

INTERNATIONAL STANDARD

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BASIC EMC PUBLICATION

PUBLICATION FONDAMENTALE EN CEM

**Electromagnetic compatibility (EMC) –
Part 4-21: Testing and measurement techniques – Reverberation chamber test
methods**

**Compatibilité électromagnétique (CEM) –
Partie 4-21: Techniques d'essai et de mesure – Méthodes d'essai en chambre
réverbérante**



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IEC 61000-4-21

Edition 2.0 2011-01

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

PRICE CODE
CODE PRIX

XE

ICS 33.100.10; 33.100.20

ISBN 978-2-88912-324-7

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROMAGNETIC COMPATIBILITY (EMC) –**Part 4-21: Testing and measurement techniques –
Reverberation chamber test methods**

FOREWORD

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International Standard IEC 61000-4-21 has been prepared by subcommittee 77B: High frequency phenomena, of IEC technical committee 77: Electromagnetic compatibility, in co-operation with CISPR subcommittee A: Radio-interference measurements and statistical methods.

It forms Part 4-21 of IEC 61000. It has the status of a basic EMC publication in accordance with IEC Guide 107.

This second edition cancels and replaces the first edition published in 2003. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the first edition.

- In Clause 8, the use and specifications of *E*-field probes for application to reverberation chambers has been added. Additional Notes refer to general aspects and procedures of

probe calibrations. The specified range for linearity of the probe response is larger and covers an asymmetric interval compared to that for use in anechoic chambers (see Annex I of IEC 61000-4-3), because

- the fluctuations of power and fields in reverberation chambers exhibit a larger dynamic range, and
- the chamber validation procedure is based on using maximum field values, as opposed to the field itself or its average value,

respectively.

- In Annex A, additional guidance and clarifications on the use of reverberation chambers at relatively low frequencies of operation (i.e., close to the lowest usable frequency of a given chamber) are given, and its implications on the estimation of field uncertainty are outlined. Guidelines on cable-layout have been added. A rationale has been added that explains the relaxation of the field uniformity requirement below 400 MHz, being a compromise between scientific-technical and economical reasons when using chambers around 100 MHz. A first-order correction for the threshold value of the correlation coefficient at relatively low numbers of tuner positions has been added. Issues regarding the use of non-equidistant tuner positions at low frequencies are discussed in an additional Note.
- In Annex B, symmetric location of the field probes when the chamber exhibits cylindrical symmetry has been disallowed, as such placement could otherwise yield a false indication of field uniformity and chamber performance at different locations. The difference between start frequency for chamber validation and lowest test frequency has been clarified. The tuner sequencing for chamber validation and testing is now specified to be equal in both cases. In sample requirements for chamber validation, emphasis is now on the required minimum number of independent tuner steps to be used, whereas the minimum recommended number of samples per frequency interval has been replaced with the number of independent samples that the tuner can provide per frequency, for use in case when the chamber validation fails for the required minimum number.
- Annex C now contains more quantitative guidance on the setting of the maximum permissible stirring speeds that warrant quasi-static conditions of operation for chamber validation and testing. Consideration is given to all characteristic time scales of all components or subsystems of a measurement or test. Specific issues relating to chamber validation, immunity testing and bandwidth are addressed. Particular requirements for field probes when used with mode stirred operation are listed.
- In Annex D, a requirement for the EUT and equipment not to occupy more than 8 % of the total chamber volume in immunity testing has been added. The maximum number of frequency points and the formula to calculate these points have been generalized. A mandatory specification for including the measurement equipment, test plan and cable layout in the test report has been added to resolve any dispute in case of discrepancies, particularly for low-frequency immunity testing.
- Annex E has been extended with further guidance on the value of EUT directivity to be used in the estimation of radiated power and field. Extended estimates have been added for the maximum directivity of electrically large, anisotropically radiating EUTs and for radiated emissions in the presence of a ground plane. A mandatory specification for including the measurement equipment, test plan and cable layout in the test report has been added to resolve any dispute in case of discrepancies, particularly for low-frequency emissions testing.
- In Annex I, some clarifications on antenna efficiency measurements have been added.
- A new Annex K has been added that covers measurement uncertainty in reverberation chambers. The intrinsic field uncertainty for chamber validation, immunity and emissions measurements is quantified. Other contributors to measurement uncertainty are listed.

The text of this standard is based on the following documents:

CDV	Report on voting
77B/619/CDV	77B/640/RVC

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

IEC 61000 is published in separate parts according to the following structure:

Part 1: General

General considerations (introduction, fundamental principles)

Definitions, terminology

Part 2: Environment

Description of the environment

Classification of the environment

Compatibility levels

Part 3: Limits

Emission limits

Immunity limits (in so far as they do not fall under the responsibility of the product committees)

Part 4: Testing and measurement techniques

Measurement techniques

Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines

Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

Each part is further subdivided into several parts, published either as international standards or as technical specifications or technical reports, some of which have already been published as sections. Others will be published with the part number followed by a dash and a second number identifying the subdivision (example: IEC 61000-6-1).

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 4-21: Testing and measurement techniques – Reverberation chamber test methods

1 Scope

This part of IEC 61000 considers tests of immunity and intentional or unintentional emissions for electric and/or electronic equipment and tests of screening effectiveness in reverberation chambers. It establishes the required test procedures for performing such tests. Only radiated phenomena are considered.

The objective of this part is to establish a common reference for using reverberation chambers to evaluate the performance of electric and electronic equipment when subjected to radio-frequency electromagnetic fields and for determining the levels of radio-frequency radiation emitted from electric and electronic equipment.

NOTE Test methods are defined in this part for measuring the effect of electromagnetic radiation on equipment and the electromagnetic emissions from equipment concerned. The simulation and measurement of electromagnetic radiation is not adequate for quantitative determination of effects. The defined test methods are organized with the aim to establish adequate reproducibility and repeatability of test results and qualitative analysis of effects.

This part of IEC 61000 does not intend to specify the tests to be applied to a particular apparatus or system. Its main aim is to give a general basic reference to all concerned product committees of the IEC. The product committees should select emission limits and test methods in consultation with CISPR. The product committees remain responsible for the appropriate choice of the immunity tests and the immunity test limits to be applied to their equipment. Other methods, such as those covered in IEC 61000-4-3, CISPR 16-2-3 and CISPR 16-2-4 may be used.¹

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050(161):1990, *International Electrotechnical Vocabulary – Chapter 161: Electromagnetic compatibility*

Amendment 1 (1997)

Amendment 2 (1998)

IEC 60068-1, *Environmental testing – Part 1: General and guidance*

IEC 61000-4-3:2006, *Electromagnetic compatibility (EMC) – Part 4-3: Testing and measurement techniques – Radiated, radio-frequency, electromagnetic field immunity test*

Amendment 1 (2007)

¹ For further information consult with CISPR (International Special Committee on Radio Interference), or Technical Committee 77 (Electromagnetic compatibility).

CISPR 16-1-1, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-1: Radio disturbance and immunity measuring apparatus – Measuring apparatus*

CISPR 16-2-3, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 2-3: Methods of measurement of disturbances and immunity – Radiated disturbance measurements*

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions together with those in IEC 60050(161) apply.

3.1.1

antenna

that part of a radio transmitting or receiving system which is designed to provide the required coupling between a transmitter or a receiver and the medium in which the radio wave propagates

[IEC 60050-712:1992, 712-01-01]

NOTE For the purpose of this procedure, antennas are assumed to have an efficiency of 75 % or greater.

3.1.2

electromagnetic wave

EM wave

wave characterized by the propagation of a time-varying electromagnetic field and caused by acceleration of electric charges

[IEC 60050-705:1995, 705-01-09, modified]

3.1.3

far field region

that region of the electromagnetic field of an antenna or unintentional radiator wherein the predominant components of the field are those which represent a propagation of energy and wherein the angular field distribution is essentially independent of the distance from the antenna

NOTE 1 In the far field region, all the components of the electromagnetic field decrease in inverse proportion to the distance from the antenna.

NOTE 2 For a broadside antenna having a maximum overall dimension, D , which is large compared to the wavelength, λ , the far field region is commonly taken to exist at distances greater than $2D^2/\lambda$ from the antenna in the direction of maximum radiation.

[IEC 60050-712:1992, 712-02-02]

the region far from a source or aperture where the radiation pattern does not vary with distance from the source

[IEC 60050-731:1991, 731-03-92]

3.1.4

field strength

magnitude of the electromagnetic field created at a given point by a radio transmitting system operating at a specified characteristic frequency with specified installation and modulation conditions

[IEC 60050-705:1995, 705-08-31]

NOTE 1 The term "electric field strength" (in V/m) or "magnetic field strength" (in A/m) is used according to whether the magnitude of the electric or magnetic field, respectively, is measured. In the near-field region, the relationship between the electric and magnetic field strength and distance depends on the specific configuration involved. The power flux density of the field is similarly indeterminate.

NOTE 2 In the far zone, field strength is sometimes identified with power flux density P . For a plane wave in free space, $P = E^2 / \eta_V$, where

E is the electric field strength, and

η_V is the intrinsic impedance of free space, approximately equal to $120\pi \Omega$.

3.1.5

polarization

property of a sinusoidal electromagnetic wave or field vector defined at a fixed point in space by the direction of the electric field strength vector or of any specified field vector; when this direction varies with time, the property may be characterized by the locus described by the extremity of the considered field vector

[IEC 60050-726:1982, 726-04-01]

3.1.6

reverberation chamber

room specially designed to have a very long reverberation time

[IEC 60050-723:1997, 723-03-30]

(reverberation room) room having a long reverberation time, especially designed to make the field therein as diffuse as possible

NOTE 1 The room consists of a shielded enclosure that is generally equipped with mechanical tuners/stirrers that change (stir) the boundary conditions within the enclosure and, thus, alter the structure of the electromagnetic fields within the enclosure.

[IEC 60050-801:1994, 801-31-13, modified]

NOTE 2 Reverberation rooms are used in particular for the measurement of absorption coefficients of materials and measurement of the power emitted by intentional or unintentional radiating sources.

NOTE 3 Testing in a reverberation chamber can be described as a stochastic process in which the mechanical tuners/stirrers "stir" the "modes" inside the enclosure. Therefore, such chambers are also called stirred-mode, mode-stirred or mode-tuned chamber.

3.1.7

quality factor (of a reverberation chamber)

Q

(quality factor) frequency-dependent measure of sharpness of the resonance, equal to 2π times the ratio of the maximum stored energy to the energy dissipated during one period

[IEC 60050-151:2001, 151-15-46, modified]

measure of how well the chamber stores energy (see Clause A.6 [2]²)

NOTE For a given chamber, Q varies as a function of frequency and can be calculated using the following formula:

$$Q = \frac{16\pi^2 V}{\eta_{Tx} \eta_{Rx} \lambda^3} \left\langle \frac{P_{AveRec}}{P_{Input}} \right\rangle_n \quad (4)$$

where

V is the chamber volume (in m³),

² Numbers in square brackets refer to the reference documents in the respective annexes

λ is the wavelength (in m),

$P_{\text{AveRec}}/P_{\text{Input}}$ is the ratio of the received power to the input power, each averaged over one complete tuner/stirrer sequence,

$\langle \rangle_n$ denotes averaging with respect to the number of antenna locations and orientations, n ,

η_{Tx} and η_{Rx} are the antenna efficiency factors (dimensionless) for the Transmit (Tx) and Receive (Rx) antennas, respectively. If manufacturer's data is not available then the efficiency can be assumed to be 0,75 for log periodic antennas and 0,9 for horn antennas,

n is the number of antenna locations and orientations that the Q is evaluated for. Only one location is required as a minimum; however, multiple locations and orientations may be evaluated and the data averaged over them.

3.1.8

Q-bandwidth (of a reverberation chamber)

BW_Q

measure of the frequency range over which the modes in a reverberation chamber are correlated (see Clause A.2)

NOTE The BW_Q of a reverberation chamber can be calculated using the following formula:

$$BW_Q = f/Q \quad (5)$$

where

f is the frequency (in Hz),

Q is the quality factor defined in 3.1.7.

3.1.9

malfunction

loss of capability of the equipment to initiate or sustain a required function, or the initiation of undesired spurious action which might result in adverse consequences

NOTE The criteria of functional acceptance have to be precisely specified.

[IEC 60050-393:2003, 393-17-79]

3.1.10

emission

phenomenon by which energy emanates from a source in the form of waves or particles

[IEC 60050-702:2003, 702-02-03]

3.1.11

tuner/stirrer

mechanical device constructed from low-loss electrically conductive material which alters the electromagnetic boundary conditions inside a reverberation chamber

NOTE In general, a reverberation chamber is a shielded enclosure with the smallest dimension being large with respect to the wavelength at the lowest usable frequency. The chamber is normally equipped with a mechanical tuning/stirring device whose dimensions are significant fractions of the chamber dimensions and of the wavelength at the lowest usable frequency. When the chamber is excited with RF energy, the boundary conditions of the resulting multi-mode electromagnetic environment can be altered by the mechanical tuner/stirrer. The resulting environment is statistically uniform and statistically isotropic (i.e., the energy arriving from all aspect angles with all directions of polarizations) when considered over a sufficiently large number of positions of the mechanical tuner/stirrer.

3.1.12

electromagnetic mode

one solution of Maxwell's equations representing an electromagnetic field in a certain space domain and belonging to a family of independent solutions defined by specified boundary conditions

[IEC 60050-705:1995, 705-01-12]

3.1.13 validation

process of confirming that a finalized instrumentation, control system (hardware and software) and test facility complies with all of its functional, performance and interface requirements

[IEC 60050-394:2007, 394-40-42, modified]

3.1.14 chamber validation

process of confirming that a chamber complies with all of its functional, performance and interface requirements

[IEC 60050-394:2007, 394-40-42, modified]

3.1.15 intrinsic field uncertainty IFU

contribution to the overall uncertainty budget that is caused by the random (statistical) nature of the field inside a reverberation chamber

NOTE Typically, the intrinsic field uncertainty is considerably larger than the measurement instrumentation uncertainty in typical operation of a reverberation chamber, except when the chamber has an exceptionally high quality factor. As a result, the IFU is typically the only or main contribution to be considered in estimating the overall uncertainty during test or measurement.

3.1.16 working volume

region defined by 8 points inside the chamber at sufficient distance away from the walls to avoid boundary effects, for rectangular chambers typically defined by the corners of a cubic or parallelepiped region at quarter-wavelength distance from the nearest walls

NOTE For frequencies below 100 MHz, the distances can be restricted to 0,75 m.

3.2 Abbreviations

AVF	Antenna Validation Factor
CVF	Chamber Validation Factor
CDF	Cumulative Distribution Function
CISPR	Comité International Spécial des Perturbations Radioélectriques ³
CLF	Chamber Loading Factor
CW	Continuous Wave
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EUT	Equipment Under Test
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IF	Image Frequency
IFU	Intrinsic Field Uncertainty
IL	Insertion Loss
ISO	International Organization for Standardization

³ International Special Committee on Radio Interference

LUF	Lowest Usable Frequency
MIU	Measurement Instrumentation Uncertainty
MU	Measurement Uncertainty
OATS	Open Area Test Site
PDF	Probability Density Function
RC	Reverberation Chamber
RE	Radiated Emissions
RF	Radio Frequency
RMS	Root Mean Square
rps	revolutions per second
RSS	Root Sum of the Squares
Rx	Receive (antenna)
SE	Shielding Effectiveness
SW	Square Wave modulation
TFVF	Test Fixture Validation Factor
Tx	Transmit (antenna)

4 General

Most electronic equipment is, in some manner, affected by electromagnetic radiation. Sources of radiation can be natural or man-made in origin and can be intentional or unintentional. Examples of intentional radiators are wireless and personal communication systems. Examples of unintentional radiators are welders, thyristors, high-speed data buses, fluorescent lights, switches operating inductive loads, etc.

Realistic environments for propagation of electromagnetic waves are often characterized by multiple reflections and multipath effects. Reverberation chambers go some way to simulate such complex environments in an extreme manner (worst-case effect) and may be more representative than other EMC test methods in this respect. An advantage of reverberation chambers is the ability to generate a statistically isotropic, homogeneous, unpolarized and uncorrelated interior field, through action of the tuner/stirrer.

High-level electromagnetic fields are easily and safely generated using reverberation chambers. The high quality factor or “Q” of such chambers allows fairly high field strengths to be generated with relatively moderate input powers (resonant fields). The absence of absorber makes generation of high field levels safer as the risk of igniting absorbers is eliminated. Adequate screening of the enclosure confines the high fields to the interior of the chamber.

5 Test environments and limitations

The reverberation chamber method is suitable for performing tests from relatively low to extremely high field levels. Due to the high level of isolation from the ambient environment, both emissions and immunity tests can be performed for most commercial requirements without limitations. At present, the IEC sets the transition frequency between radiated and conducted testing at 80 MHz for immunity testing.

NOTE IEC 61000-4-6 also defines test methods for establishing the immunity of electrical and electronic equipment against conducted electromagnetic energy. It covers frequencies below 80 MHz.

As stated in Annex A, the frequency range of tests is determined by the size and construction of the chamber and the effectiveness of the mechanical tuner(s) in altering the spatial field pattern. There are no fundamental restrictions with regard to the shape and size of the enclosure.

eligible for use as reverberation chambers. However, good reverberant properties at a specified frequency of operation require a minimum chamber size. Room-sized reverberation chambers (e.g., volumes between 75 m³ to 100 m³) are typically operated from 200 MHz to 18 GHz without limitations. Operation below 200 MHz requires chambers that are larger than the typical shielded room.

6 Applications

6.1 Radiated immunity

The use of reverberation chambers for performing radiated immunity testing is covered in Annex D. This annex covers test set-up, chamber validation, and test procedures. Injecting a predetermined level of RF power into the chamber generates the desired field strength within the chamber. This predetermined level of RF power is derived from chamber validation data described in Annexes B and C.

6.2 Radiated emissions

The use of reverberation chambers to measure radiated emissions is covered in Annex E. The described method measures the amount of RF power radiated by the EUT within the measurement bandwidth. As with radiated immunity testing, chamber validation data described in Annexes B and C are used to determine radiated emissions levels.

6.3 Shielding (screening) effectiveness

Three annexes are devoted to performing screening effectiveness measurements. Screening effectiveness measurements of cable assemblies, cables, connectors, waveguides and passive microwave components are described in Annex F. Annex G covers screening effectiveness of gaskets and materials. The approach outlined in Annex G uses a nested chamber methodology (e.g., a reverberation chamber located inside a larger reverberation chamber). Annex G also covers validation of test fixtures that are usually necessary for conducting screening effectiveness measurements on gaskets and materials. Minor differences in test fixture design/ construction can have significant influence on test results. Fixture materials, bolt spacing, surface finishes, torque settings, etc. shall all be controlled in order to get repeatable results. Due to the large number of variations that would be needed in order to accommodate the many different gaskets and materials that require evaluation, this annex does not contain detailed design guidance for test fixtures. Annex H covers screening effectiveness measurements of enclosures. As in Annex G, the methodology described in Annex H uses the “nested chamber” approach.

7 Test equipment

The following types of test equipment are recommended:

- Reverberation chamber: having a size that is adequate to maintain a multi-mode electromagnetic environment with respect to the lowest test frequency. This implies that the chamber dimensions in all directions shall be large compared to the wavelength;
- Mechanical tuner(s)/stirrer(s) (see Annex A): having one dimension that is at least one-quarter wavelength at the lowest frequency. Each tuner/stirrer should also be as large as possible with respect to the overall chamber size in that one dimension and should be at least three-quarters of the smallest chamber dimension. In addition, each tuner/stirrer should be shaped asymmetrically, i.e., such that a non-repetitive field pattern is obtained over one revolution of the tuner/stirrer;
- Field generating antennas (see Annex B): log periodic or other well-matched antenna capable of satisfying frequency and power requirements and avoiding direct illumination of the test volume;
- Field strength reference antennas (see Annex B): log periodic or other linearly polarized well-matched antenna system capable of satisfying frequency requirements;

- Isotropic field strength monitoring probe (see Annex B): capable of monitoring the electric field along all three orthogonal axes. Any probe-head circuitry and opto-electronics shall have adequate immunity to the field strength to be measured and a fibre-optic link to the indicator outside the chamber. An adequately filtered line may also be used;

NOTE 1 Reverberation chambers require a field probe that allows the electric field to be measured individually along all three orthogonal axes. If a small single-axis antenna is used then it should be repositioned to measure each field component separately in different directions.

- Field strength monitoring antenna that is a small (calibrated) dipole antenna (i.e., less than $0,1 \lambda$) may be substituted for the probe, provided that the antenna is positioned at three non-coplanar orientations (mutually perpendicular preferred) for each measurement location. Care should be taken to maintain the balance of this antenna with respect to its feed cable;
- EMI filters: care should be taken to ensure that the filters introduce no additional resonance effects on the connected lines;
- RF signal generator(s) capable of covering the frequency band of interest and which, if used for immunity testing, can be amplitude modulated by a 1 kHz sine-wave to 80 % depth. They shall have either an automated sweep capability or, in the case of RF synthesizers, be capable of being programmed with frequency-dependent stepsizes and dwell times. They shall also be capable of being set manually;

NOTE 2 Product committees may select alternative modulation schemes.

The use of low-pass or band-pass filters may be necessary to avoid problems caused by harmonics to equipment which is intended to receive signals for monitoring purposes;

- Power amplifiers: for amplifying a signal (unmodulated and modulated) and provide antenna power to the necessary field level. The harmonics and distortion produced by the power amplifier shall be at a level less than or equal to 15 dB below carrier level;

WARNING – High reflections are present in reverberation chamber tests, amplifier protection may be required against impedance mismatch.

- Associated equipment to record the power levels necessary for the determination of emission limits or field strength, and to control the generation of that level for testing. A directional coupler can be used to monitor the forward power.

NOTE 3 Any specification of the type of receiver to be used (e.g., EMI receiver specified in CISPR) should be determined by the relevant product committee.

Care shall be taken to ensure adequate immunity of the auxiliary equipment.

8 Chamber validation

Following the initial construction of the chamber or after any major modification, a performance-based field uniformity validation technique to demonstrate adequate reverberation chamber performance is carried out in accordance with Annex B. The procedure can be used to determine the lowest useable frequency (LUF) of the chamber employed. The chamber field uniformity validation procedure is carried out over a test/working volume, which includes the location of the test bench and equipment under test (EUT) inside the reverberation chamber. The chamber validation addresses only mode-tuned (i.e., stepped tuner rotation) operation of the chamber, whereas mode-stirred (continuous tuner rotation) operation is addressed separately in Annex C. The field uniformity measurement should be carried out with all support equipment (including the test bench) removed from the chamber. The validation is to be carried out at 8 sufficiently widely separated locations for 3 mutually orthogonal axes (x, y, z) at each test location, i.e., 24 measurement values in total per frequency (B.1.2). The field within the chamber is considered uniform if the standard deviation is within 3 dB above 400 MHz, 4 dB at 100 MHz decreasing linearly to 3 dB at 400 MHz, and within 4 dB below 100 MHz.

The validation technique requires the use of linear/passive field monitoring antennas during EUT testing. The antennas are calibrated against a three-axis *E*-field sensor (calibrated in an anechoic environment, e.g., in accordance with Annex I of IEC 61000-4-3, valid for chamber

validation). The purpose of this aspect of the procedure is to allow continuous monitoring of the field during the test with an antenna and associated monitoring equipment with a fast response time.

NOTE 1 The dynamic range across which a field probe should exhibit a linear response is significantly larger in a reverberation chamber than in other test facilities. This is due to the resonant nature of its interior field, which causes large variations of the field strength at any point inside the working volume as a function of rotation angle of the tuner/stirrer, typically by 30 dB or more.

NOTE 2 The linearity of the probe which is used for the chamber validation shall be within $\pm 0,5$ dB from an ideal linear response in a range of (–6 dB, +10 dB) relative to the average field strength. The asymmetry of this interval is due to the corresponding asymmetry of the probability density function of the field strength inside a reverberation chamber, which favours higher field strengths. For field monitoring during immunity testing, this range applies with respect to the average value of the maximum field strength.

WARNING A particular issue in the use of field probes is the susceptibility of the attached control electronics of the probe (meter unit) to local field strength inside the reverberation chamber. High values of the local field strength may cause malfunction or inaccurately measured values by the probe. This requires the calibration of the probe to be performed by exposing the entire meter unit of the probe (not just its sensor elements) to the expected maximum field strength in the chamber during chamber validation and/or testing.

In addition, a check on the impact of chamber loading on field uniformity is performed (B.1.6) to determine the maximum acceptable loading of the chamber for future testing.

Prior to the start of each test with the test bench and EUT installed in the chamber, the following procedure is carried out.

- A “quick check” chamber performance measurement is made with the equipment to be tested and test bench installed in the chamber (Clause B.2). The purpose of this test is to confirm that the loading of the chamber is less than that during the initial chamber validation.
- Calculations based on the validation measurements are used to determine the minimum pulse width (Clause B.3) that can be sustained in a given chamber for pulse modulation testing.

NOTE 3 The chamber validation detailed in Clause B.1 need only be undertaken after initial chamber construction, and after major modification to the reverberation chamber. The maximum chamber loading verification (subclauses A.5.4, B.1.5) need only be undertaken after initial chamber construction or after major modifications to the reverberation chamber. Changes to the tuners/stirrers are considered major modifications if the changes result in a reduction of the tuner efficiency as outlined in Clause A.3.

9 Testing

The test set-up and procedures are dependent upon the type of test being performed. Refer to the annex that pertains to the type of test being performed to determine the test requirements for a specific test.

Refer to the annex that pertains to the type of test methodology desired (i.e., mode-tuned or mode-stirred). For guidance on applicability of mode-tuning versus mode-stirring, refer to Annexes A and C.

10 Test results, test report and test conditions

Tests shall be performed according to a test plan, which shall be included in the test report.

Test results and reporting requirements are dependent upon the type of test being performed. Refer to the annex that pertains to the type of test being performed to determine what needs to be included in the test report.

Unless otherwise stated in the test plan, tests shall be carried out in standard climatic conditions in accordance with IEC 60068-1.

NOTE The generation of high field strengths may give rise to significant local heating effects or arcing in extreme cases.

Annex A (informative)

Reverberation chamber overview

A.1 Preliminary remarks

A.1.1 General

Research on electromagnetic reverberation chambers has been performed for more than 50 years [1 to 5]⁴ (see [6 to 8] for reviews) and has provided a better understanding of the methods of operation and analysis [8 to 11]. While the initial focus of this research was on measuring electromagnetic absorption of materials [1 to 3], the scope has expanded to include radiated emissions [4, 30], susceptibility testing of electronic equipment [5, 30], immunity testing, and the shielding effectiveness of cables, connectors and enclosures [31]. Reverberation chambers can also be used for characterisation of certain antenna and propagation parameters.

A.1.2 Chamber size, shape, construction and operation

A reverberation chamber is an electrically large, highly conductive cavity or chamber, furnished with a mechanism for altering (stirring) its modes, to perform electromagnetic (EM) measurements (both emissions and immunity) on electronic equipment. Any facility that fits this description can be considered a reverberation chamber (also called a mode-stirred chamber or mode-tuned/mode-stirred reverberation chamber or stirred-mode cavity). However, other conditions may need to be fulfilled before such a facility can be used with acceptable low uncertainty.

In general, a reverberation chamber is a shielding enclosure whose smallest dimension is large with respect to the wavelength at the lowest useable frequency (LUF, see A.1.3). It shall also be sufficiently large to accommodate the equipment under test, the stirrers and the measurement antennas. The chamber is normally equipped with a mechanical tuning/stirring device, whose dimensions are significant fractions of the chamber dimensions and of the wavelength at the LUF (see A.1.4). When the chamber is excited with RF energy, the resulting multi-mode electromagnetic environment can be “stirred” by the mechanical tuner/stirrer. The resulting field is statistically uniform, statistically isotropic (i.e., the energy having arrived from all aspect angles) and statistically randomly polarised (i.e., with all possible directions of polarisation) when averaged over a sufficient number of positions of the tuner/stirrer. By “sufficient number” is meant the number of tuner steps that is required to yield the specified field uniformity.

It is not practical to define a minimum size test chamber and it is outside the scope of this standard to provide detailed design guidance. The critical factor is that if a chamber fulfils the validation procedure (see B.1.2) then this demonstrates that it provides the required electromagnetic environment at the desired level of statistical confidence.

All power measurements are normally taken relative to the antenna terminals. Hence the chamber input power (P_{Input}) is taken to be the forward power delivered at the antenna terminals. In some cases it is necessary to take into account the reflected power caused by antenna/excitation-induced mismatch. In such cases the input power shall be the net input power, which is equal to (in linear units, e.g. W):

$$P_{\text{Net}} = P_{\text{Forward}} - P_{\text{Reflected}} \quad (\text{A.1})$$

⁴ Figures in brackets refer to Clause A.6, Reference documents, at the end of this annex.

A.1.3 Lowest usable frequency (LUF)

The chamber size, shape, quality factor, and the effectiveness of the mechanical tuner/stirrer determine the LUF. The LUF is generally defined as the frequency at which the chamber meets operational requirements. In practice, for the criteria set out in this standard, this typically occurs at a frequency slightly above three times the first chamber resonance. For the procedure described in this standard, the LUF is the lowest frequency at which the specified field uniformity can be achieved over a volume enclosed by eight corner locations.

A.1.4 Chamber quality (Q-) factor

The quality factor is a measure for the ability of a chamber or cavity to store energy relative to its rate of dissipation. The ability of a chamber to store energy is determined by the frequency, volume (and, to a lesser extent, shape), and electromagnetic losses present in the chamber. The dominant loss mechanism in an empty chamber (i.e., without EUT in place) is due to the chamber walls and the antennas. Other losses may occur as a result of leakage through unintentional apertures or intentional loading. The higher the conductivity of the materials used to construct the chamber walls and the smaller the apertures, the lower the chamber losses. Materials such as silver, copper and aluminium sheet offer the highest conductivity and therefore the lowest ohmic losses. Other materials such as bare or painted steel or galvanised sheet are also common. For miniature microwave cavities, superconducting materials at low temperatures may be considered if exceptionally high Q values are desired.

Copper and aluminium screen and flame spray, however, have large surface areas and do not result in high Q environments. Additional losses such as antennas, support structures, and the equipment under test (EUT) can also affect the overall Q of the chamber.

The contribution by ohmic losses in an antenna is often sufficiently small to be negligible, as in this clause (see also Annex I). The power needed to generate a specific field inside a chamber can be determined from the empty chamber validation procedure outlined in Annex B. However, the EUT, the required support equipment, or any absorbing material present may load the chamber, reduce the chamber Q, and hence reduce the test fields for the same input power. Therefore, the fields in a loaded chamber shall be monitored and input power shall be increased where necessary, in order to compensate for this loading as described in Clause B.2 (7).

A.1.5 Tuner/stirrer considerations

Techniques exist, other than using mechanical tuners/stirrers that can also achieve a statistically uniform and statistically isotropic environment. Examples include flexible walls or moving boundaries, moving transmitting or receiving antennas or EUT, and changing the frequency over some bandwidth (single-tone frequency variation (scanning) or band-limited noise excitation), or a combination of these. While these techniques may produce a valid test, this standard assumes that the chamber is configured with at least one rotating tuner/stirrer. Some of these alternative methods of stirring may not be applicable to certain EMC tests, e.g. frequency stirring cannot be used in emissions testing. The combined use of different stirring techniques (so-called hybrid stirring) may assist in achieving lower uncertainties in a given chamber, or allowing for smaller chambers for a given uncertainty level.

The tuners/stirrers should be adequate to provide the desired field uniformity. Symmetries in the design and placement of the stirrer should be avoided, to maximize the maximum number of independent positions that it can generate. A method of evaluating tuner/stirrer performance is given in Clause A.3.

In some chambers, it may be necessary to use multiple tuners/stirrers to obtain the desired field uniformity at the required frequencies.

Stepping motors or encoder-equipped servo-motors with computer control are recommended. Variable-speed continuous motors with belt-drive mechanism are acceptable, but the time

response of the EUT shall be fast relative to tuner/stirrer speed for this option to be viable and positioning of the position of the paddle wheel may be less accurate or repeatable. A check on possible EMI by the motor should be conducted during commissioning of the chamber.

In the past, testing was performed using a fixed number of samples or tuner steps (typically 200) at all frequencies of interest [5]. This resulted in uncertainties (i.e., statistical inhomogeneity and anisotropy) of the field that varied as a function of frequency due to the increase in modal density (see A.2.1) at the higher frequencies. As shown in Figure A.1, the uncertainty for a typical chamber varied considerably as a function of frequency in this case.

In this standard, the procedure optimises the number of steps or samples to obtain a given level of uncertainty (i.e., standard deviation of the field uniformity, here specified in terms of the measured maximum field) as a function of frequency. This allows for the number of samples to be decreased with increasing frequency. The procedure provides an accurate and economical method for validating reverberation chambers. It allows for an operator to adjust the number of tuner steps generated to obtain the desired level uncertainty as well as to maximize the ability of the chamber to generate higher fields by increasing the number of tuner steps as far as possible.

A.1.6 General remarks on chamber validation

The validation procedure places a stringent requirement on the time- (i.e., ensemble-) averaged fields [9, 10, 16] generated within the test volume to be uniform, to within a specified uncertainty. To ensure this, three measurements are required at each one of eight locations for three mutually perpendicular orientations. Each measurement is independent, which results in a total of 24 measurements per frequency. A chamber that passes the validation procedure will have demonstrated its ability to generate the required field uniformity within the accepted uncertainty level.

A.1.7 Cable lay-out

As a general rule, for cables connected to an EUT, test results are insensitive to cable layout, because of the statistical field homogeneity. Specific guidance on cable layout, where necessary, is provided in the relevant annexes.

A.2 Cavity theory

A.2.1 Cavity modes, mode density and Q-bandwidth

A cavity mode (also known as eigenmode or natural mode), as defined in 3.1.12, is a particular field distribution generated by standing waves. The modes in a cavity are governed by the boundary conditions (shape and size of the cavity and mode stirrer). For an ideal, lossless, empty, closed rectangular cavity of dimensions L (length), W (width), and H (height), the modal or resonance frequencies $F_{l,m,n}$, in MHz, can be shown to be

$$F_{l,m,n} = 150 ((l/L)^2 + (m/W)^2 + (n/H)^2)^{0.5} \quad (\text{A.2})$$

where

l , m , and n are the mode indices (at least two of which are nonzero), and

L , W , and H are the chamber dimensions (in m).

Figure A.2 shows the theoretical mode distribution as a function of frequency for a 10,8 m × 5,2 m × 3,9 m ($L \times W \times H$) rectangular chamber. Each mode represents a unique spatial field variation (modal structure) as a function of location throughout the cavity. The lowest resonance frequency of this chamber ($F_{1,1,0}$) occurs at 32,096 MHz. Any losses tend to marginally decrease the resonance frequencies. Each mode has its own modal Q-factor $Q_{l,m,n}$. The modal Q values increase approximately with the square root of frequency. An

“effective” Q of an overmoded cavity can be defined as a weighted average over the excited modes [28]. The quality factor bandwidth, BW_Q , of the cavity is defined as $F_{l,m,n}/Q$ at the 3 dB points of a second order resonance characteristic. A representative BW_Q is shown at $F_{4,2,2}$ (the 60th mode) in Figure A.3. In this case, only a few modes are excited when the cavity is driven by a CW source at $F_{4,2,2}$.

Figure A.4 shows the effect of decreasing the Q of the cavity (see A.1.3 and A.5.7). In this case, additional modes can be excited when the cavity is driven at the frequency of the 60th mode because of modal overlap due to lower Q and smaller frequency spacing. The effective modal structure is the vector sum of the excited modes weighted with different amplitudes. The spatial field variation will now be different from that obtained with the higher Q cavity. Thus, varying the cavity Q can change the “effective” modal structure. Note that if the frequency were increased, more modes would be available within a given BW_Q , giving rise to a finer structure of the field. Again, the effective modal structure would be the vector sum of the modes.

Figures A.3 and A.4 show that, at the lower frequencies, the modal population of a chamber is sparse and it is with frequency gaps of different size (spectrally non-uniform). The figures also show that as frequency is increased the number and density of the modes increases on average (proportionally to f^3 and f^2 , respectively). The effective modal structure combined with the ability of the tuner to change the boundary conditions of the chamber determines how well a reverberation chamber will perform.

NOTE A chamber may have an arbitrary geometry. However, some shapes such as spherical and circular cylindrical ones are normally not used for reverberation chambers, because the curved surfaces can produce caustics (focusing of rays) that make it difficult to obtain spatial field uniformity, unless they are furnished with diffractors of sufficiently large size relative to the wavelength [12, 13] or if the focal region is avoided.

The effective modal structure depends on both the mode density and the quality factor bandwidth at the frequency of interest. The mode density at frequency f is $m = 8\pi Vf^2/c^3$. To first order in frequency, the value of m is independent of the shape of the cavity [11]. However, second-order corrections that depend on the curvature of surfaces and on the length of edges and joints [12] may become significant at lower frequencies. The number of modes, M , excited within the BW_Q at f can be estimated as

$$M = m \times BW_Q = \frac{8\pi Vf^3}{c^3 Q} \quad (\text{A.3})$$

where

f is the frequency (in Hz),

c is the speed of light in free space, approximately 3×10^8 m/s,

V is the cavity volume (in m³), and

Q is the quality factor (dimensionless) at f .

More generally, the number of modes within a receiver bandwidth Δf for a wideband non-CW (e.g., pulsed) excitation signal can be estimated as $m\Delta f$, where $\Delta f \geq BW_Q$.

A.2.2 Ideal versus imperfect chamber performance – Effect on field uncertainty

Theory suggests that an “overmoded” condition exists when a sufficiently large number of modes are excited. In ideal overmoded condition and subject to a sufficiently efficient stirring process, the power distribution at any location fits a chi squared (χ^2) distribution and the field strength fits a chi (χ) distribution [10, 11, 23]. Both distributions are notably asymmetric around their mean value (heavy right-tailed). At lower (finite) mode densities, i.e., at lower frequencies, the distribution of received power does no longer fit a χ^2 distribution but instead a more complicated distribution [14, 15]. Also, different distributions and statistics apply to fields close to a conducting boundary, relevant to floor-standing or wall-mounted devices [16].

to 18], or for empirical sampling distributions when the number of generated tuner positions n (see Clause A.3) is relatively small, typically when $n < 30$ [27]. These differences in field distributions increase the uncertainty and width of confidence intervals of the measured field. They also affect the mean maximum or minimum field strength and its confidence intervals.

A.3 Assessment of tuner efficiency

In order to apply statistics to data obtained from a reverberation chamber, the number of independent samples shall be known. For a given frequency, a tuner (or multiple tuners) shall alter the boundary conditions sufficiently to effect a statistically significant change in the field pattern of the chamber. Once such a change has occurred in the field structure, any samples obtained from the fields resulting from the new tuner position are said to be statistically independent from those of the previous tuner position. Tuner performance data shall be obtained in order to determine the number of statistically independent samples that a given tuner (or tuners) can provide at a desired frequency. Tuner performance data is obtained by recording the received power at n evenly spaced angular intervals over one tuner rotation. The tuner performance can then be estimated by calculating the correlation coefficient between tuner steps [20]. The correlation coefficients for multiples of a unit tuner step combine to the autocorrelation function with respect to tuner step size. A typical correlation coefficient calculation involves consecutively shifting the data vector x by one sample for each tuner step to produce y as shown below, assuming a total set of 450 samples:

D1, D2, D3, D4, D5, D6, ... , D450

D450, D1, D2, D3, D4, D5, D6, ... , D449

D449, D450, D1, D2, D3, D4, D5, D6, ... , D448

D448, D449, D450, D1, D2, D3, D4, D5, D6, ... , D447

The correlation coefficient r can then be calculated using the following formula:

$$r = \frac{\frac{1}{n-1} \sum_i^n (x_i - u_x)(y_i - u_y)}{\sqrt{\left(\frac{\sum_i^n (x_i - u_x)^2}{n-1} \right) \left(\frac{\sum_i^n (y_i - u_y)^2}{n-1} \right)}} \quad (\text{A.4})$$

$\uparrow \qquad \qquad \qquad \uparrow$
 $\sigma_x^2 \qquad \qquad \qquad \sigma_y^2$

in which y_i is the same as x_i but shifted by one sample for each tuner step, and n is the number of samples taken over one tuner rotation.

NOTE 1

- x_i and y_i are received power values. Using field strength or in-phase or quadrature field values instead of power will typically give similar, but slightly different values of r .
- u_x and u_y are the mean of the original received power versus tuner position data set.

Since the distribution for y is the same as for x , it follows that

$$u_y = u_x \text{ and } \sigma_x = \sigma_y$$

The correlation coefficient r can be calculated using the correlation function built into most spreadsheets based on the original data set and the shifted data set. By convention, in this standard the data are regarded as uncorrelated when the magnitude of the correlation

coefficient for increasing shifts drops below and remains less than the value $1/e \approx 0,37$. Other criteria or threshold values are sometimes used in other applications. Due to the statistical nature of the correlation coefficient, this threshold value is only valid in the case of infinite n . For any given finite n and confidence level, the limit has to be lowered [21]. For example, for 95 % confidence and values of n not less than 100, the threshold of the correlation coefficient can be approximated by the equation

$$r \approx 0,37 \cdot \left(1 - \frac{7,22}{n^{0,64}} \right) \quad (\text{A.5})$$

Dividing the total number of samples across one full rotation (e.g., 450 above) by the number of steps necessary to reduce the correlation coefficient to less than 0,37 (so-called decimation) yields an estimate of the number of independent samples the tuner can provide at a particular frequency.

EXAMPLE Carry out the above procedure for a chamber by rotating the mechanical tuner over 360° in 450 evenly spaced steps at 80 MHz, 100 MHz, and 500 MHz. If r becomes less than $0,37 \times (1 - 7,22/450^{0,64}) = 0,32$ after 25, 15, and 5 steps of the tuner, respectively, then the tuner can be expected to deliver 18 independent samples at 80 MHz, 30 independent samples at 100 MHz, and 90 independent samples at 500 MHz. As shown in Clause A.4, the number of tuner steps required may exceed the ability of a single tuner to provide these. In these cases, a second tuner will be necessary, but this is not necessarily sufficient.

NOTE 2 Equation (A.5) has been obtained from curve fitting to numerical data [21].

NOTE 3 The procedure described above implies the use of equidistant tuner positions. This is known to work well for sufficiently high frequencies and for one tuner. For more than one tuner, equidistant tuner positions cannot be defined. Near the chamber LUF, symmetries of the tuner might become relevant. In that case, equidistant tuner positions are not guaranteed to be uncorrelated and a set of tuner positions has to be determined where each pair correlation is less than the limit given above. This procedure is also applicable in the case of more than one tuner. Details of the procedure are under consideration. For non-equidistant tuner positions at low frequencies, the actual positions that yield statistical independence may be dependent on the location and orientation of the antennas and, during testing, on the size and location of the EUT.

A.4 Reverberation chamber statistics

A.4.1 Field fluctuations

For the following discussion, it is assumed that the chamber dimensions are large compared to the excitation wavelength (the chamber is overmoded) and that the chamber has a complex geometry. The introduction of antennas and efficient tuners assures complexity in an otherwise regular cavity.

The validation procedure for this standard is based on the statistical nature of fields in complex cavities. It has been experimentally validated that the fluctuating fields in a reverberation chamber can be theoretically modelled using the appropriate statistical distributions, e.g., [9, 10, 14, 15 et 18] for (1) the received power by an antenna which is related to the chamber scalar power density and to the electric field squared (field intensity), (2) the maximum received power or the maximum electric field squared, (3) a rectangular component of the electric field, and (4) the maximum of a rectangular component of the electric field. These four distributions are different but related. Distributions for their sample averages, standard deviations, and maximum values [19], as well as for small sets of independent samples [27] are also available. Impedance mismatch and other measurement-related issues further affect the field statistics [19]. Some specific properties of some of the distributions will be discussed below.

The function of a reverberation chamber is to generate a statistically uniform (i.e., statistically isotropic, homogeneous and uniformly polarized) test environment within acceptable uncertainty and confidence limits. This is accomplished by a mechanical tuner, which is used to redistribute (diffuse) the field energy. The tuner changes the boundary conditions within the

chamber when it is moved or rotated. Once the tuner has been moved to a sufficient number of independent positions, the field variations resulting from rotating the tuner provide a set of field values involving many directions of propagation and polarization. At any location, the local field shows large and irregular fluctuations during rotation due to varying levels of constructive or destructive interference of reflected waves (phasors) from different spatial directions of incidence and polarization at this location. The magnitude and directionality of the fields is on average the same, within bounded uncertainty limits, for all points within the chamber. The terms “isotropic” and “homogeneous” are often used to refer to the environment generated by a reverberation chamber. This term is somewhat misleading since the field or energy in the environment does not exhibit equal magnitude from all directions and polarizations simultaneously, nor is the energy density equal at all locations simultaneously, hence the adjective “statistical”.

We restrict our discussion to the fields within the working volume of the chamber. The working volume is defined by points or imaginary surfaces at a distance of $\lambda/4$ away from the chamber walls and from any antenna, tuner or other conducting object, at the lowest frequency of operation. For a chamber operating above 100 MHz, the distance is 0,75 m. A typical reverberation chamber facility is shown in Figure A.5.

A.4.2 Required number of independent samples

Given the distribution of the fields within a cavity, the number of samples that has to be taken in order to determine the level of uncertainty for the field can be determined. Figure A.6 shows a theoretical prediction for the number of independent samples (boundary condition changes or steps of the mechanical tuners) required to obtain a 6 dB field uncertainty at a 95 % level of confidence, for a specific cavity with dimensions as indicated in the figure. As Figure A.6 shows, at a lower mode count M , as defined by Equation (A.3), the required number of independent samples increases rapidly with decreasing frequency. In this calculation, the field is undermoded and no longer obeys an ideal chi distribution, but a more complicated distribution [15], [27], governed by an additional parameter that depends on the maximum achievable number of an independent tuner position at the chosen frequency of operation, which in turn depends on the shape and size of the chamber. If the confidence level is lowered, then the number of samples required to obtain the same level of uncertainty is reduced. In practice, a mechanical tuner may not be capable of providing the number of independent samples required to yield the desired performance within a given cavity. For this reason, tuner performance should be evaluated as detailed in Clause A.3 to determine the number of samples that can be provided in a given cavity at a given frequency.

A.4.3 Effect of tuner on the mean field

For an ideal reverberation chamber, the volumetric (i.e., spatial) mean value of the field for a fixed boundary condition and the “ensemble” average, are equivalent [9, 10, 16]. An ensemble average is the average of the field at a fixed location for multiple boundary conditions. Boundary condition changes are typically achieved by rotating a mechanical tuner, but can also occur from changes in the configuration of objects such as antennas, test devices, and supporting instrumentation and equipment.

Figure A.7 shows the probability density function (PDF) of the field at a location within an ideal reverberation chamber normalised by the “true” volume or ensemble average (expected value). As shown in this figure, the field in the chamber at an arbitrary location for a fixed single boundary condition or at a fixed single location and arbitrary boundary condition (tuner position) ($N = 1$) can vary by more than 30 dB.

Figure A.8 shows that, as the number of independent boundary conditions (tuner steps) is increased, the measured mean of the chamber field at any given location in the chamber converges toward the “true” ensemble mean value. The measured mean value is the “expected value” of multiple samples. The width of each curve is a measure of the spread of field values (uncertainty interval) that can be expected at an arbitrary location in the working volume for N samples. The uncertainty of the mean field decreases as $1/\sqrt{N}$ [19]. Figure A.8 also shows that for 12 tuner steps the uncertainty of the mean field is about 5 dB at 100 MHz.

confidence interval and about 2,4 dB for 100 tuner steps. This would correspond to an eight-fold increase in test time for a 2,6 dB reduction in uncertainty of the mean field level.

A.4.4 Effect of tuner on the maximum chamber field

The distribution for $N = 1$ shown in Figure A.7 is valid for both mean and maximum fields, because the maximum, minimum and mean measured at a location are all the same value, for a fixed position of the tuner. The PDF for the maximum field at an arbitrary location within a chamber is shown in Figure A.9. As N increases, the distribution moves to the right and gets narrower (improved uncertainty). The reduction in uncertainty for the maximum field level is initially very rapid as the number of tuner steps is increased and then slows as N becomes larger.

Figure A.9 shows that for 12 tuner steps the uncertainty of the maximum field is about 7,2 dB at the 95 % confidence interval and about 4,8 dB for 100 tuner steps. This would correspond to an eight-fold increase in test time for a 2,4 dB reduction in uncertainty in the maximum field level. Generally, the width of the uncertainty interval for the mean-normalised maximum or minimum value decreases more slowly than $1/\sqrt{N}$ [19]. Also, increasing the number of tuner steps from 12 to 100 steps increases the expected value of the maximum field by about 3 dB.

Since the PDF for the maximum field applies at any arbitrary location, as it does with the mean field, the PDF is also a measure of the spatial uniformity for N samples of the maximum field over the working volume of the chamber. With the aid of the field statistics, a measurement of the mean field strength at one location allows to estimate the maximum field strength at any other location inside the working volume. However it does not allow to predict at which particular tuner position this maximum value will be reached. This tuner position is different for each spatial location.

A.5 Chamber validation

A.5.1 General

The purpose of the validation is to verify that the fields generated have the same magnitude, within a defined uncertainty interval, for all polarizations and for all directions of arrival at all locations within the working volume, for a given number of tuner steps. In order to meet this requirement the use of isotropic probes, which allow access to each axis of the probe, is required in order to perform the validation. A calibrated electrically short dipole antenna may be substituted (see Clause B.1). The validation procedure should be performed when commissioning the chamber and after major modifications.

The empty chamber validation procedure is based on a comparison of the peak fields measured by E -field probes to the mean received power of a reference antenna. To enhance accuracy, the reference antenna mean data is obtained for eight locations within the working volume. Even then, the effect of the limited number of locations on the uncertainty can be substantial for small N . An estimate of the uncertainty of the field uniformity level of the chamber (but for rectangular field components only) is calculated in [19].

The number of samples recommended for validation is based on a “theoretical” chamber of approximately 3 m × 7 m × 15 m size and typical Q for a chamber constructed of welded steel. The number of samples required was rounded up to account for variations from this “theoretical” chamber in order to ensure a conservative test. It is possible that a larger chamber or one with a lower Q than the “theoretical” chamber could meet this validation requirement using less than the recommended number of steps.

A.5.2 Validation procedure

The validation procedure collects E -field probe data (maximum data only), as well as chamber input power and the maximum and mean received power from a reference antenna placed within the working volume. The probe data are used to determine field uniformity. The

chamber input power and probe data are used to determine the chamber validation factor (CVF). The mean received power from the reference antenna and chamber input power are used to calculate the antenna validation factor (AVF). The AVF is used as a reference value when determining if the chamber has been significantly “loaded” by equipment under test (EUT). The maximum received power from the reference antenna is used to verify the probe readings. Probe data are collected from the eight locations that form the corners of the “volume of uniform field” or “working volume” as shown in Figure A.10. Each time the probe is moved to a new location, the reference antenna is moved to a new location within the working volume. The orientation of the reference antenna relative to the chamber axes is also changed by at least 20° relative to each axis at each position. This ensures that any bias in the polarization of the local field is detected. A minimum of eight locations for both the probe and reference antenna is required.

Table B.1 lists the number of tuner steps recommended for performing the validation. The number of steps may need to be decreased or increased to optimise performance. The minimum number of tuner steps shall be at least 12.

NOTE 1 Once a chamber has been shown to operate properly over a frequency span of 300 MHz to 400 MHz at the minimum number of tuner steps (i.e., 12), the number of locations may be reduced to three. For the chamber used to collect the data presented in this annex, the reduction in the number of locations occurred at 1 000 MHz.

Every chamber will have a frequency below which it is no longer overmoded [5, 10, 14] and hence can then no longer be used as a reverberation chamber. This frequency will mostly depend on chamber size, and the cut-off will be gradual rather than abrupt as frequency decreases. Chamber loading by an EUT or by a conducting or lossy artefact may also reduce the LUF (see A.5.4).

NOTE 2 In some cases, it is possible to compensate for decreased modal density that results as the operational frequency approaches the “undermoded” condition. In general and with care, compensation can be achieved by increasing the number of tuner steps, but effects may be limited and specific to a configuration.

A.5.3 Field uniformity

The goal of a reverberation chamber is to generate a statistically uniform environment for all locations within the defined working volume. The procedure just described is designed to measure the expected magnitude and uniformity for a given chamber using a given number of tuner steps. A typical set of probe data obtained using the validation procedure (x-axis data only, for clarity) is shown in Figure A.11. Figure A.12 shows the data of Figure A.11 normalized to the mean of the eight maximum x-axis probe readings at each frequency (B.1.2 (10) (a)). The data show that the measured field uniformity is about ± 10 dB at 100 MHz and decreases as frequency increases. Also, note that data at higher frequencies show good uniformity even though the number of tuner steps is decreased.

NOTE 1 The number of steps used to collect the data shown in Figure A.12 was set prior to determining the values in Table B.1. This explains the revision of 20 steps to 18 steps and 16 steps to 18 steps.

At present, there are two schools of thought as to which is the best method to determine acceptable uniformity. For the first method [29], acceptable uniformity is decided by throwing away 25 % of the data that have the most variation and then requiring the remaining data to be within a given limit. In the second method [30, 31], acceptable uniformity is determined by calculating the standard deviation of all the data and requiring that the standard deviation be within a given limit. The first method’s major drawback is that there is no “weight” given to the data that are thrown away. This could result in the uncertainties being essentially unknown. For the purposes of this standard, it has been agreed to use the standard deviation method, because all data are then considered and given appropriate weight.

The standard deviation of the data shown in Figure A.12 is shown in Figure A.13. The data show that in this case the standard deviation exceeded 3 dB below about 200 MHz. For example and by way of reference, the tolerance for the commercial aircraft avionics standard is also shown [30].

NOTE 2 The chamber is considered to pass the field uniformity requirements provided that the standard deviation for both the three individual field components (E_x , E_y , and E_z) and the total data set (E_{Total}) are within the specified tolerance. The total data set consists of the 24 measurements made by combining the three individual field components (E_x , E_y , and E_z) from the 8 probe locations. The chamber used to collect this data could not be used below 130 MHz, according to the limit in [30], unless the field uniformity is improved [25]. A committee made up of representatives from both industry and government developed the proposed limit.

NOTE 3 An exceptional allowance is made for increased field non-uniformity, that is to say, up to 4 dB between 100 MHz and 400 MHz, compared to 3 dB at any frequency above 400 MHz (see Figure A.13). This allowance was influenced by both the desire to have this IEC standard harmonized with other standards [29], as well as for economical reasons. Chamber dimensions drive the LUF. Often, the ceiling height of most facilities results in lower performance. The relaxed field uniformity values below 400 MHz allows for testing of very large EUTs (e.g., aircraft) in a reverberation chamber without a need for an excessively large chamber.

NOTE 4 The total data set is NOT the commonly used root sum of the squares (RSS) of E_x , E_y , and E_z [30].

A.5.4 Chamber E -field

The “expected” value of the amplitude of the chamber E -field during the validation is simply the arithmetic average of the 24 maximum probe readings (the mean of the maximums). The “expected value” is the value to which the chamber is calibrated (see Figure A.9).

It is also possible to estimate the chamber E -field (E_{Est}) based on the reference antenna measurements. Equation (A.6):

$$E_{Est} = \left\langle \frac{8\pi}{\lambda} \sqrt{5 \frac{P_{MaxRec}}{\eta_{rx}}} \right\rangle_n \quad (A.6)$$

was derived using methods similar to those used to derive expressions for the mean field [11] and gives an estimate of the chamber E -field (in V/m) based on the maximum readings from the reference antenna averaged over the number of antenna locations or orientations, where

- P_{MaxRec} is the maximum received power (in W) over the given number of tuner steps at an antenna location or orientation,
- η_{rx} is the antenna efficiency factor for the receive antenna which can be assumed (if not known) to be 0,75 for a log periodic antenna and 0,9 for a horn antenna. This parameter can be determined from the information contained in Annex I, and
- n is the number of antenna locations and orientations.

For all measurements, it is assumed that the forward input power is the same for all data collected. If so, then the data can be normalized after taking the average of the probe readings. If not, then the probe readings need to be equalized by normalizing to the value of the input power that corresponds to that probe reading. Normalizing the E -field to the chamber input power is done by dividing the probe reading by the square root of the input power. This can also be done for the estimated E -field based on a reference antenna.

It is recommended to perform a cross-check by comparing the average E -field measured by the probes to the estimated expected E -field based on the eight antenna measurements. Any discrepancies greater than ± 3 dB between the probe and antenna based measurements, should be resolved (see also Clause 8). Note that significant disagreement at the lower frequencies is expected due to loading caused by the transmitting and receiving antennas. For this reason, the agreement between the two methods is not expected at frequencies where the difference between the chamber input power and the measured maximum received power from the reference antenna is 10 dB or less.

A.5.5 Loading effects

When an EUT or other object is placed inside a reverberation chamber there is the possibility that the EUT will “load” the chamber. The energy absorbed by the EUT or other objects is

then no longer available to generate the desired environment. For this reason, the chamber input power needs to be increased to compensate for this loading. Any “loading” caused by reduction of the working volume (even when the EUT is non-absorbing) is limited by the requirement that the EUT and all supporting equipment shall not occupy more than 8 % of the total chamber volume (see Clause D.1).

NOTE 1 The source of the fields is actually the reflection of RF energy from the walls. Although an antenna is used to inject RF energy into the chamber, that energy is not directed at the EUT. If the EUT absorbs energy then that energy is no longer available to contribute to the generation of the test environment. The following data will demonstrate the concept.

Prior to performing any test, a check for loading effects shall be made. This is done by measuring the mean power received by the reference antenna for the same number of tuner steps used to perform the validation with the EUT in place. The data from this single measurement are then compared to the eight measurements from the validation. If the mean received power measured with the EUT in place does not lie within the acceptable range of the mean field measured during the validation (i.e., if it is significantly greater or smaller than the validation data), then the chamber is considered to have been loaded by the EUT. A correction factor will then be required when calculating the input power necessary to generate the desired test field. This factor is referred to as the “chamber loading factor” (CLF). The CLF is obtained by taking the ratio between a measurement taken with the EUT in place and the mean or “expected value” from the eight measurements taken during the validation, i.e., for the same configuration except for the EUT being removed [30].

To determine the limit to which a chamber may be loaded, an evaluation shall be performed to evaluate the field uniformity under severe loading conditions (B.1.6). An example of such an evaluation is shown in Figure A.14. The working volume of this reverberation chamber was loaded with 27 pieces of 122 cm pyramidal absorber. Figure A.15 shows the amount of loading induced into the chamber by the absorbers. The chamber loading, or the amount of loading, over the frequency range of 100 MHz to 18 GHz varied from a maximum of about 23 dB to a minimum of 10 dB with a mean loading of about 14 dB. Figure A.16 shows the standard deviation of the fields in the loaded chamber. The standard deviation of the loaded chamber, while varying slightly from the empty chamber validation shown in Figures A.12 and A.13, did not show significant degradation.

NOTE 2 The standard deviation increased (instead of decreased) by approximately 0,5 dB, most probably due to probe proximity to absorber, which causes the field magnitude to adopt a different distribution with larger uncertainty [14].

A.5.6 Generating a test field – Immunity

Injecting the proper amount of power into the chamber generates the desired test environment. The power necessary to generate the desired field strength can be calculated using Equation (A.7).

$$P_{\text{input}} = \left[\frac{E_{\text{Test}}}{\bar{E} \cdot \sqrt{\text{CLF}}} \right]^2 \quad (\text{A.7})$$

where

E_{Test} is the required field strength (in V/m),

CLF is the chamber loading factor (Clause B.2 (7)) (dimensionless), and

$\bar{E}$ is the average of the maximum E-field values measured by the respective probes divided by the square root of the input power used during validation (in (V/m)/W^{0.5}) (see B.1.2 (9)).

Note that the probe measurements used to determine the chamber E -field are the rectangular components of the probe, not the RSS.

A.5.7 Determining radiated power – Emissions

The amount of RF power radiated by a device placed in the chamber can be determined by measuring the amount of power received by the reference antenna and correcting for the insertion loss of the chamber [4]. The power radiated from a device can be calculated using either average or peak received power from a given number of tuner steps and/or tuner rotations. Equation (A.8) is used for mean-received-power-based measurements, while Equation (A.9) is used for peak-received-power-based measurements. The advantage of using measurements based on mean power is a lower uncertainty. The disadvantage is that the measurement system shall have a sensitivity that is 20 dB lower than the actual mean to get an accurate average measurement and intermittent signals may be artificially lowered due to insufficient sampling.

$$P_{\text{Radiated}} = \frac{P_{\text{AveRec}} \times \eta_{\text{Tx}}}{CVF} \quad (\text{A.8})$$

$$P_{\text{Radiated}} = \frac{P_{\text{MaxRec}} \times \eta_{\text{Tx}}}{CLF \times IL} \quad (\text{A.9})$$

where

P_{Radiated} is the radiated power (in W) from the device within the measurement band width,
 CVF is the chamber validation factor (dimensionless) (Clause B.2 (6)),
 CLF is the chamber loading factor (dimensionless) (Clause B.2 (7)),
 IL is the chamber insertion loss (dimensionless) (B.1.4),
 P_{AveRec} is the received power (in W) as measured by the reference antenna averaged over the number of tuner steps (B.1.2 (5)),
 P_{MaxRec} is the maximum power received (in W) over the number of tuner steps (B.1.2(5)), and
 η_{Tx} is the antenna efficiency factor (dimensionless) for the Tx antenna used in calibrating the chamber and can be assumed to be 0,75 for a log periodic antenna and 0,9 for a horn antenna.

NOTE CISPR 16-1-1 should be consulted when selecting detectors of measuring receivers.

A.5.8 Q-factor of the chamber for CW and pulse testing

The validation is based on using CW excitation. When using modulated waveforms, distortion caused by the chamber quality factor or “Q” shall be considered (Clause B.3). The chamber Q can be calculated using Equation (A.10):

$$Q = \left(\frac{16\pi^2 V}{\eta_{\text{Tx}} \eta_{\text{Rx}} \lambda^3} \right) \left\langle \frac{P_{\text{AveRec}}}{P_{\text{Input}}} \right\rangle_n \quad (\text{A.10})$$

where

η_{Tx} and η_{Rx} are the antenna efficiency factors (dimensionless) for the Tx and Rx antenna, respectively and can conservatively be assumed to be 0,75 for a log periodic antenna and 0,9 for a horn antenna,
 V is the chamber volume (in units m³),
 λ is the free space wavelength (in m) at the specific frequency,
 P_{AveRec} is the averaged received power (in units W) for the reference antenna,
 P_{Input} is the chamber input power (in W) [30], and
 n is the number of antenna locations and orientations used to collect the validation data at the frequency being evaluated.

For pulse testing the chamber time constant τ is given by Equation (A.11)

$$\tau = \frac{Q}{2\pi f} \quad (\text{A.11})$$

where

Q is the quality factor of the chamber, calculated using (A.10), and

f is the test frequency (in Hz).

The chamber time constant should not be greater than a fraction 0,4 of any test waveform pulse width. If it is, however, then absorber shall be added to the chamber or the pulse width should be increased. If absorber is used, add absorber until the time constant requirement is satisfied with the least possible amount of absorber. A new *CLF* shall be obtained if absorber is used. If the loading due to the absorber is greater than that obtained in the chamber loading verification (B.1.6), then the chamber validation shall be repeated.

A.6 Reference documents

- [1] BECKER, GE. and AUTLER, SH., Water vapor absorption of electromagnetic radiation in the centimeter wave-length range, *Phys. Rev.*, Sep. 1946, vol. 70 no. 5/6, pp. 300–307.
- [2] LAMB, WE. (Jr.), Theory of a microwave spectroscope, *Phys. Rev.*, Sep. 1946, vol. 70 nos. 5/6, pp. 308–317.
- [3] MEYER, E., HELBERG, H.-W., and VOGEL, S., Hallraummesstechnik und Bau eines grossen Hallraums für elektromagnetische Wellen, *Z. Angew. Physik*, Aug. 1960, vol. 12 no. 8, pp. 337–346.
- [4] CORONA, P., LATMIRAL, G., PAOLINI, E., and PICCIOLI, L., Use of a reverberating enclosure for measurements of radiated power in the microwave range, *IEEE Trans. EMC.*, vol. 18 no. 2, May 1976, pp. 54–59; Comments and corrections, *IEEE Trans. EMC*, vol. 18 no. 4, Nov. 1976, p. 205.
- [5] CRAWFORD, ML. and KOEPKE, GH., Design, evaluation, and use of a reverberation chamber for performing electromagnetic susceptibility/vulnerability measurements, National Bureau of Standards (US) Technical Note 1092, April 1986.
- [6] CORONA, P., LADBURY, J., and LATMIRAL, G., Reverberation-chamber research then and now: a review of early work and comparison with current understanding, *IEEE Trans. EMC*, Feb 2002, vol. 44 no. 1, pp. 87–94.
- [7] BÄCKSTRÖM, M., LUNDÉN O., and KILDAL, P.-S., Reverberation Chambers for EMC Susceptibility and Emission Analyses, *Review of Radio Science 1999-2002*, Chapter 18, Wiley-Interscience, Inc., New York, 2002.
- [8] ARNAUT, LR., On the maximum rate of fluctuation in mode-stirred reverberation, *IEEE Trans. EMC*, Nov. 2005, vol. 47 no. 4, pp. 781–804.
- [9] KOSTAS, J. G. and BOVERIE, B., Statistical model for a mode-stirred chamber, *IEEE Trans. EMC*, Nov. 1991, vol. 33 no. 4, pp. 366–370.
- [10] HILL, DA., Electromagnetic theory of reverberation chambers, National Institute of Standards and Technology (US) Technical Note 1506, Dec. 1998.

- [11] LADBURY, JM., KOEPKE GH., and Camell, DG., Evaluation of the NASA Langley research center mode-stirred chamber facility, National Institute of Standards and Technology (US) Technical Note 1508, Jan. 1999.
- [12] ARNAUT, LR., Operation of electromagnetic reverberation chambers with wave diffractors at relatively low frequencies, IEEE Trans. EMC, Nov. 2001, vol. 43 no. 4, pp. 637–653.
- [13] MARVIN, AC., ANGUS, JAS., DAWSON, JF., and CLEGG, J., Enhancements to stirred mode chambers by the use of pseudo-random phase reflection gratings, Proc. EMC'94 Int. Symp. EMC, Rome, Italy, 1994, pp. 218–221.
- [14] ARNAUT, LR., Compound exponential distributions for undermoded reverberation chambers, IEEE Trans. EMC, Aug. 2002, vol. 44 no. 3, pp. 442–457.
- [15] ARNAUT, LR., Limit distribution for imperfect electromagnetic reverberation, IEEE Trans. EMC, May 2003, vol. 45 no. 2, pp. 357–379.
- [16] DUNN, JM., Local, high-frequency analysis of the fields in a mode-stirred chamber, IEEE Trans. EMC, Feb. 1990, vol. 32 no. 1, pp. 53–58.
- [17] HILL, DA., Boundary fields in reverberation chambers, IEEE Trans. EMC, May 2005, vol. 47 no. 2, pp. 281–290.
- [18] ARNAUT, LR. and WEST, PD., Electromagnetic reverberation near a perfectly conducting boundary, IEEE Trans. EMC, May 2006, vol. 48 no. 2, pp. 359–371.
- [19] ARNAUT, LR. Measurement uncertainty in reverberation chambers - I. Sample statistics, National Physical Laboratory (UK), Report TQE 2, Ed. 2.0, Dec. 2008. [http://publications.npl.co.uk/npl_web/pdf/TQE2.pdf]
- [20] LUNDÉN, O. and BÄCKSTRÖM, M., Stirrer efficiency in FOA reverberation chambers, evaluation of correlation coefficients and chi-squared tests, Proc. IEEE Int. Symp. EMC, Washington, DC, Aug. 2000, pp. 11–16.
- [21] KRAUTHÄUSER, H. G., WINZERLING, T., NITSCH, J., EULIG, N., and ENDERS, A., Statistical interpretation of autocorrelation coefficients for fields in mode-stirred chambers. Proc. IEEE Int. Symp. EMC, Chicago, IL, Aug. 2005, pp. 550–555.
- [22] LEHMAN, TH., A statistical theory of electromagnetic fields in complex cavities, Note 494, USAF Phillips Laboratory Interaction Note Series, May 1993.
- [23] ARNAUT, LR. and WEST, PD., Evaluation of the NPL stadium reverberation chamber using mechanical and electronic stirring techniques, National Physical Laboratory Report (UK), Report CEM 11, Aug. 1998.
- [24] FREYER, GJ., HATFIELD, MO., JOHNSON, DM., and SLOCUM, MB., Comparison of measured and theoretical statistical properties of complex cavities, Proc. IEEE Int. Symp. on EMC, Santa Clara, CA, Aug. 1996, pp. 250-253.
- [25] LADBURY, JM. and GOLDSMITH, K., Reverberation chamber verification procedures, or how to check if your chamber ain't broke and suggestions on how to fix it if it is, Proc. IEEE Int. Symp. on EMC, Washington DC, Aug. 2000, pp.17-22.
- [26] LADBURY, JM., Reverberation chamber relationships: corrections and improvements, or three wrongs can (almost) make a right, Proc. IEEE Int. Symp. EMC, Seattle, WA, Aug. 1999, pp.1-6.

- [27] ARNAUT, LR., Sampling distributions of random electromagnetic fields in mesoscopic or dynamical systems, Phys. Rev. E, vol. 80 no. 3, 036601, 2009.
- [28] LIU, B.-H., CHANG, DC., and MA, MT., Eigenmodes and the composite quality factor of a reverberating chamber, National Bureau of Standards (US), Technical Note 1066, 1983.
- [29] IEC 61000-4-3, Electromagnetic compatibility (EMC) – Part 4-3: Testing and measurement techniques – Radiated, radio-frequency, electromagnetic field immunity test
- [30] RTCA/DO-160E, Environmental conditions and test procedures for airborne equipment (Change Notice to Section 20), Dec. 2004.
- [31] MIL-STD-461E, Requirements for the control of electromagnetic interference emissions and susceptibility, Aug. 1999.
- [32] MIL-STD-1377, Effectiveness of cable, connector, and weapon enclosure shielding and filters in precluding hazards of electromagnetic radiation to ordnance, Aug. 1977.

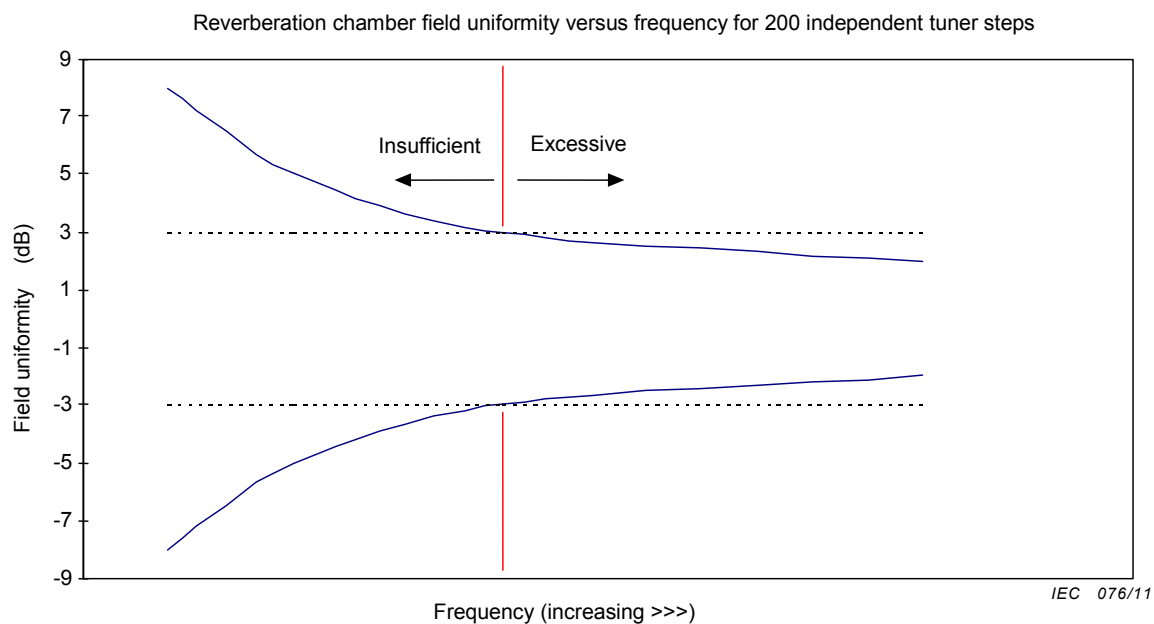
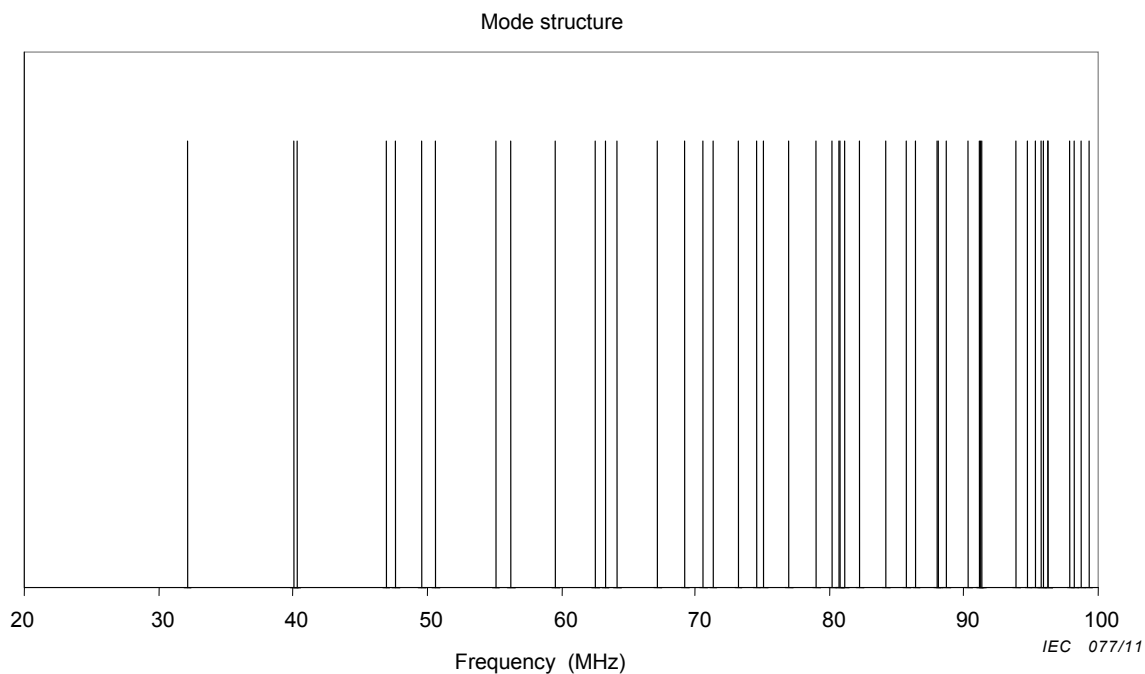


Figure A.1 – Typical field uniformity for 200 independent tuner steps



NOTE Vertical axis has no meaning other than to represent the presence of a mode.

Figure A.2 – Theoretical modal structure for a 10,8 m × 5,2 m × 3,9 m chamber

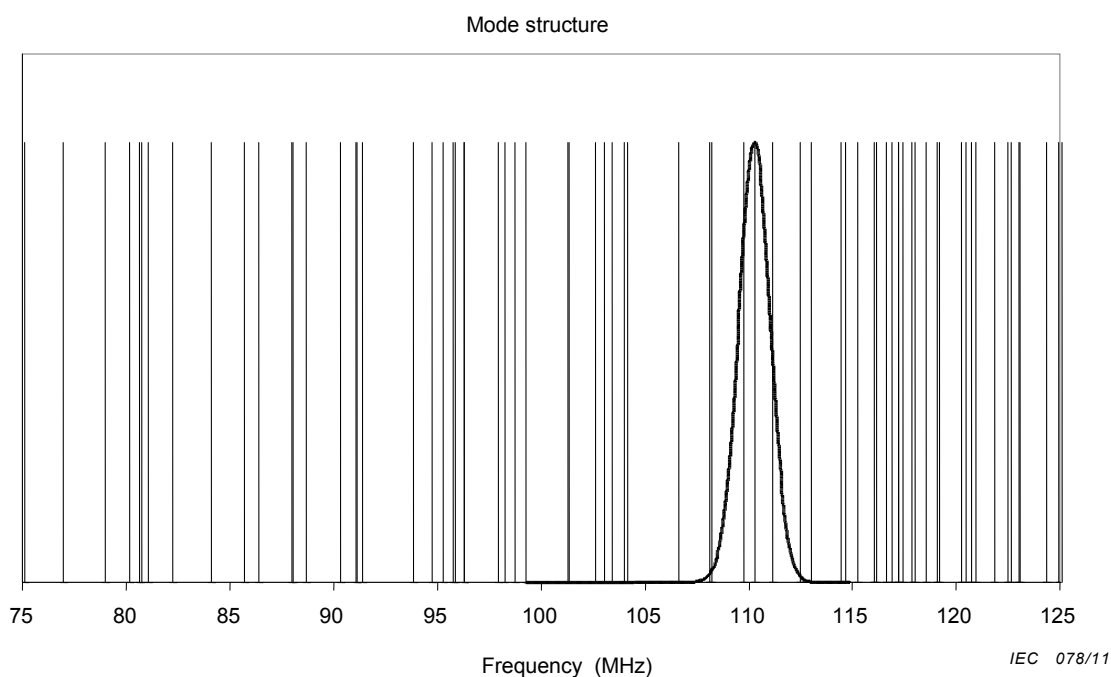


Figure A.3 – Theoretical modal structure with small Q-bandwidth (high Q) superimposed on 60th mode

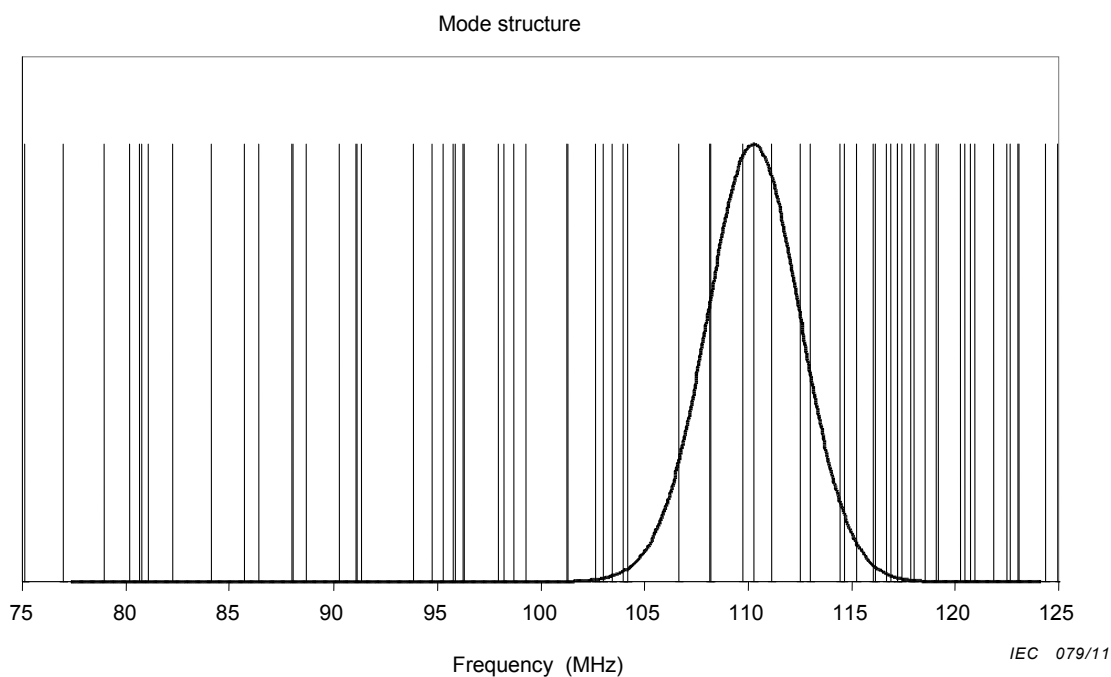


Figure A.4 – Theoretical modal structure with greater Q-bandwidth (lower Q) superimposed on 60th mode

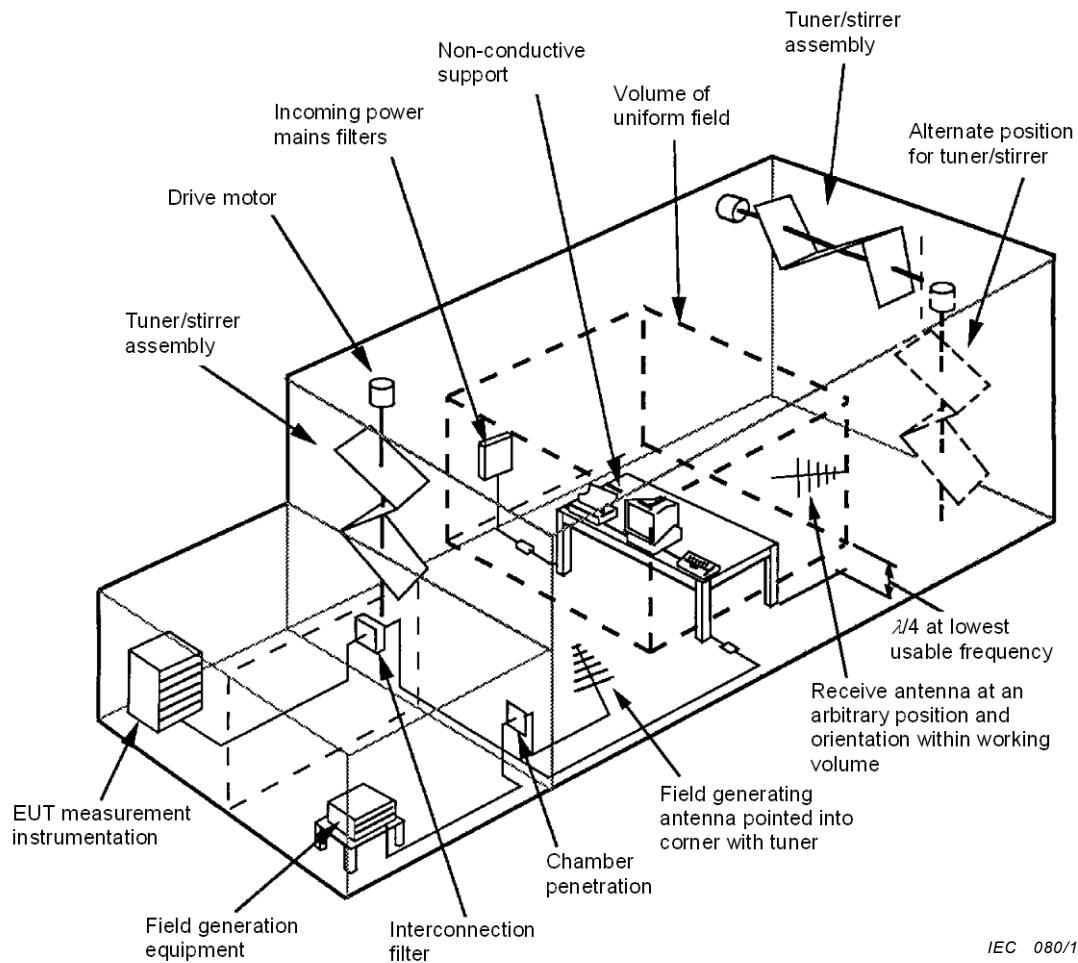
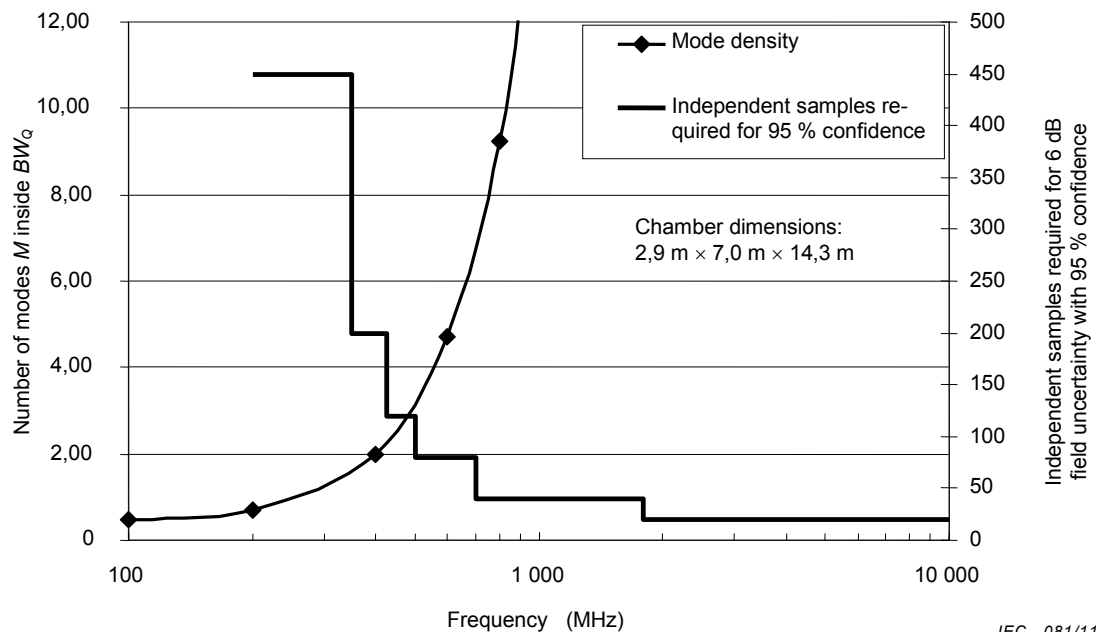


Figure A.5 – Typical reverberation chamber facility

Modes/ BW_Q and sampling requirements for 6 dB field uncertainty with 95 % confidence



NOTE See Equation (A.3) on calculating M .

Figure A.6 – Theoretical sampling requirements for 95 % confidence

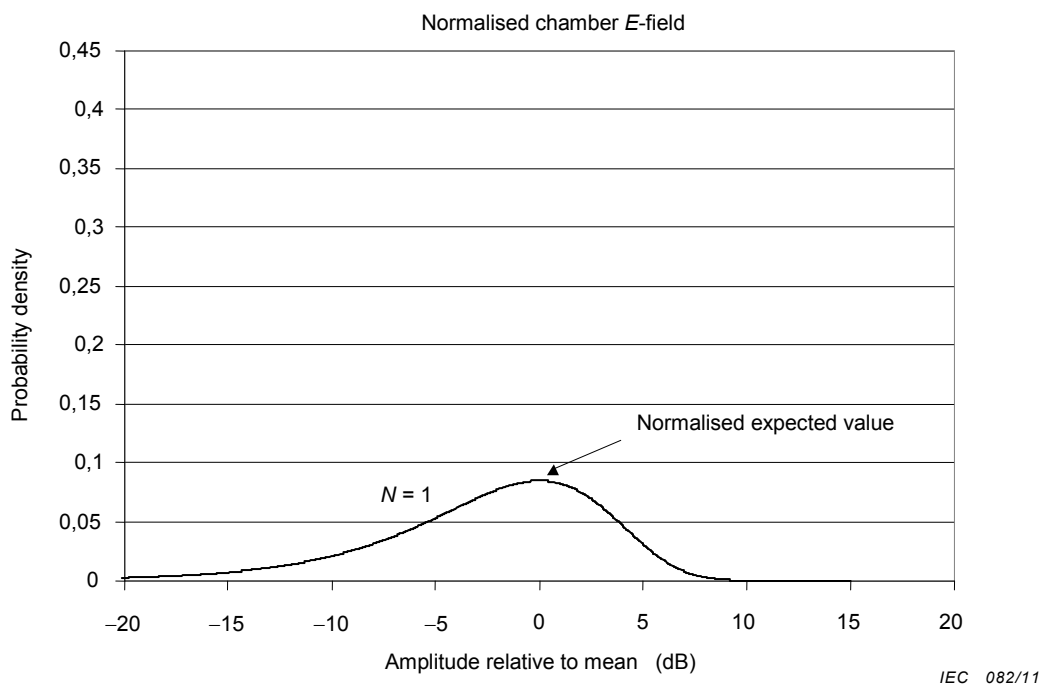


Figure A.7 – Normalized PDF of an electric field component at a fixed location for a measurement with a single sample

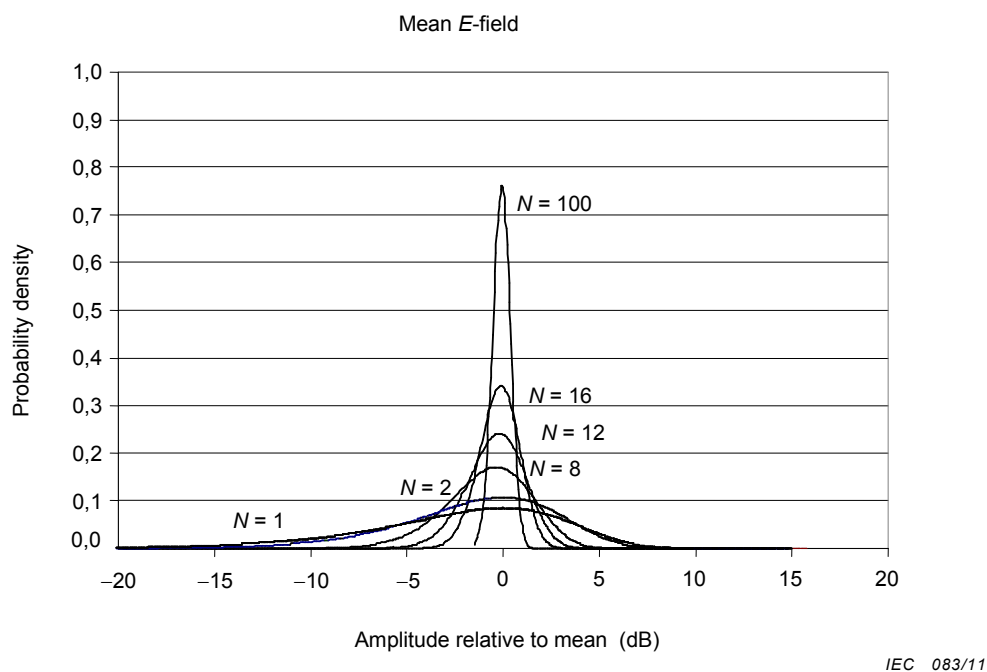


Figure A.8 – Normalized PDF of the mean of an electric field component at one fixed location for a measurement with N independent samples

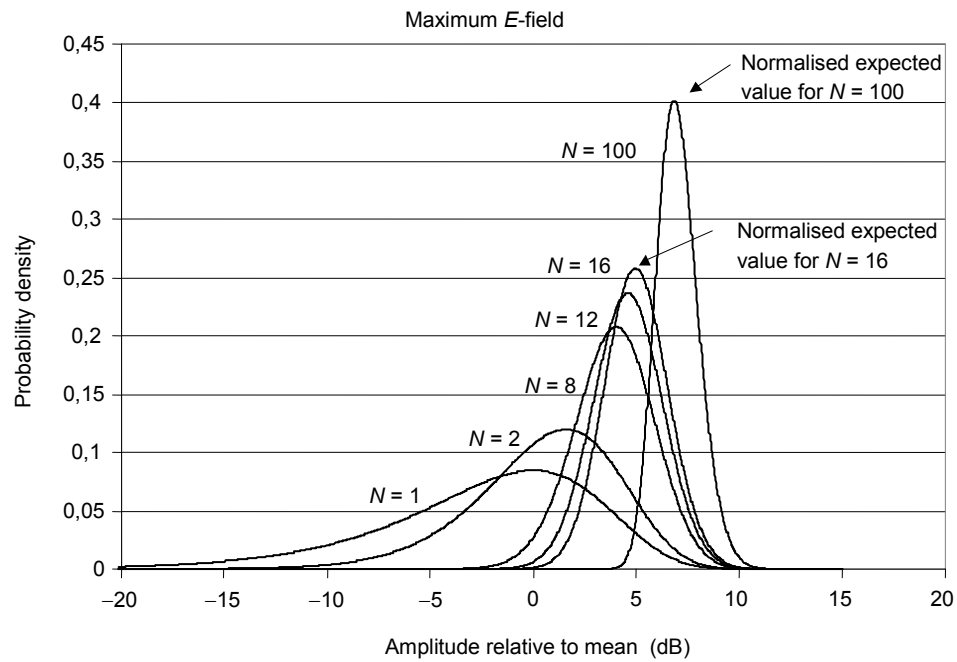
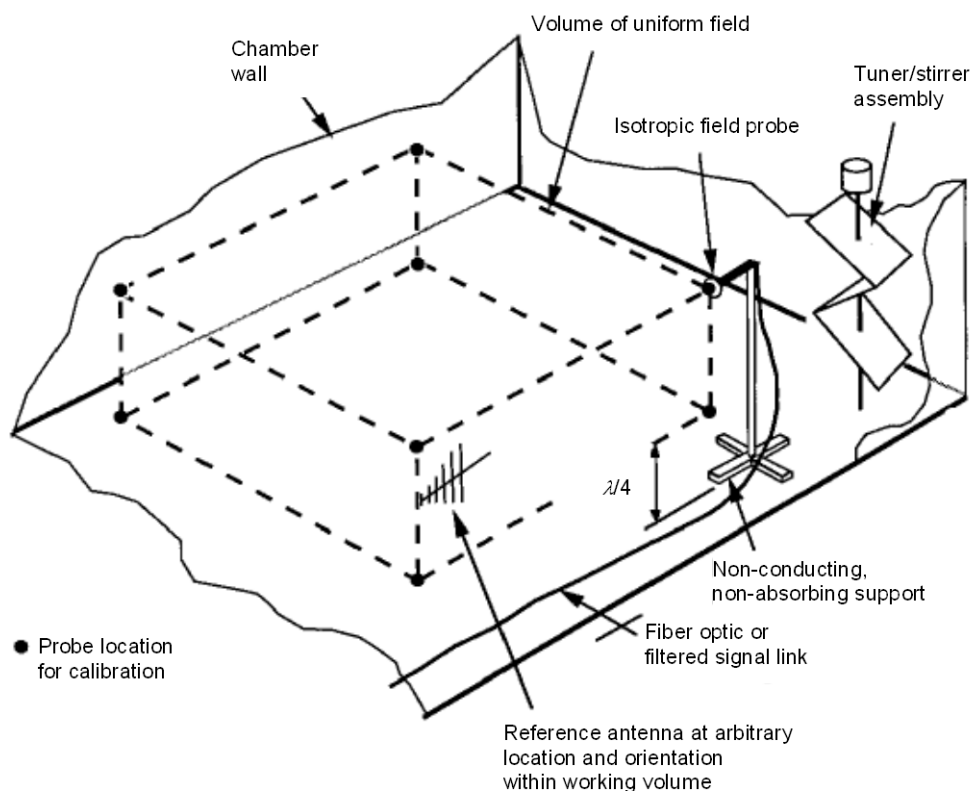
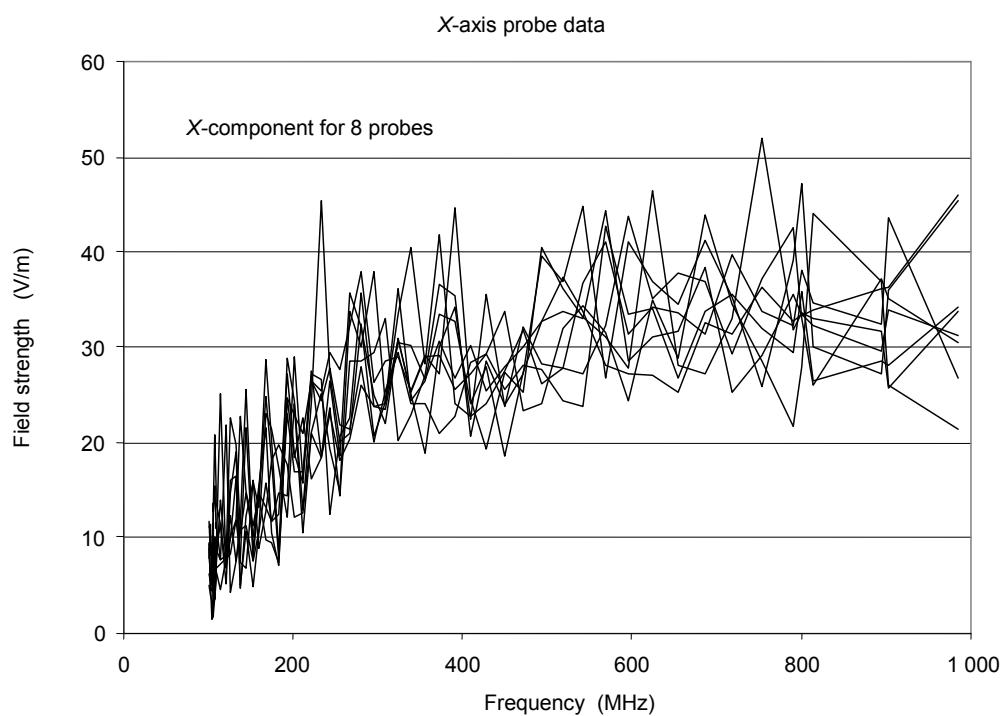


Figure A.9 – Normalised PDF of the maximum of an electric field component at a fixed location for a measurement with N independent samples



IEC 085/11

Figure A.10 – Chamber working volume

IEC 086/11

Figure A.11 – Typical probe data

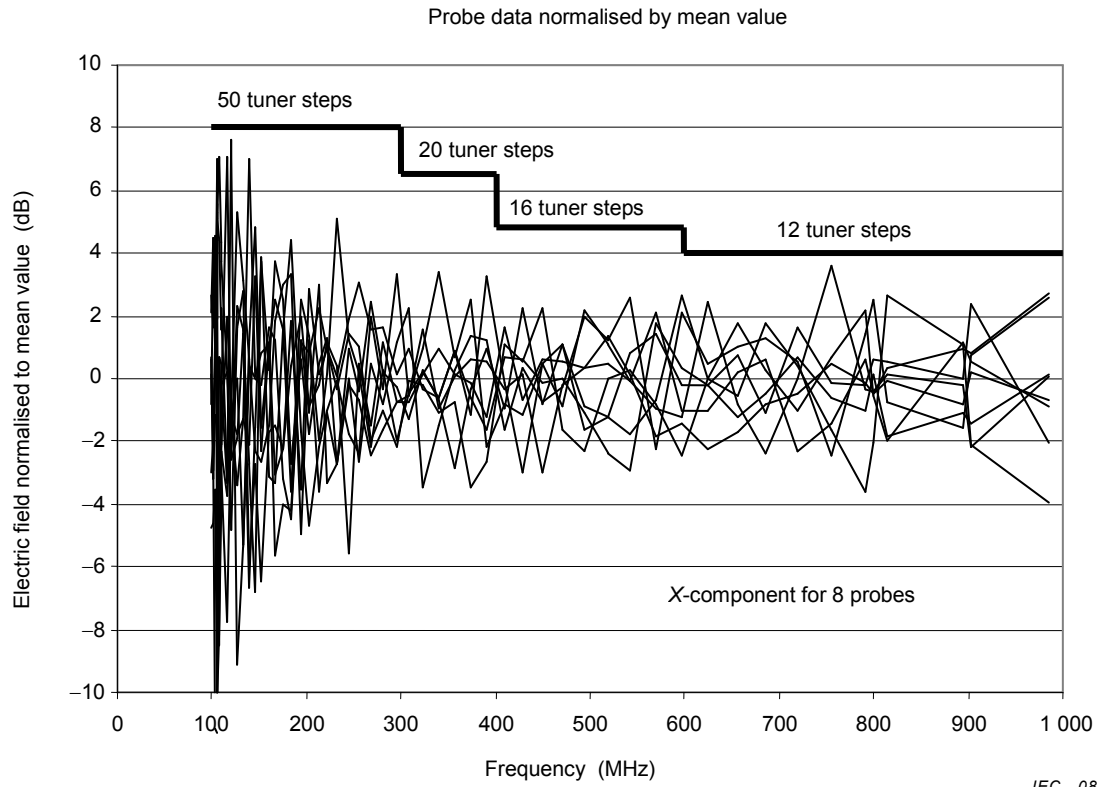


Figure A.12 – Mean-normalized data for x-component of 8 probes

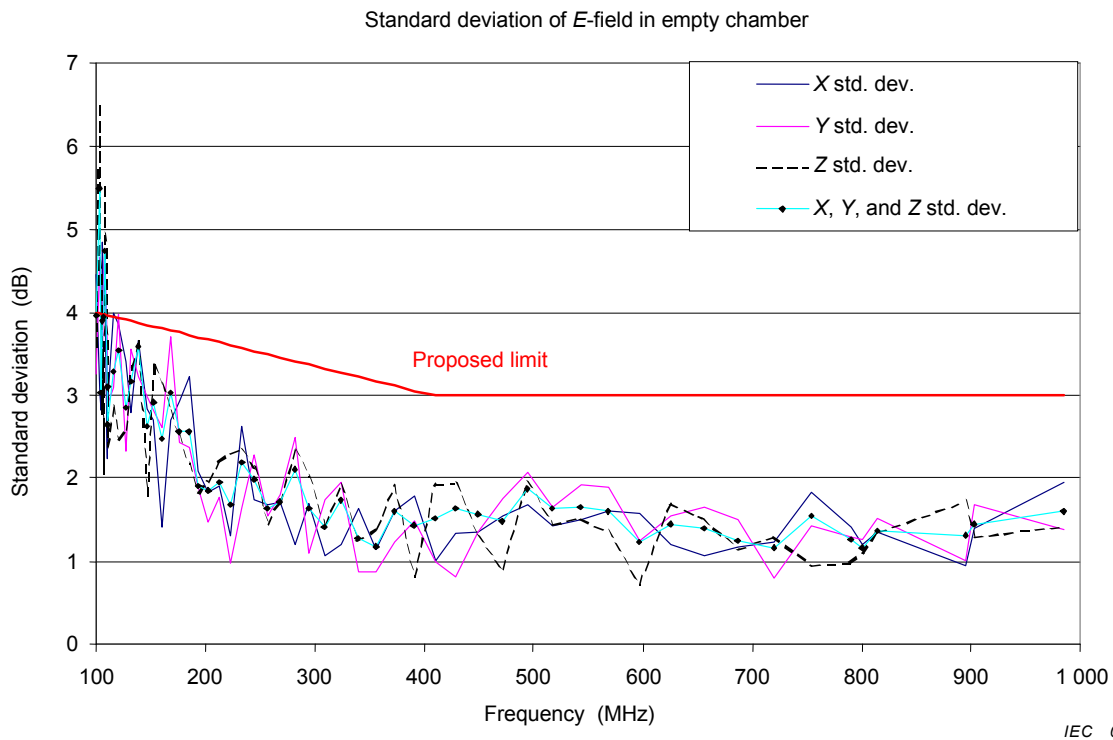
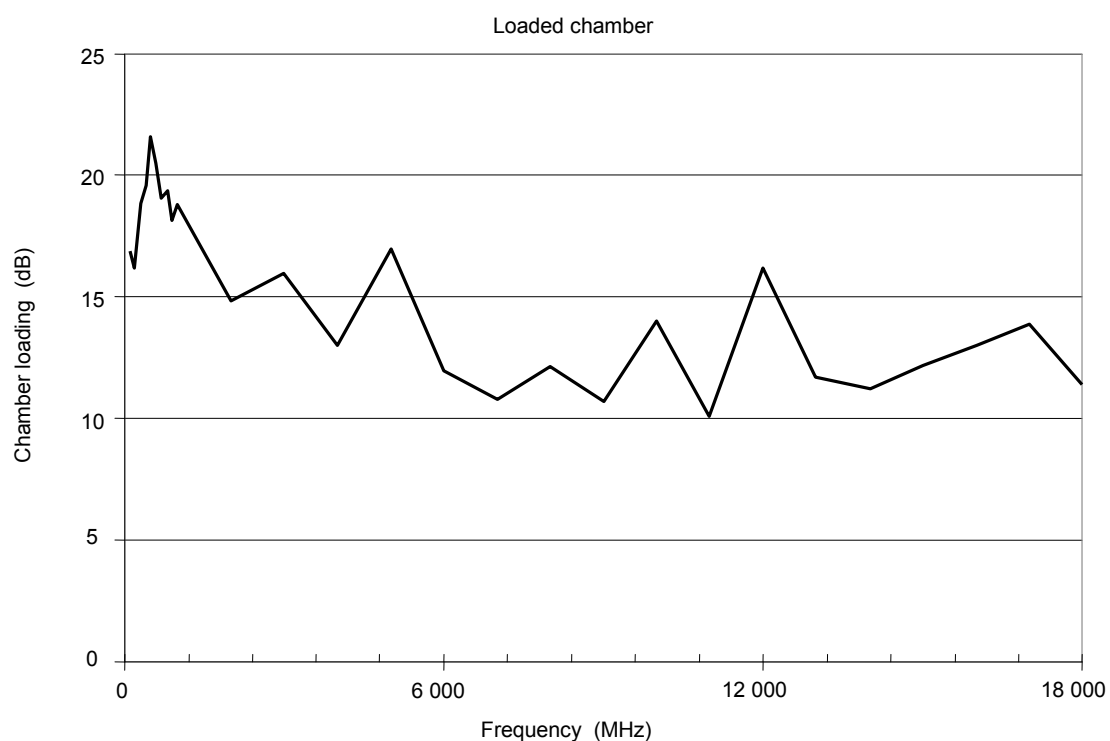


Figure A.13 – Standard deviation of data for *E*-field components of 8 probes



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Figure A.14 – Distribution of absorbers for loading effects test

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Figure A.15 – Magnitude of loading from loading effects test

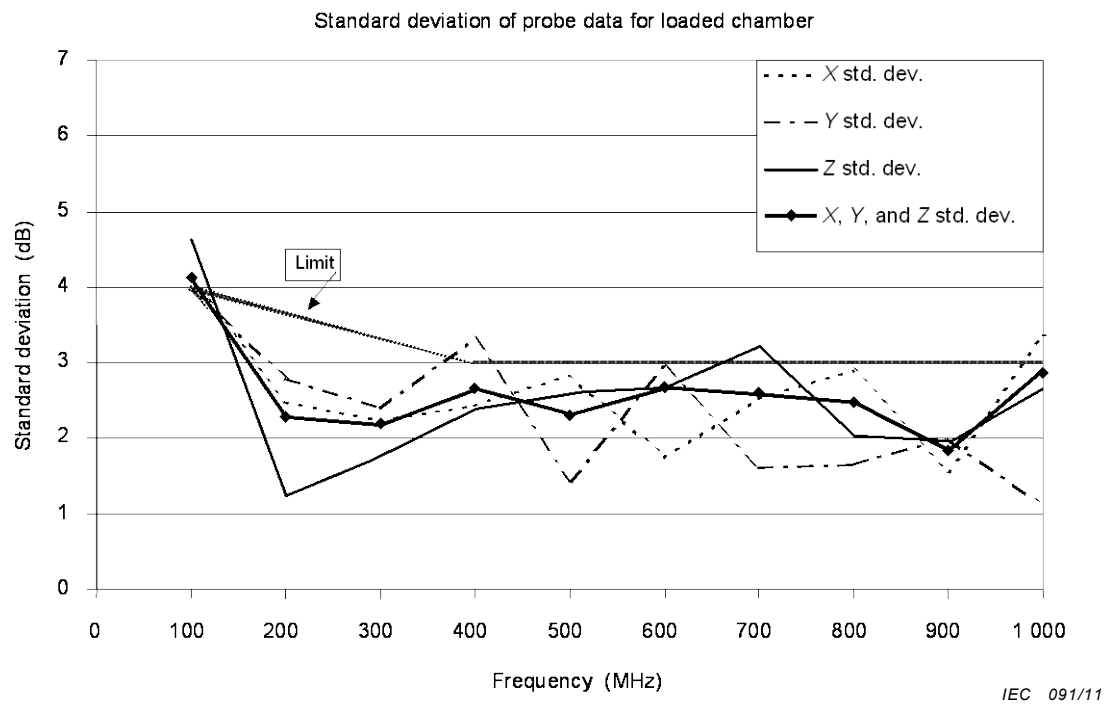


Figure A.16 – Standard deviation data of electric field components for eight probes in the loaded chamber

Annex B (normative)

Chamber validation for mode-tuned operation

B.1 Validation: chamber field uniformity and loading validation

B.1.1 General

As an initial guide to chamber performance and input power requirements, perform a “one-time” empty chamber validation (no EUT) using the procedures of this clause. Prior to each test a validation shall be performed using the procedures of Clause B.2.

The chamber field uniformity shall be verified over the first decade of the operational frequency range. A chamber can be used to perform tests at and above the frequency at which the chamber meets the field uniformity requirements in Table B.2.

B.1.2 Field uniformity validation

The following steps are necessary.

- (1) Clear the working volume (i.e., remove test bench and any other artefacts, whether or not they load the chamber) and place the receiving antenna at a location within the working volume of the chamber as outlined in the notes of Figure B.1. Set the amplitude measurement instrument to monitor the receive antenna on the correct frequency.
- (2) Place the *E*-field probe at a location on the perimeter of the chamber working volume as shown in Figure B.1.
- (3) Starting at the lowest test frequency (f_s), adjust the RF source to inject an appropriate input power into the transmitting antenna to get a reliable probe reading. The transmitting antenna shall not directly illuminate the working volume or the receiving antenna and probes. Directing the transmitting antenna into one corner of the chamber is often an optimum configuration. The frequency shall be in-band for both transmitting and receiving antennas, which shall be linearly polarized antennas. Care shall be taken to ensure that the harmonics of the RF input to the chamber are at least 15 dB below the fundamental.

NOTE 1 For normal operation the lowest test frequency (f_s) is typically of the order of 80 MHz, and field uniformity is demonstrated over the first decade of operation. If a lowest test frequency other than 80 MHz is chosen, for example in a small chamber used to generate high field strengths, then the chamber field uniformity is still verified over the first decade of operation. The start frequency for acceptable measurements is never lower than the frequency at which the chamber meets the field uniformity requirements in Table B.2.

- (4) Step the tuner(s) through 360° in equally sized discrete steps (mode-tuned operation) so that the amplitude measurement instrument and *E*-field probe captures the minimum number of samples as outlined in Table B.1 over one complete tuner rotation. Care shall be taken to ensure that the dwell time is sufficiently long in such a manner that the amplitude measurement instrumentation and *E*-field probes have time to respond properly.
- (5) Record the maximum and average power (linear average: i.e., in W, not dBm) of the receive signal (P_{MaxRec} , P_{AveRec}), the maximum field strength ($E_{\text{Max } x,y,z}$) for each axis of the *E*-field probe, and the average value of the input power (P_{Input}) over the tuner rotation.

NOTE 2 The value of the input power, P_{Input} , is the forward power averaged over the tuner rotation. The number of samples used to determine the average should be at least the same as the number of samples used for chamber validation. Large variations in input power (i.e., 3 dB or more) are an indication of poor source/amplifier performance. All validations are antenna specific. Changing antennas may void validations. All power measurements are relative to the antenna terminals. The antennas are assumed to be high efficiency antennas (i.e., greater than 75 % efficient).

- (6) Repeat the above procedure in log-spaced frequency steps as outlined in Table B.1 until frequency is at least $10 f_s$.
- (7) Repeat for each of the eight probe locations shown in Figure B.1 and for eight Rx antenna locations (one of which shall be at the center of the working volume) until $10 f_s$.

NOTE 3 Steps (4) and (6) may be interchanged if desired, i.e., step through the frequencies at each step of the tuner.

NOTE 4 If the room and mode tuner have strong geometrical symmetry, and if the mode tuner is located symmetrically with respect to all chamber walls, then the set of probe locations should not be chosen so as to exhibit cylindrical symmetry. The symmetry is most easily removed by placing the probes at different locations from their nearest wall.

- (8) Above $10 f_s$ only three probe and Rx antenna locations need to be evaluated. The probe and antenna should maintain the required clearance from each other and from chamber fixtures. One location for the probe and antenna shall be at the centre of the working volume. Repeat Steps (4) and (5) for the remainder of the validation frequencies, as outlined in Table B.1.

NOTE 5 The Rx antenna should be moved to a new location within the working volume of the chamber for each change in probe location. The antenna should also be placed in a new orientation relative to the chamber axis at each location (at least 20° in each axis). For reference purposes, x = chamber length (longest dimension), y = chamber width, and z = chamber height. The probe does not necessarily need to be oriented along the chamber axes during validation.

Care should be taken to ensure that a proper separation distance between the antenna and probe is maintained. Each location of the antenna or probe should be at least $\lambda/4$ (or 1 m at the lowest test frequency, if $\lambda/4 > 1\text{m}$) from any previous location. The same minimum separation should be observed between the antenna and the probe. If the Rx antenna is mounted in a fixed position during routine testing, it is suggested that one of the locations should be the intended location of the receive antenna during measurement or testing.

- (9) Using the data from Step (5), normalize each of the maximum E -field probe measurements (i.e., each of the $8 \times 3 = 24$ rectangular components below $10 f_s$ and $3 \times 3 = 9$ rectangular components above $10 f_s$) to the square-root of the average input power:

$$\bar{E}_{x,y,z} = \frac{E_{\text{Max } x,y,z}}{\sqrt{P_{\text{Input}}}} \quad (\text{B.1})$$

where

$E_{\text{Max } x,y,z}$ is the maximum measurement (in V/m) from each probe axis (i.e., 24 or 9 measurements) across all generated tuner positions,

$\bar{E}_{x,y,z}$ is the normalized maximum field (in (V/m)/W^{0.5}), defined as the maximum measurement from each probe axis data divided by the square root of the input power, and

P_{Input} is the average input power (in W) to the chamber during the tuner rotation at which $E_{\text{Max } x,y,z}$ was recorded.

- (10) For each validation frequency, calculate the average of the normalized maximum values across the probe positions for each probe axis of the E -field probe measurements, $\langle \bar{E}_{x,y,z} \rangle$, as follows.

- (a) For each frequency below $10 f_s$ calculate

$$\langle \bar{E}_x \rangle_8 = \frac{(\sum \bar{E}_x)}{8}, \quad \langle \bar{E}_y \rangle_8 = \frac{(\sum \bar{E}_y)}{8}, \quad \langle \bar{E}_z \rangle_8 = \frac{(\sum \bar{E}_z)}{8} \quad (\text{B.2})$$

- (b) For each frequency below $10 f_s$ calculate the average of the normalized maximum of all the E -field probe measurements giving equal weight to each axis (i.e., each rectangular component), $\langle \bar{E} \rangle_{24}$. This is done by calculating the sum of all 24 rectangular (normalized) E -field maximum values divided the product of the number of probe axes with the number of probe locations, i.e., $3 \times 8 = 24$.

$$\langle \vec{E} \rangle_{24} = \frac{\sum \vec{E}_{x,y,z}}{24} \quad (\text{B.3})$$

NOTE 6 $\langle \rangle$ denotes arithmetic mean across a number of probe positions and/or probe axes.

- (c) For each frequency above $10 f_s$, calculate the average of the normalized maximum values across all three probe positions giving equal weight to each axis (i.e., each rectangular component). This results in the same calculation as in (b) upon replacing 24 with 9.
- (11) For each frequency below $10 f_s$, determine if the chamber meets the field uniformity requirements as follows:
- (a) The field uniformity is specified as a standard deviation from the normalized mean value of the normalized maximum values obtained at each of the eight locations during one rotation of the tuner. The standard deviation is calculated using data from each probe axis independently and the total data set.

The standard deviation is given by:

$$\sigma = \sqrt{\frac{\sum (\vec{E}_i - \langle \vec{E} \rangle)^2}{n-1}} \quad (\text{B.4})$$

where

n is the number of measurements i ,

$\vec{E}_i$ is the individual E -field measurement normalized (to the square root of the input power), and

$\langle \vec{E} \rangle$ is the arithmetic mean of the normalized maximum E -field measurements.

For example, for the x-vector:

$$\sigma_x = \sqrt{\frac{\sum (\vec{E}_{x,i} - \langle \vec{E}_x \rangle_8)^2}{8-1}} \quad (\text{B.5})$$

where

$\vec{E}_{x,i}$ is the individual measurement of x-vector,

$\langle \vec{E}_x \rangle_8$ is the arithmetic mean of normalized $E_{\text{Max } x}$ vectors for all eight measurement locations.

and for all vectors:

$$\sigma = \sqrt{\frac{\sum_{m=1}^8 \sum_{n=1}^3 \left(E_{m,n}^{\leftrightarrow} - \langle \vec{E} \rangle_{24} \right)^2}{24-1}} \quad (\text{B.6})$$

where

$\vec{E}_{m,n}$ is the individual measurements of all vectors (m = probe locations 1 through 8 and n = isotropic probe axis 1 through 3, i.e., x, y, and z),

$\langle \vec{E} \rangle_{24}$ is the arithmetic mean of the normalized vectors $E_{\text{Max } x,y,z}$ vectors from all 24 measurements, and

σ is the standard deviation of all vectors (x, y, and z).

Finally, the standard deviation is expressed relative to the mean and converted to dB:

$$\sigma(\text{dB}) = 20 \log_{10} \left(\frac{\sigma + \langle \vec{E}_{x,y,z} \rangle}{\langle \vec{E}_{x,y,z} \rangle} \right) \quad (\text{B.7})$$

- (b) The chamber passes the field uniformity requirements if the standard deviation for both the individual field components and the total data set is within tolerance as outlined in Table B.2. If the chamber fails to meet the uniformity requirement, it may not be possible for the chamber to operate at the desired lower frequency. If the margin by which the chamber fails to meet the uniformity requirement is small, it may be possible to obtain the desired uniformity by:
- 1) increasing the number of samples (i.e., tuner steps) by 10 % to 50 %,
 - 2) normalizing the data to the average net chamber input power ($P_{\text{Net}} = P_{\text{Input}} - P_{\text{Reflected}}$), or
 - 3) reducing the size of the working volume.

If the chamber exceeds the required field uniformity, the number of samples required may be reduced, but not below a minimum of 12 tuner steps. This offers the ability to optimize each chamber for the minimum number of samples and therefore minimum test time.

NOTE 7 If the tuner fails to provide the required uniformity then the uniformity may be improved by increasing the number of tuners, making the tuner(s) larger, or lowering the Q by adding absorber. The chamber characteristics (size, construction method, and wall materials) should also be evaluated to determine if the chamber is likely to pass the requirement. Chambers with no more than 60 to 100 modes at the lowest test frequency or very high Q (such as those encountered in welded aluminium chambers) are likely to encounter difficulty in meeting the required uniformity at low frequencies.

IMPORTANT: Once a chamber has been modified (e.g., absorber added, etc.) or the validation procedure has been modified (e.g., changed number of tuner steps, etc.) to obtain a desired characteristic, that configuration and/or procedure shall remain the same for the duration of the test for that validation to remain valid.

B.1.3 Receive antenna validation

The receive antenna validation factor (*AVF*) for an empty chamber is determined to provide a baseline for comparison with a loaded chamber (Clause B.2).

Calculate *AVF* for each frequency using the following equation:

$$AVF = \left\langle \frac{P_{\text{AveRec}}}{P_{\text{Input}}} \right\rangle_{8 \text{ at } \leq 10 f_0 \text{ or } 3 \text{ at } > 10 f_0} \quad (\text{B.8})$$

where P_{Input} is the average input power obtained from B.1.2 (5) for the corresponding location at which the average received power (P_{AveRec}) from B.1.2 (5) was measured. The *AVF* is necessary to correct the antenna measurements for several effects including antenna efficiency.

NOTE $\langle \rangle$ denotes arithmetic mean, i.e., $\langle P_{\text{AveRec}} \rangle_8 = (\sum P_{\text{AveRec}})/8$ evaluated at 8 probe locations if the frequency is below $10 f_s$, or at 3 locations if the frequency is in excess of $10 f_s$.

B.1.4 Chamber insertion loss

The chamber insertion loss (*IL*) for the empty chamber is determined to provide information for calculations required by other annexes.

Calculate IL for each frequency using the following equation:

$$IL = \left\langle \frac{P_{\text{MaxRec}}}{P_{\text{Input}}} \right\rangle_{8 \text{ at } \leq 10 f_0 \text{ or } 3 \text{ at } > 10 f_0} \quad (\text{B.9})$$

where P_{Input} is the average input power from B.1.2 (5) for the corresponding location at which the maximum received power (P_{MaxRec}) from B.1.2 (5) was measured.

NOTE $\langle \rangle$ denotes arithmetic mean, i.e., $\langle P_{\text{MaxRec}} \rangle_8 = (\sum P_{\text{MaxRec}})/8$ evaluated at 8 probe locations if the frequency is below $10 f_s$, or at 3 locations if the frequency is in excess of $10 f_s$.

B.1.5 Chamber E-field estimation using antennas

The empty chamber validation outlined in B.1.2 is based on readings from E -field probes. The chamber E -field can be estimated based on measurements using antennas. This alternative procedure is contained in Annex A.

NOTE Significant disagreement at the lower frequencies is expected. This is due to loading caused by the Tx and Rx antennas. For this reason, the agreement between the two methods is not expected at frequencies where the difference between the chamber input power and the measured maximum receive power from the reference antenna is 10 dB or less.

B.1.6 Verification of maximum chamber loading

In order to determine if the chamber is adversely affected by an EUT which “loads” the chamber, perform a one-time check of the chamber field uniformity under simulated loading conditions. It is suggested the “loaded” chamber validation be carried out only once in the life of the chamber or after major modification to the chamber. Prior to each test a validation shall be performed using the procedures of Clause B.2.

- (1) At random locations within the working volume of the chamber, install a sufficient amount of absorber to load the chamber to at least the level expected during normal testing (a factor of 16 change in AVF (12 dB) should be considered as a nominal amount of loading).

NOTE Each chamber is unique. The easiest way to determine the amount of absorber necessary is by trial and error.

- (2) Repeat the validation outlined in B.1.2 using the eight locations of the E -field probe. Care should be taken to ensure that the E -field probe and receiving antenna maintain a distance of greater than $\lambda/4$ from any absorber. Determine the chamber loading by comparing the antenna validation factor (AVF) from the empty chamber to that obtained from the “loaded” chamber (B.1.3)

$$\text{Loading} = \frac{AVF_{\text{Empty Chamber}}}{AVF_{\text{Loaded Chamber}}} \quad (\text{B.10})$$

- (3) Repeat the calculation of the field uniformity using the data from the eight locations of the E -field probe.

If the chamber loading results in the rectangular component of the fields exceeding the allowed standard deviation, or if the standard deviation for all vectors (i.e., σ_{24}) exceeds the allowed standard deviation (see Table B.2) then the chamber has been loaded to the point where field uniformity is unacceptable. In this case the amount of chamber loading shall be reduced and the loading effects evaluation shall be repeated.

B.2 Validation: verification of chamber performance with EUT in place

Prior to each test, with the EUT and supporting equipment in the chamber, perform a chamber validation according to the following procedure.

- (1) Place the receive antenna at a location within the working volume of the chamber and maintain 1 m (or $\lambda/4$ at the lowest test frequency) separation from the EUT, supporting

equipment, etc., as outlined in this annex for the type of test being performed. Set the amplitude measurement instrumentation to monitor the receive antenna on the correct frequency.

- (2) Beginning at the lowest test frequency (f_s), adjust the RF source level to inject an appropriate input power, (P_{Input}), into the transmit antenna. Care shall be taken to ensure that the harmonics of the RF input to the chamber are at least 15 dB below the fundamental.
- (3) Operate the chamber and the tuner taking into account the possible additional features defined in B.1 that have been required to meet the homogeneity criterion. Care shall be taken to ensure that the dwell time is sufficiently long to ensure that the amplitude measurement equipment has time to respond properly.
- (4) Record the maximum amplitude and average amplitude of the receive signal (P_{MaxRec} , P_{AveRec}), and the average value of the input power, P_{Input} . The measurement instruments should have a noise floor at least 20 dB below the maximum received power (P_{MaxRec}) in order to collect accurate average data.
- (5) Repeat the above procedure for each test frequency as defined in the test plan.
- (6) Calculate the chamber validation factor (CVF) for each frequency using the following equation:

$$CVF = \left\langle \frac{P_{\text{AveRec}}}{P_{\text{Input}}} \right\rangle_n \quad (\text{B.11})$$

where

CVF is the normalized average received power over one tuner rotation with the EUT and supporting equipment present,

P_{AveRec} is the average received power over one tuner rotation from Step (4),

P_{Input} is the forward power averaged over one tuner rotation from Step (4), and

n is the number of antenna locations the CVF is evaluated for. Only one location is required; however, multiple locations may be evaluated and the data averaged over the number of locations.

- (7) Calculate the chamber loading factor (CLF) for each frequency using the following equation:

$$CLF = \frac{CVF}{AVF} \quad (\text{B.12})$$

where

CVF is the ratio of the average received power to input power obtained in Step (6) above, and

AVF is the ratio of the average received power to input power obtained in the antenna validation in B.1.2. Interpolation will be required to obtain the AVF .

If the reciprocal value of the magnitude of the chamber loading factor is in excess of the loading that is measured in B.1.2 (5) by more than is expected due to instrument uncertainty, there is a possibility that the chamber may be loaded to the point where field uniformity is affected. In such a case, the chamber uniformity measurements outlined in B.1.2 shall be repeated with the EUT in place or with a simulated loading equivalent to the EUT.

NOTE If the value of P_{AveRec} measured in Clause B.2 (5) is within (i.e., neither greater nor less than) the values recorded for all eight locations in B.1.2 (5), calculation of the CLF is not necessary and the value of the CLF should be assumed to be 1. If the dynamic range of the measurement system was insufficient to get accurate average received power measurements, the AVF and CVF may be recalculated using maximum received power and then used to calculate the CLF . If maximum received power is used, it should be used to recalculate both the AVF and CVF .

CAUTION: This applies ONLY to the calculation of the CLF . Do NOT use the AVF or CVF based on maximum power to determine any other parameters!

B.3 Q and time constant validation

In order to assure that the time response of the chamber is fast enough to accommodate pulsed waveform testing, determination of the chamber time constant shall be accomplished using the following procedure:

- (1) Using the *CVF* from the chamber validation Equation (B.11), calculate the quality factor, *Q* for every frequency using:

$$Q = \left(\frac{16\pi^2 V}{\eta_{Tx} \eta_{Rx} \lambda^3} \right) (CVF) \quad (B.13)$$

where

η_{Tx} , η_{Rx} are the antenna efficiency factors for the transmit and receive antennas, respectively, which can conservatively be assumed (if not known) to be 0,75 for a log periodic antenna and 0,9 for a horn antenna,

V is the chamber volume (in m³),

λ is the free space wavelength (in m) at the specific frequency, and

CVF is the chamber validation factor.

NOTE If the value of P_{AveRec} measured in Clause B.2 (4) is within (i.e., not greater than or less than) the values recorded for all eight locations in B.1.2 (5), calculation of the *CLF* is not necessary and the value of the *CLF* is assumed to be 1. In this case, the *AVF* from B.1.2 should be used in place of the *CVF* when calculating the chamber *Q*.

- (2) Calculate the chamber time constant τ (in s) for every frequency using:

$$\tau = \frac{Q}{2\pi f} \quad (B.14)$$

where

Q is the value calculated in Step (1) above, and

f is the test frequency (in Hz).

- (3) If the chamber time constant is greater than 0,4 of the modulation test pulse width for more than 10 % of the test frequencies, absorber shall be added to the chamber or the pulse width increased. If absorber is added, repeat the *Q* measurement and the calculation until the time constant requirement is satisfied with the least possible absorber. A new *CLF* shall be defined if absorber material is required.

Table B.1 – Sampling requirements

Frequency range	Minimum number of samples ^a required for validation and test ^d	Number of frequencies ^b required for validation
f_s to $3 f_s$ ^c	12	20
$3 f_s$ to $6 f_s$	12	15
$6 f_s$ to $10 f_s$	12	10
Above $10 f_s$	12	20/decade

^a The minimum number of tuner steps is 12 for all frequencies. For many chambers the number of tuner steps will need to be increased at the lower frequencies. The maximum number of tuner steps is the number of independent samples that a given tuner can produce. This number varies with frequency and needs to be verified when commissioning the chamber. In the event that the chamber fails to meet the uniformity requirement, the number of tuner steps may be increased up to the number of independent tuner samples. An example of increased numbers of tuner steps in this case is shown in Figure A.12.

^b Log spaced.

^c f_s = Start frequency (see A.1.3 for LUF)

^d The tuner sequencing used for validation of the chamber shall be the same as for subsequent testing.

Table B.2 – Field uniformity tolerance requirements

Frequency range MHz	Tolerance requirements for standard deviation
80 to 100	4 dB ^a
100 to 400	4 dB at 100 MHz decreasing linearly to 3 dB at 400 MHz ^a
Above 400	3 dB ^a

^a A maximum of three frequencies per octave may exceed the allowed standard deviation by an amount not to exceed 1 dB of the required tolerance.