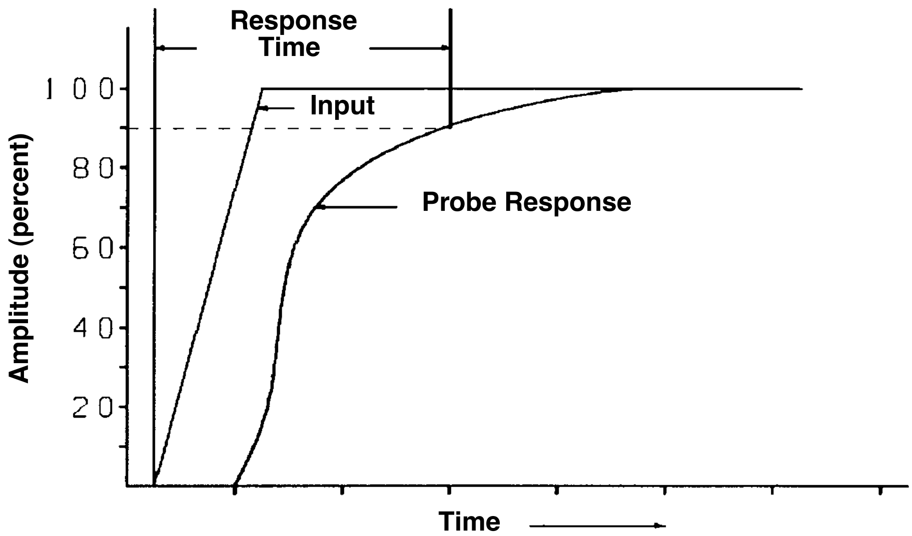


Figure 4—Typical response time curve

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

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

where

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

7.1.6 Modulation (Optional)

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

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

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

7.2 Time domain calibration

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

7.2.1 Amplitude

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

7.2.2 Dynamic range

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

7.2.3 Rise time

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

7.2.4 Fall time (droop)

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

7.2.5 Overshoot and ringing

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

8. Procedures (measurement techniques)

8.1 Transfer standard sensors and probes

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

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

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

8.2 Transfer and working standard sensors and probes

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

8.3 Frequency domain calibration procedure

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

8.3.1 Lead/cable effect

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

8.3.2 Frequency domain measurement procedures

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

The following constraints are recommended for accurate and repeatable measurements:

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

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

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

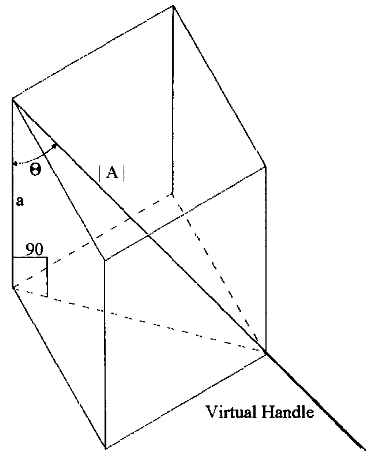
8.3.2.1 Frequency range and/or dynamic range measurements procedure

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

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

8.3.2.2 Isotropic measurements procedure

This measurement is designed for field probe characterization and does not provide coherent information for field sensors (single element directional devices). For probes based on the three element orthogonal design, the rotational axis should be about the axis handle, or a virtual handle, as shown in figure 5. If the probe is not based on the three element orthogonal design, then the rotational axis should be selected and documented to reflect isotropicity as required during normal use of the probe.



NOTE—The ortho-angle is defined as Θ = arcsec[|A|/a] = arccos[a/|A|].

Figure 5—Ortho-angle (Θ)and virtual handle

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 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 at the diagonal of a cube. If the field probe is not based on the three element orthogonal design, then the orientation shall be selected and documented.

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 axis 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 the speed of rotation shall 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 rotation versus response 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 [B55], to determine the anisotropy of the field probe.

8.3.3 Response time

Refer to figure 4 for a description of response time. The procedure is as follows:

a) Set up equipment as shown in figure 6.

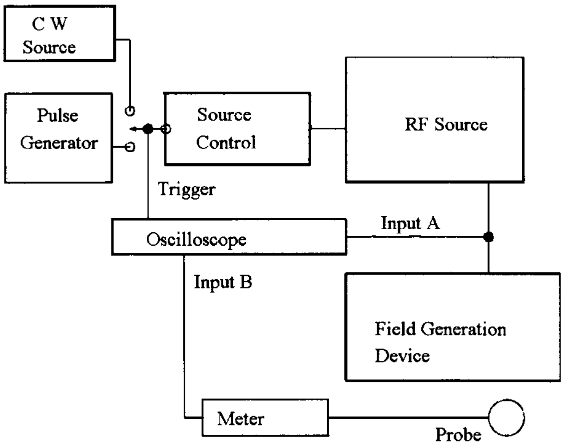


Figure 6—Typical probe response time and time constant measurement setup

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.

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 2 PPS* and a pulse width 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 settings of 0.02 s ** to 0.1 s **.
g) Calculate $T = -t / \ln(1-K)$ 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.

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 in which the measured response of the sensor is compared to that of a 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. The direct substitution technique allows for the effects of the entire measurement system to be removed from the sensor measurement. This leaves only the characteristics of the sensor, the unit impulse response function, or the unit step response function. This process is performed by deconvolution techniques.

Instrumentation requirements are as follows:

a) 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 (50 Ω) into which the sensors can be mounted (ground plane versions) or emplaced (free field versions). The simulator must have a sufficient clear 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 [B6]. A cone and ground plane simulator can also be used [B8].

c) A fast transient recorder. 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, if used, 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.

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

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 sensor being calibrated. If this is not possible, then the instrumentation system must be at least as fast as the sensor, and computational deconvolution techniques used to determine the sensor rise time (see annexes F and I).

8.4.4 Fall time (droop)

Fall time is defined as the last transition duration. It shall 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.

8.4.5 Overshoot and ringing

Overshoot is the level to which the response of the sensor overshoots the final level measured in response to a step input. Ringing is the damped oscillation that occurs when a sensor response is underdamped. Overshoot and ringing occur simultaneously, and shall be measured along with the rise time. Annex I describes the waveforms in more detail.

9. Documentation

9.1 Proper documentation

Proper documentation of calibration results is essential for a complete calibration process. A calibration shall be performed within a control structure such as ANSI/NCSL Z540-1-1994. This structure contains the elements necessary for the procedures, equipment, and status of each process part 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 manufacturer provides a recommended initial calibration interval.

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 customer

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

Annex A

(normative)

Grades of calibration

A.1 Grades of calibration

As 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 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, 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 A.1—Calibration types

Type	Description
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.
FD	Calibration is done using a field that is measured in the frequency domain. This field may be modulated or unmodulated.

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 A.2—Frequency calibrations grades

Type	Description	Usage Notes
F1	One single frequency	—
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 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.

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. The three grades of calibration with respect to amplitude are defined in table A.3.

Table A.3—Amplitude calibration grades

Type	Description
A1	One level for each selected frequency (see NOTE below) 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.
A2	Three levels for each selected frequency point or time domain pulse type as a minimum. The levels chosen 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
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 frequency at which calibration is performed, there are five grades of calibration with respect to isotropy (table A.4). Refer to figures 1, 2, and 3 for axis.

Table A.4—Isotropy measurement grades

Type	Description
I0	Isotropy not measured (for single axis probes and sensors only)
I1	Isotropy at maximum interception alignment
I2	Isotropy at physical major alignment
I3	Isotropy at physical minor alignment
IX	Isotropy at axis specified by user

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. It should be noted that this item is specifically intended for verification of a probe or sensor's specified response time (i.e., is the indication on the probe valid within *xx* seconds after exposure to a given field?).

Table A.5—Response time calibration grades

Type	Description
R0	Response time not measured
R1	Response time 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. It should be noted that this item is not specifically intended for verification of a probe or sensor's specified response time (i.e., is the indication on the probe 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).

Table A.6—Time constant measurement grades

Type	Description
T0	Time constant not measured
T1	Time constant 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.

Table A.7—Modulation measurement grades

Type	Description
M0	No modulation, CW field used
M1	Modulated field. In addition to the CW field calibration (modulation to be specified)
MX	Not applicable, time domain (TD) calibration

A.2 Grades of calibration notation summary

The notation for the grades of calibration are summarized below.

GRADE CHOICES:
TD or FD
A1, A2, or A3*
F1, F2, F3, F4, F5, F6, FX, or FZ*
R0, R1
T0, T1
M0, M1,* or MX
I0, I1, I2, I3, or IX*
* Additional information required in the description.

A.3 Cautions and examples

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

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, F2 frequency grade, A2 dynamic range grade at one frequency point (i.e., 300 MHz), MO 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), a total of one frequency-amplitude point will have to be measured, with an isotropicity (anisotropicity) measurement at this one point.

Annex B

(normative)

Methods of field generation and field calculations

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 C95.1-1991, 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

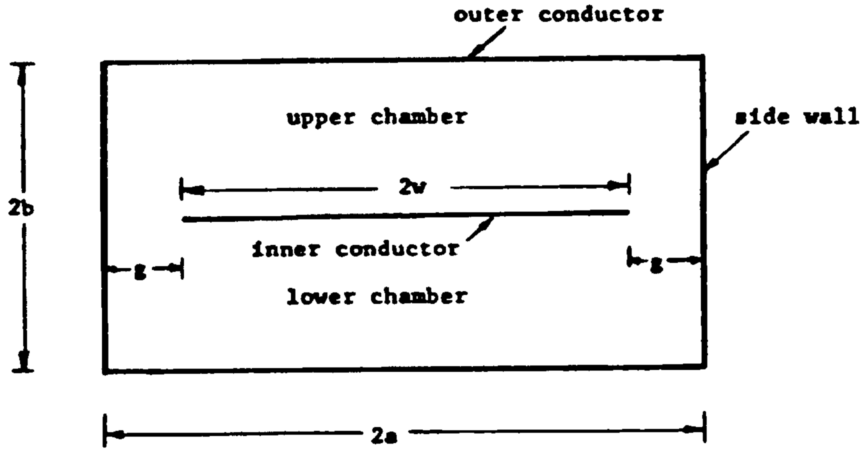
The rectangular transverse electromagnetic or TEM cell is the preferred method for generating *E*- and *H*-fields from 9 kHz to 200 MHz. TEM cells may be used for up to 500 MHz if the probe or sensor dimensions are small enough to ensure a uniform field.

This device is fully shielded, and does not emit energy that may be hazardous 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 operating in the transverse electromagnetic mode, hence the name. As shown in figure B.1, the main body 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 50 Ω characteristic impedance along the entire length of the cell [B19]. When the cell is properly designed and terminated in a reflectionless load, the input VSWR is usually less than 1.50 for frequencies below the cutoff limit. In the center of the calibration zone, 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 Ω. 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 [B19, B21, B48] if the maximum probe dimension is less than $b/3$, where b is the distance from the top wall to the septum (center plate). Cells can be made in various sizes to suit particular needs and to cover specific frequency ranges. However, since the width [surface parallel to the surface of the septum (center plate)] should be less than a 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 [B25] and [B47].



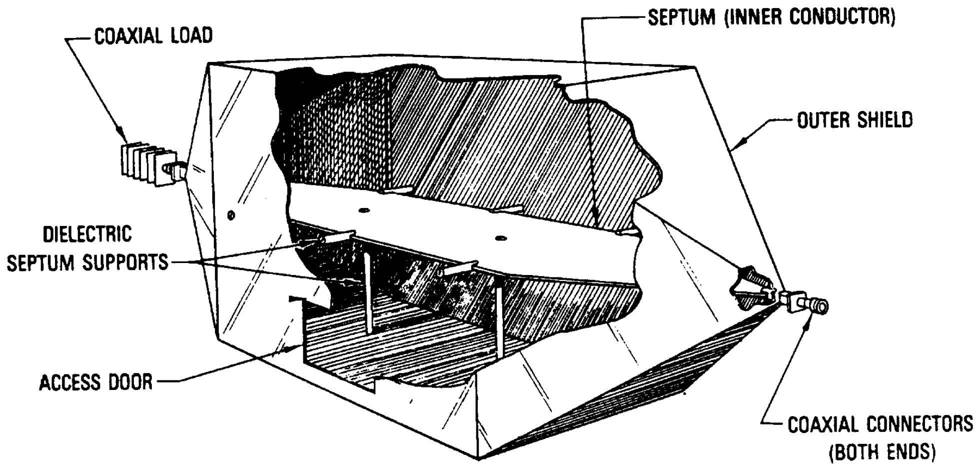


Figure B.1—Typical transverse electromagnetic (TEM) cell

B.1.1 Electrical characteristics

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

$$Z_o = \frac{9.42}{\frac{w}{b} + \frac{2}{\pi} ln\left(1 + \text{ctnh}\left(\frac{\pi g}{2b}\right)\right)} \quad (4)$$

where the dimensions *w, b*, and *g* are given in figure B.1 [B46].

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

$$E = \frac{V}{b} = \frac{\sqrt{P_{net} Z_o}}{b} \quad (5)$$

$$H = \frac{E}{377} \quad (6)$$

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

$$W = \frac{E^2}{377} \quad (7)$$

or

$$W = 377H^2 \quad (8)$$

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 TE01 cutoff frequency f_c is given by the relationship

$$f_c = \frac{75}{a}\sqrt{\left[1 + \frac{4a}{\pi b} ln\left(\frac{8a}{\pi g}\right)\right]} \quad (9)$$

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 [B25].) 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 using *E*-field and *H*-field probes with small sensors. When using the cell, forward and reflected power measurements should be made at the input port. Constant values assure consistent cell calibration. The error due to standing waves can be estimated by calculating the ratio of the field at the test point to the 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 [B20]. However, as 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 of the chamber, 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 of 5 cm.

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 cell output, this is not a preferred method.

B.1.5 TEM cell operated with a termination impedance different from 50 Ω

TEM cells with termination impedance different from 50 Ω are not applicable to this standard.

B.1.6 Absorber-loaded TEM cells

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

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

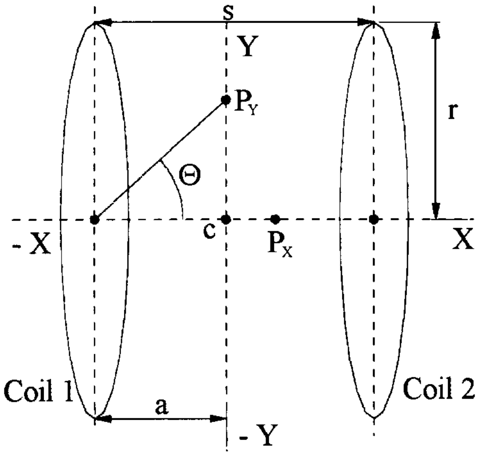
B.2.1 Introduction

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. Secondarily, 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 to 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.)



NOTES:
s=r
c (0,0) is center

Figure B.2—Helmholtz coil arrangement

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) [B45] 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.

$$H_x = \frac{N_1 I r_1^2}{2(r_1^2 + a_1^2)^{\frac{3}{2}}} + \frac{N_2 I r_2^2}{2(r_2^2 + a_2^2)^{\frac{3}{2}}} \tag{10}$$

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).

$$H_c = \frac{NI}{r(1.25)^{\frac{3}{2}}} \approx \frac{0.7155NI}{r} \tag{11}$$

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 [B52].

$$\varepsilon = \frac{\Delta H_c}{H_c} = -0.2\left(\frac{\Delta r}{r_1} + \frac{\Delta r}{r_2}\right) - 0.6\frac{\Delta s}{s} + \frac{\Delta I}{I} + \frac{\Delta N}{N} \qquad (12)$$

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 B.1—Errors in H_c versus errors in r_1,r_2, and s

Dimension	ε = 1 %	ε = 2 %	ε = 5 %
r_1	5 %	10 %	25 %
r_2	5 %	10 %	25 %
$r_1 + r_2$	2.5 %	5 %	12.5 %
s	1.66 %	3.33 %	8.33 %

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.

An integral 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 $0.5(\Delta N1/N + \Delta N/2/N)$, 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_ρ, at a point off of the coil-axis, e.g., P_y 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 equation (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 $x = \pm r/2$.

$$H_\rho = H_{\rho 1} + H_{\rho 1} \tag{13A}$$

$H_{\rho 1}$ is the field contribution from coil 1 and $H_{\rho 2}$ is the field contribution from coil 2.

$$H_{\rho 1} = \frac{NI}{2\pi r} D[f(\rho_1) + g(\rho_1)E] \tag{13B}$$

$$H_{\rho 2} = \frac{NI}{2\pi r} F[f(\rho_2) + g(\rho_2)G] \tag{13C}$$

$$D = \frac{1}{\sqrt{\left(1 + \frac{y}{r}\right)^2 + K_1^2}} \tag{13D}$$

$$E = \frac{1 - \left(\frac{y}{r}\right)^2 - \left(\frac{x}{r} + \frac{1}{2}\right)^2}{\left(1 - \frac{y}{r}\right)^2 + K_1^2} \tag{13E}$$

$$F = \frac{1}{\sqrt{\left(1 + \frac{y}{r}\right)^2 + K_2^2}} \tag{13F}$$

$$G = \frac{1 - \left(\frac{y}{r}\right)^2 - \left(\frac{x}{r} - \frac{1}{2}\right)^2}{\left(1 - \frac{y}{r}\right)^2 + K_2^2} \tag{13G}$$

where

$$f(\rho_c) = \int_0^{\frac{\pi}{2}} \frac{d\theta}{\sqrt{1 - \rho_c^2 \sin^2\theta}} \tag{14}$$

$$g(\rho_c) = \int_0^{\frac{\pi}{2}} \sqrt{1 - \rho_c^2 \sin^2\theta}\ d\theta \tag{15}$$

with

$$\rho_c = \sqrt{\frac{4\left(\frac{y}{r}\right)}{\left(1 + \frac{y}{r}\right)^2 + K_c^2}} \tag{16}$$

Note that f_c and g_c are complete elliptic integrals of the 1st and 2nd kind, respectively of modulus r_c.

The subscript $_c$ is 1 for coil #1 and 2 for coil #2

$$K_1 = \frac{x}{r} + \frac{1}{2} \tag{17A}$$

$$K_2 = \frac{1}{2} - \frac{x}{r} \tag{17B}$$

B.2.6 Determining coil size

Table B.3 shows 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 ($\Delta H/H_c$)

Uniformity	1%	2%	5%	10%
± *x*/*r*	0.3	0.4	0.5	0.6
± *y*/*r*	0.3	0.4	0.4	0.5

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 $r = 20/(2*0.3) = 33.33$ cm. The diameter of both coils should be 0.67 m or greater.

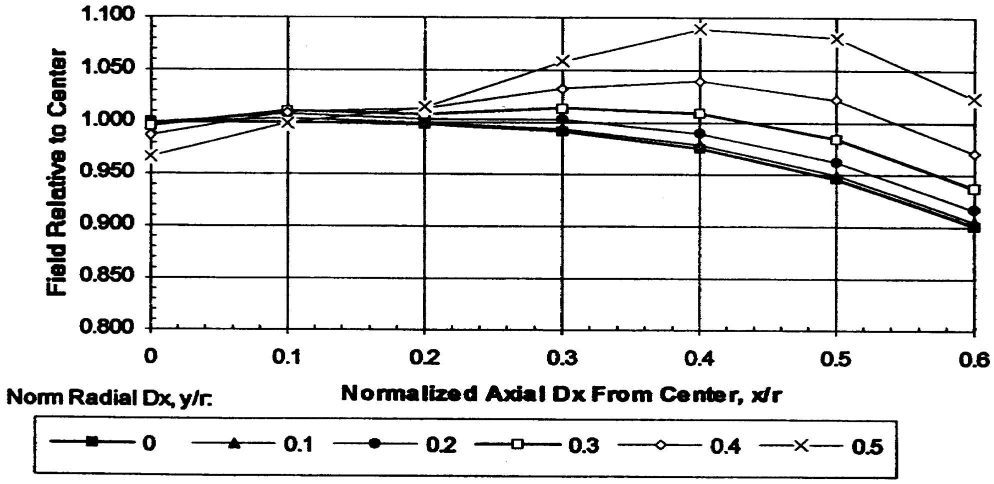


Figure B.3—Normalized magnetic field strength computed from equation 14

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 [B52]. 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 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 0.15λ or 0.10λ. Since it is the highest of the limiting frequencies, it is of little practical importance.

Table B.4—Upper frequency limit

1	Length of wire in coils	Highest frequency
2	Secondary field effects	Lower than 1
3	Self resonance	Lower than 2
4	Falloff of drive current	Lowest frequency

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 [B52].

The self-resonance frequency of the coils is given by the familiar equation, $f_0 = 1/2\pi\sqrt{LC}$. 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.

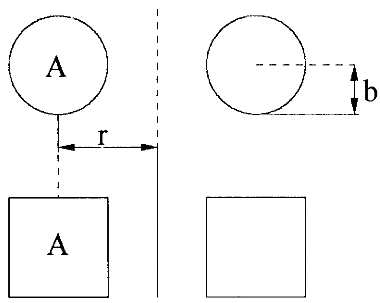
A practical maximum frequency is reached before the coils begin to approach resonance. About two orders of magnitude below the self-resonance frequency of the coils is the frequency where for a given generator power, the drive current begins to fall off. The impedance (mostly reactance) of the coils 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).

$$f_U = \frac{R_g + R_c}{2\pi L_T}\sqrt{\frac{P_U}{P_O} - 1} \tag{18}$$

$$L_T = 2N^2 r\left\{a + \mu\left[1\text{n}\left(\frac{8r}{b}\right) - 2\right]\right\} \tag{19}$$

where

a is the mutual inductance factor, $0.494*10^{-6}$ for Helmholtz coils [B52]
b is the effective radius of the coil winding, m (see figure B.4) [B58]
R_g is the generator source impedance, Ω
R_c is the total resistance of both coils, Ω
P_U/P_o is the ratio of the generator power at the upper frequency to the generator power at low frequencies.



A is the area of the windings.
For square windings: $b = (A/\pi)^{1/2}$

Figure B.4—Alternative coil winding configurations

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.

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

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 ($\Delta I_{cpa}/I + \Delta I_{cpr}/I$), where $\Delta I_{cpa}/I$ 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 ($\Delta I/I + 0.5\Delta I_{cpr}/I$), 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 Effect 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 [B13]:

— 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 a^2/λ. 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 [B32]

$$g = 21.6fa \tag{21}$$

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 [B53] is useful when applied as follows. Let B_d be the meter indication with the probe at an arbitrary near-field distance d andB_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

$$B_o = KW_o \tag{22}$$

$$B_d = KW_d \tag{23}$$

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, Bd is measured over a range of d distance, and a power series is fitted to the product $B_d d^2$ over the measurement interval. This series is then used to determine $B_o d_o^{\,2}$ by extrapolation. The following ratio can then be obtained

$$\frac{B_d d^2}{B_o d_o^2} = F_d \tag{24}$$

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 $B_o d_o^{\,2}$ directly. Combining the above equations yields

$$W_d = F_d W_o \left(\frac{d_o}{d}\right)^2 = \frac{F_d P_{net} g}{4\pi d} \tag{25}$$

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

since

$$W_0 = \frac{P_{net} g}{4\pi d^2} \tag{26}$$

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 do not yield accurate results for 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 [B12, B26]. 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/m^2 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/η. By equating these two expressions, the free-space field may be determined from the relationship:

$$E = \sqrt{\frac{\eta P g}{4\pi d^2}} \tag{27}$$

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
η 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.

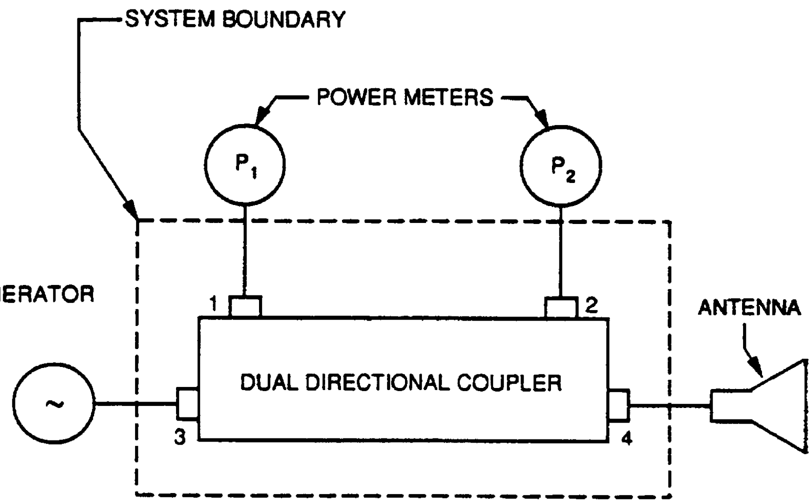


Figure B.5—System for measuring RF power delivered to an antenna

The ratio of power emerging from port 4 (i.e., P_{inc}) to the power P_1 read by the power meter on port 1 is the incident coupling factor C_{inc}. The reflected coupling factor C_{refl} is the ratio of power entering port 4 (i.e., P_{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_{net}, however, both coupling factors should be known at each measurement frequency. Then, at a given frequency

$$P_{net} = C_{inc}P_1 - C_{refl}P_2 \quad (28)$$

Equation (28) is valid for use with directional couplers having high directivity (at least 25–30 dB), but may give inaccurate values for P_{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 [B33]. The net power delivered to the transmitting antenna is given by

$$P_{net} = P_{inc} - P_{ref} \quad (29A)$$

$$P_{net} = \frac{P_1}{(1-|\Gamma_1|^2)}\left|\frac{S_{34}}{S_{13}}\right|^2 |g(S,\Gamma)|^2 \quad (30B)$$

$$P_{net} = \frac{P_2}{(1-|\Gamma_2|^2)}\frac{1}{|S_{24}|^2}|h(S,\Gamma)|^2 \quad (31C)$$

The symbols Γ_1 and Γ_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, Γ) and h(S, Γ) 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 ($S_{11} = S_{22} = S_{33} = S_{44} = S_{14} = S_{41} = S_{23} = S_{32} = S_{12} = S_{21} = 0$), with matched power meters at ports 1 and 2 ($\Gamma_1 = \Gamma_2 = 0$), the terms g(S,Γ) = h(S,Γ) = 1. Unless the magnitudes and phases of the system S-parameters and the reflection coefficients of a real system are well determined, g(S,Γ) and h(S,Γ) are not calculable. The deviation of g(S, Γ) and h(S,Γ) 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 Γ parameters, it is found to be, in general, less than 1%, see [B33].

To compute the net power using equation (29), the terms S_{34}/S_{13} and $1/S_{24}$ need to be determined. Although the magnitudes of S_{13}, S_{24}, and S_{34} 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

$$\frac{P_2}{P_1} = \left|\frac{S_{24}S_{34}}{S_{13}}\right|^2 \frac{1-|\Gamma_2|^2}{1-|\Gamma_1|^2}(1+|\Delta_1|^2) \quad (32)$$

where $\Delta_1(S,\Gamma)$ is a complex quantity much less than unity (see [B46]).

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 Ω. The ratio of the two power measurements P_1 and P_4 is

$$\frac{P_1}{P_4} = \left|\frac{S_{13}}{S_{34}}\right|^2 \frac{1-|\Gamma_1|^2}{1-|\Gamma_4|^2}(1+|\Delta_2|^2) \quad (33)$$

where Δ_2 is another complex quantity much less than unity.

From the four power measurements and values for the power meter reflection coefficients Γ_1, Γ_2, and Γ_4, the quantities $|S_{34}/S_{13}|^2$ and $|S_{24}|^2$ may be computed from equations (30) and (31). The terms Δ_1 and Δ_2 involve products of the system S-parameters and reflection coefficients Γ whose phases are not known. Therefore, the magnitudes of Δ_1 and Δ_2 cannot be determined, and the deviation of Δ_1 and Δ_2 from zero is unknown. Moreover, the uncertainty 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 $|S_{24}|$. The detailed discussion on this topic is given in [B32].

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 relative to an isotropic antenna *g*. 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 [B62]. 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 l (in meters) is given by [B31]

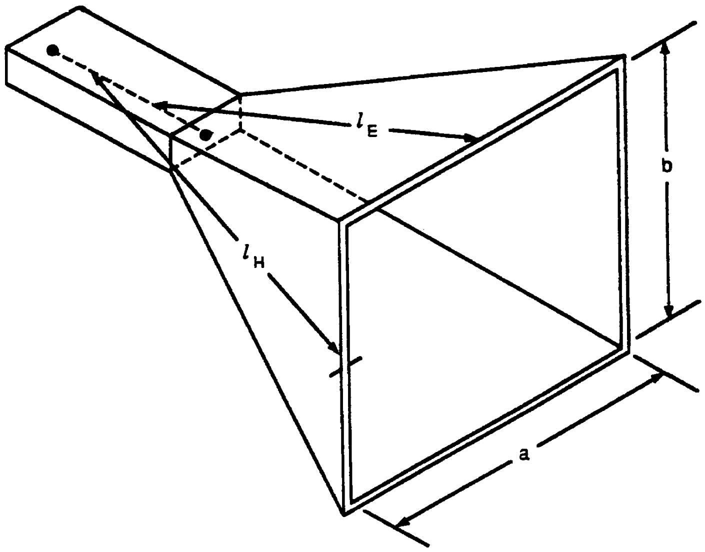


Figure B.6—Sketch of a pyramidal horn showing the dimensions

$$g = \frac{32ab}{\pi\lambda^2} R_E R_H = 113.3 f^2 ab R_E R_H \tag{34}$$

where *f* is in GHz.

The terms R_E and R_H are often written in terms of Fresnel integrals [B30] 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 [B31] to which polynomial expressions have been fitted [B36].

$$R_E = -(0.1\beta^2)(2.31 + 0.053\beta) \tag{35}$$

$$R_H = -(0.01a)(1 + 10.19a + 0.51a^2 - 0.097a^3) \tag{36}$$

where

$$a = \frac{a^2 f}{0.3}\left(\frac{1}{l_H} + \frac{1}{d}\right) \tag{37A}$$

$$\beta = \frac{b^2 f}{0.3}\left(\frac{1}{l_E} + \frac{1}{d}\right) \tag{38B}$$

and

a, b, l_E, l_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 (32) are gain reduction factors that are positive and less than unity. Though their values in decibels are negative, the tabulation in [B31] gives these decibel values as positive. Therefore, a minus sign (not present in [B36]) is included in equations (33) and (34) to make equation (36) consistent with equation (32).

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

$$G = 10\log(g) = 20.54 + 10\log(ab) + 20\log(f) + R_E + R_H \tag{39}$$

The numeric gain g is then

$$g = 10^{G/10} \tag{40}$$

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.

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 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, B69].

Figure B.7 shows how a section of rectangular waveguide can be used for calibrations. A reflectionless load 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 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 [B27, B37]. The "equivalent power density" can be determined in terms of E^2 (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

$$W = \frac{4P_{net}}{a^2}\left[1 - \left(\frac{\lambda}{2a}\right)^2\right]^{-1/2} \qquad (41)$$

See B.4.2 for details on measuring power to the transmitting device.

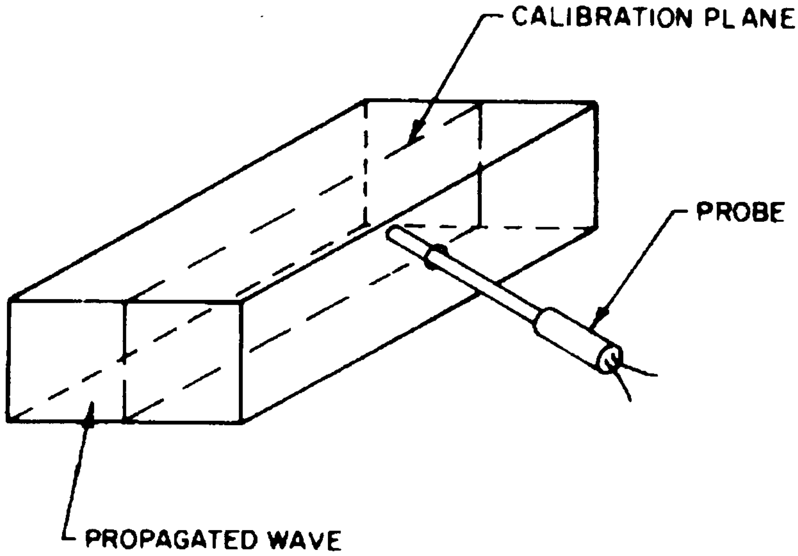


Figure B.7—Rectangular waveguide calibration system

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 [B23, B34]. The GTEM cell consists of a tapered 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 Ω characteristic impedance along the length. A GTEM can be constructed to have a much larger working volume than a TEM cell. There are no geometrical discontinuities, as in a standard TEM cell, so moding may not be seen in VSWR measurements below 20 GHz. The septum (or center plate) is terminated in a series/parallel 50 Ω resistor array, which dissipates fields and currents up to low

MHz frequencies. Pyramidal absorber covering the back wall dissipates the approximately plane wave fields at all higher frequencies.

The GTEM characteristic impedance and quasistatic field are approximately calculated using asymmetric TEM cell theory [B67, B68]. 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 ± 4 dB. At present, a rigorous method of GTEM field calculation for all frequencies is not available. 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.

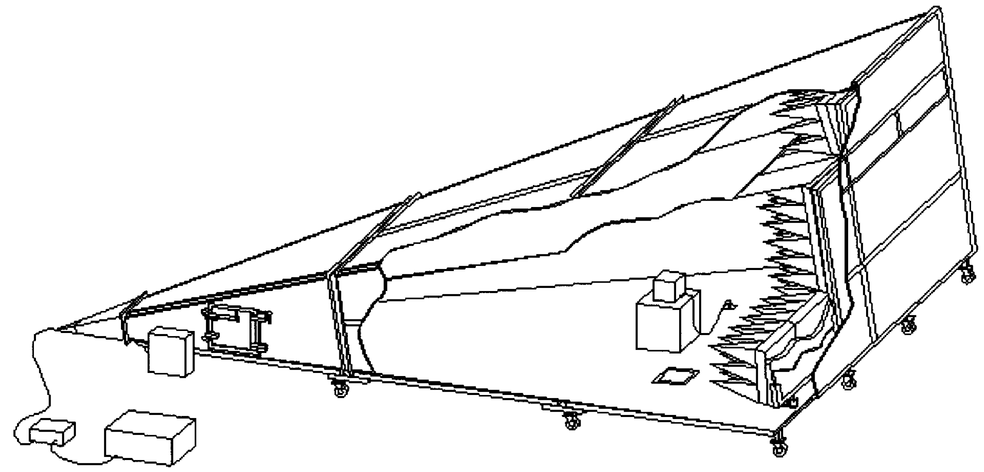


Figure B.8—Typical gigahertz transverse electromagnetic (GTEM) cell

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.

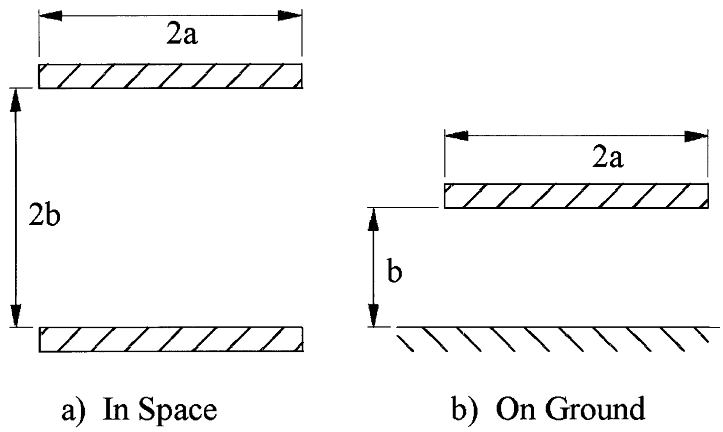


Figure B.9—Parallel plate transmission line

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 [B5, B7, B8,

B10, B15, B16, B17, B18, B22, B24, B28, B39, B40, B44, B49, B50, B57, B73]. 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 [B3, B4, B38, B59, B60, B61, B70], 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 [B7, B24] 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.

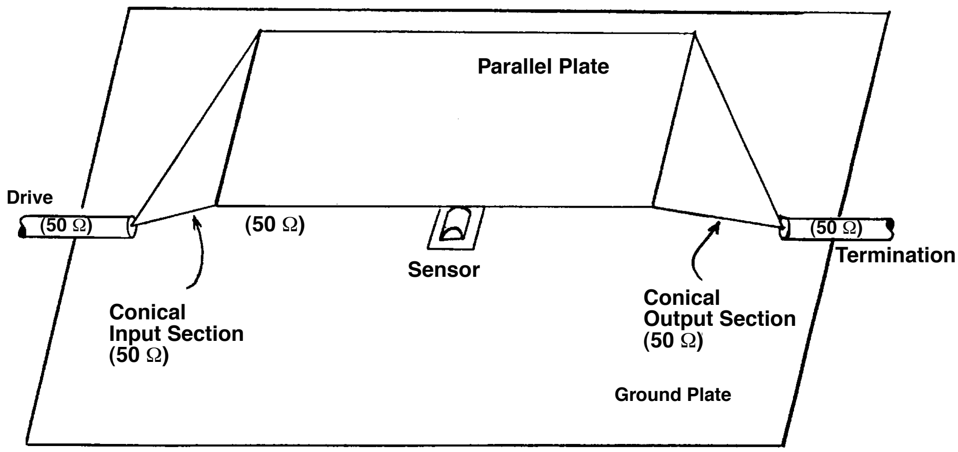


Figure B.10—Parallel plate transmission line with conical input and output sections

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 relectometer or *s*-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

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 [B3, B4, B38, B59, B60, B61, B70] with a distributed termination [B2, B6, B35, B71, B72] as shown in figure B.11.

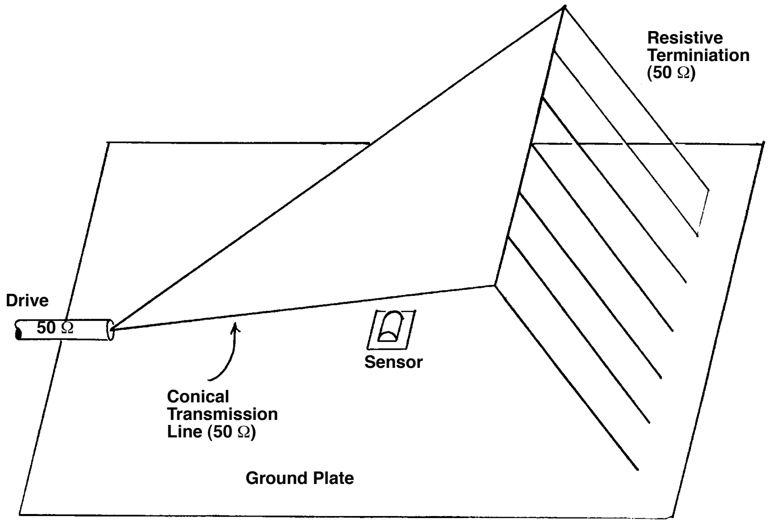


Figure B.11—Conical transmission line with distributed terminations

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) [B63, B64, B65].

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 [B42] 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 θ/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

$$Z_c = 60 ln\left[\text{ctn}\left(\frac{\theta_0}{2}\right)\right] \tag{42}$$

If the impulse generator and the associated driven transmission line has a characteristic impedance Z_d , an outward traveling spherical wavefront is generated with an electric field

$$E(t) = \frac{V(t)}{r\sin(\theta)}\left(\frac{2Z_c}{Z_c + Z_d}\right) \tag{43}$$

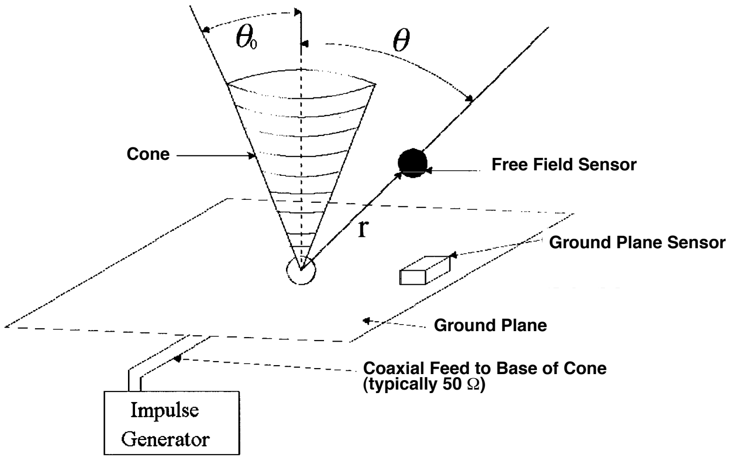


Figure B.12—Cone and ground plane

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.

$$0 \le t \le \frac{2c}{\min[r_{\text{cone,}} r_{\text{gp}}]} \tag{44}$$

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 θ- directed electric field that is constant at a fixed radius r and angle θ.

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 [B54] 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.

Annex C

(informative)

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 easily and inexpensively done 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 101–102 Ω cm resistivity, and often must be insulated from conductors.

The nickel-zinc ferrite material resistivity increases from about 30 Ω cm at 10 MHz to about 70 Ω cm 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 resistivity of 105–109 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

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.

Annex D

(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

(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 [B56, B57, B63, B64], 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.

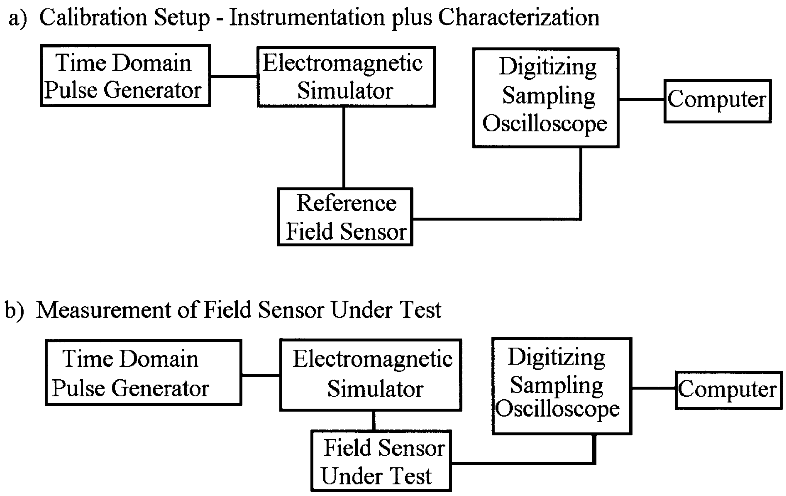


Figure F.1—Instrumentation setup

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 filed 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.

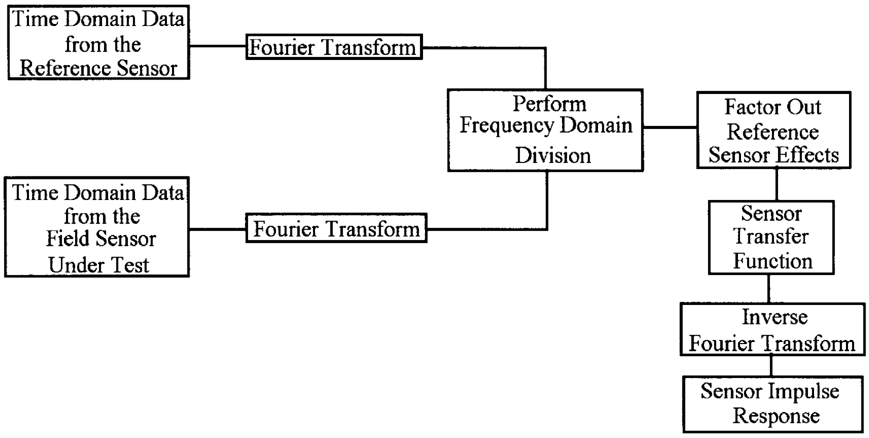


Figure F.2—Block diagram of the deconvolution procedure

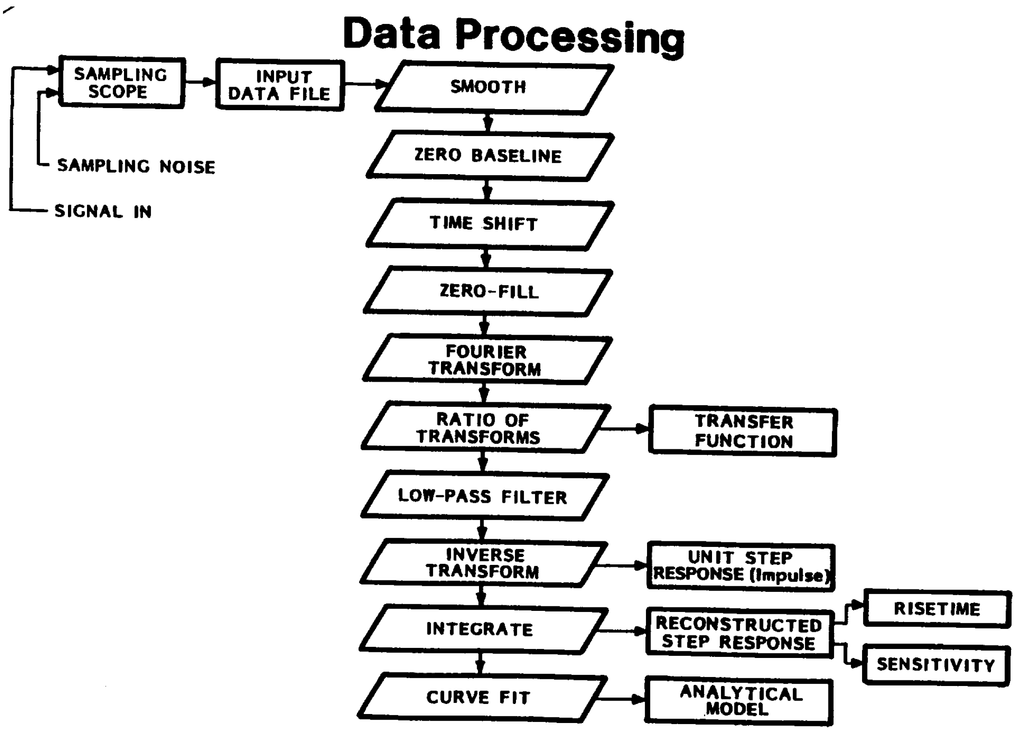


Figure F.3—Time domain deconvolution data processing

Annex G

(informative)

Burst peak measurement

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 measurement is an example.

Many field probes used for this type of measurement have a time constant to the recorder output and the maximum hold mode meter indication is approximately 0.25 s. The probe elements' (sensors') 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 illumination of a rotating radar beam if it 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.

$$t = \frac{\text{beamwidth}}{\text{r/min}} \quad (45)$$

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

$$K = \frac{E_{\text{hold}}}{E_{\text{cw}}} = 1 - e^{-t/T} \quad (46)$$

where

t is period of illumination in seconds
T is time constant of probe and circuitry
K is maximum hold ratio
E_{hold} is maximum indication
E_{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:

$$t = 0.167\frac{1.3}{12} = 0.018 \tag{47}$$

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

$$\frac{t}{T} = \frac{0.018}{0.291} = 0.062 \tag{48A}$$

$$K = 1-e^{-0.062} = 0.060 \tag{49B}$$

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

The time averaged power density P_{dAvg} can be calculated as the product of the burst peak power density and the radar sweep duty factor. The burst peak power density P_{dBurst} 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 º).

Annex H

(informative)

Examples on determining uncertainty

H.1 Standard uncertainty

List each component that contributes to the overall measurement uncertainty and its independent uncertainty (u_i). Each component should be identified 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 [B66]. 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

Type B (other methods)—overall measurement uncertainties and independent uncertainties

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

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

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 the √3.

NOTE—The conversion process between uncertainty in percent and in decibels is not symmetric. As an example using the power meter uncertainty above, $|1 - 10^{0.21/10}| \neq |1 - 10^{-0.21/10}|$.

The relationship between decibels and ratio is

$$P_{db} = 10\log_{10}(P_{ratio}) \quad (50A)$$

and

$$P_{ratio} = 10^{P_{dB}/10} \quad (51B)$$

or for voltage dependent data,

$$V_{\mathrm{dB}} = 20\log_{10}(V_{\mathrm{ratio}}) \tag{52A}$$

and

$$V_{\mathrm{ratio}} = 10^{V_{\mathrm{dB}}/20} \tag{53B}$$

For example: if $P_{\mathrm{dB}} = 0.21$ dB, then $P_{\mathrm{ratio}} = 1.05$, giving an uncertainty (not u_{i}) of 5%, and if $V_{\mathrm{dB}} = 0.21$ dB, then $V_{\mathrm{ratio}} = 1.025$, 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:

$$u_{\mathrm{c}} = \sqrt{\sum (u_{\mathrm{i}})^2} \tag{54A}$$

$$u_{\mathrm{c}} = RSS = \sqrt{(0.01)^2 + (0.0289)^2 + (0.0115)^2} = 0.037 \tag{55B}$$

This shows that $u_{\mathrm{c}} = 6.2$ %. In this example, the probe was calibrated in terms of power, or E^2, the u_{c} of 3.7% would convert to decibels as 10log (1.037). Thus, u_{c}= 0.16 dB. For voltage probe calibration the conversion would be 20log (quantity). If the errors are correlated, see ISO/TAG 4/WG or NCSL PR-12 for further instructions.

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

$$U = ku_{\mathrm{c}} \tag{56}$$

Using the same values as before, where $u_{\mathrm{c}} = 3.7$ % (0.16 dB) and $k = 2$, gives the expanded uncertainty:

$$U = 2 \times (3.7\%) = 7.4\%(0.31\mathrm{dB}) \tag{57}$$

Again, as the example probe was calibrated in terms of power or E_2, the conversion to decibels would be done as 10log (quantity).

H.4 Reporting uncertainty

The simplest approach is to display the uncertainty results in a table (for example, table H.1) with some additional explanation, if necessary.

Table H.5—Table of uncertainties

Description of uncertainty	Type B measurement uncertainty	Standard uncertainty ui (%)
Variations in readings		1 (Type A)
Power meter with sensor # 001	0.21 dB (rectangular)	2.89 (Type B)
TEM cell field uniformity	0.12 dB (rectangular)	1.73 (Type B)
Placement of device under test (DUT)	0.09 dB (rectangular)	1.15 (Type B)
Combined standard uncertainty: u_c =		3.7%
Expanded uncertainty: ±	0.31 dB	7.4 %

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.

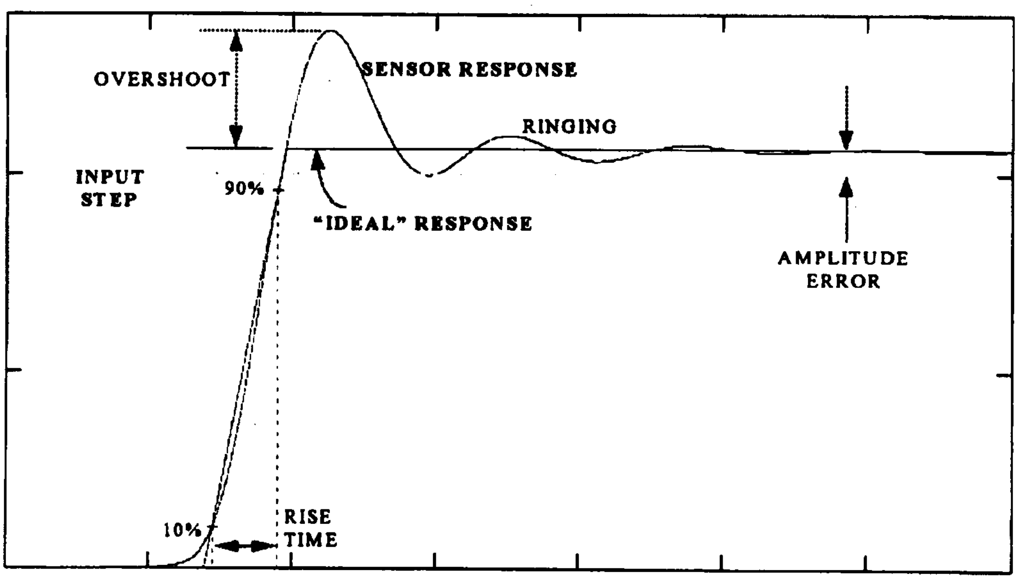


Figure I.1—Waveform parameter for definition of pulse fidelity

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.

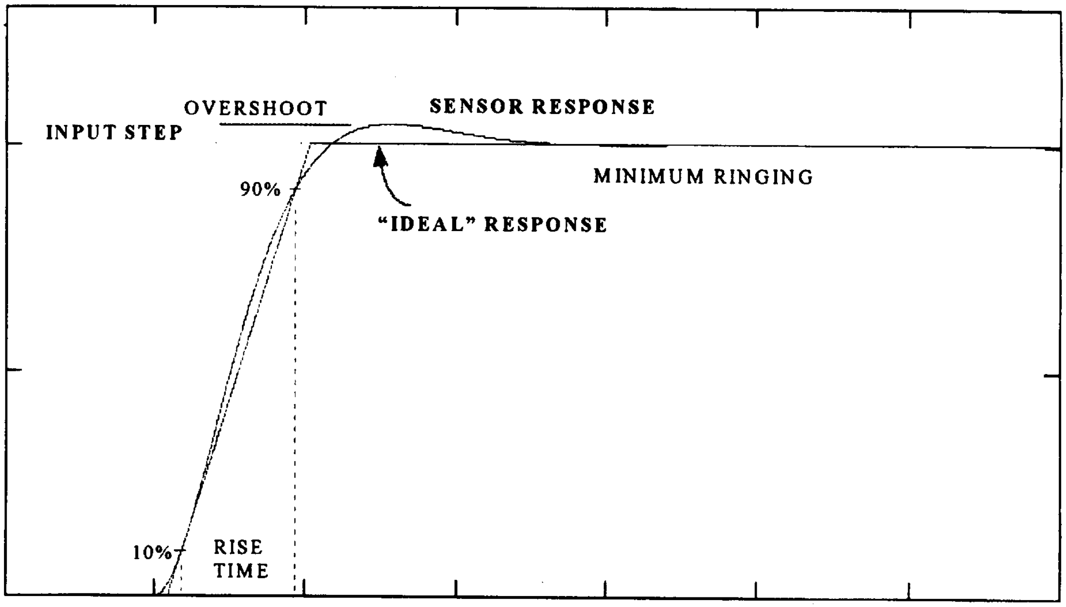


Figure I.2—Waveform parameters for maximally flat sensor response

Annex J

(informative)

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