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SUBCOMMITTEE A OF CISPR: RADIO-INTERFERENCE MEASUREMENTS AND STATISTICAL METHODS

Subject: CD on IEC 61000-4-20 Electromagnetic compatibility (EMC) - Part 4-20: Testing and measurement techniques - Emission and immunity testing in transverse electromagnetic (TEM) waveguides

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Secretary, CISPR/A

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Title:
IEC 61000-4-20 Electromagnetic compatibility (EMC) - Part 4-20 : Testing and measurement techniques - Emission and immunity testing in transverse electromagnetic (TEM) waveguides

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IEC 61000-4-20: Compatibilité électromagnétique (CEM) – Partie 4-20 : Techniques d'essai et de mesure – Essais d'émission et d'immunité dans les guides d'onde TEM

Introductory note

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 4-20: Testing and measurement techniques – Emission and immunity testing in transverse electromagnetic (TEM) waveguides

FOREWORD

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International Standard IEC 61000-4-20 has been prepared by subcommittee 77B: High-frequency phenomena, of IEC technical committee 77: Electromagnetic compatibility, in cooperation with CISPR (International Special Committee on Radio Interference) subcommittee A: Radio interference measurements and statistical methods.

This third edition cancels and replaces the second edition published in 2010 and constitutes a technical revision.

It forms Part 4-20 of IEC 61000. It has the status of a basic EMC publication in accordance with IEC Guide 107.

The main changes with respect to the second edition of this standard are the following:

- provide information on the testing of large EUTs (including cables);
- apply uncertainties work by adapting work completed in CISPR and TC 77 (for emissions and immunity);
- update validation procedure for the test volume regarding field uniformity and TEM mode verification;
- provide information concerning 2-port and 4-port TEM waveguides;

- a new informative annex has been added to deal with transient TEM waveguide characterization; and
- add information dealing with dielectric test stands for EUTs.

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

FDIS	Report on voting
77B/xxx/FDIS	77B/xxx/RVD

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.

A list of all parts of the IEC 61000 series, published under the general title *Electromagnetic compatibility (EMC)*, can be found on the IEC website.

The committee has decided that the contents of the base publication and its amendments will remain unchanged until the stability result 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.

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, Technical Specifications or Technical Reports, some of which have already been published as sections. Others are and will be published with the part number followed by a dash and a second number identifying the subdivision (example: IEC 61000-6-1).

This part of IEC 61000 is an International Standard which gives emission, immunity and HEMP and IEMI transient testing requirements.

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 4-20: Testing and measurement techniques – Emission and immunity testing in transverse electromagnetic (TEM) waveguides

1 Scope and object

This part of IEC 61000 relates to emission and immunity test methods for electrical and electronic equipment using various types of transverse electromagnetic (TEM) waveguides. These types include open structures (for example, striplines and electromagnetic pulse simulators) and closed structures (for example, TEM cells). These structures can be further classified as one-, two-, or multi-port TEM waveguides. The frequency range depends on the specific testing requirements and the specific TEM waveguide type.

The object of this standard is to describe

- TEM waveguide characteristics, including typical frequency ranges and EUT-size limitations;
- TEM waveguide validation methods for EMC tests;
- the EUT (i.e. EUT cabinet and cabling) definition;
- test set-ups, procedures, and requirements for radiated emission testing in TEM waveguides and
- test set-ups, procedures, and requirements for radiated immunity testing in TEM waveguides.

NOTE Test methods are defined in this standard for measuring the effects of electromagnetic radiation on equipment and the electromagnetic emissions from equipment concerned. The simulation and measurement of electromagnetic radiation is not adequately exact for quantitative determination of effects for all end-use installations. The test methods defined are structured for a primary objective of establishing adequate repeatability of results at various test facilities for qualitative analysis of effects.

This standard does not intend to specify the tests to be applied to any particular apparatus or system(s). The main intention of this standard is to provide a general basic reference for all interested product committees of the IEC. For radiated emissions testing, product committees should select emission limits and test methods in consultation with CISPR standards. For radiated immunity testing, product committees remain responsible for the appropriate choice of immunity tests and immunity test limits to be applied to equipment within their scope. This standard describes test methods that are separate from those of IEC 61000-4-3.[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), *International Electrotechnical Vocabulary – Chapter 161: Electromagnetic compatibility*

IEC TR 61000-1-6:2012, *Electromagnetic compatibility (EMC) – Part 1-6: General – Guide to the assessment of measurement uncertainty*

IEC 61000-2-11:1999, *Electromagnetic compatibility (EMC) – Part 2-11: Environment – Classification of HEMP environments*

IEC 61000-4-23, *Electromagnetic compatibility (EMC) – Part 4-23: Testing and measurement techniques – Test methods for protective devices for HEMP and other radiated disturbances*

IEC/TR 61000-4-32, *Electromagnetic compatibility (EMC) – Part 4-32: Testing and measurement techniques – High-altitude electromagnetic pulse (HEMP) simulator compendium*

[1] These other distinct test methods may be used when so specified by product committees, in consultation with CISPR and TC 77.

IEC/TR 61000-5-3, *Electromagnetic compatibility (EMC) – Part 5-3: Installation and mitigation guidelines – HEMP protection concepts*

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 16-1-4, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-4: Radio disturbance and immunity measuring apparatus – Antennas and test sites for radiated disturbance measurements*

CISPR 16-2-3:2006, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 2-3: Methods of measurement of disturbances and immunity – Radiated disturbance measurements*

CISPR 22, *Information technology equipment – Radio disturbance characteristics – Limits and methods of measurement*

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050(161), as well as the following, apply.

3.1.1
transverse electromagnetic mode
TEM mode
waveguide mode in which the components of the electric and magnetic fields in the propagation direction are much less than the primary field components across any transverse cross-section

3.1.2
TEM waveguide
open or closed transmission line system, in which a wave is propagated in the transverse electromagnetic mode to produce a specific field for testing purposes

3.1.3
TEM cell
closed TEM waveguide, often a rectangular coaxial transmission line, in which a wave is propagated in the transverse electromagnetic mode to produce a specific field for testing purposes and with an outer conductor completely enclosing an inner conductor

3.1.4
two-port TEM waveguide
TEM waveguide with an input/output port at each end

3.1.5
one-port TEM waveguide
TEM waveguide with a single input/output port

NOTE Such TEM waveguides typically feature a broadband transmission-line termination at the non-port end.

3.1.6
stripline
terminated transmission line consisting of two or more parallel plates between which a wave is propagated in the transverse electromagnetic mode to produce a specific field for testing purposes

NOTE Striplines usually have open sides for EUT access and monitoring.

3.1.7
four-port TEM waveguide
TEM waveguide with two input-output ports at each end

3.1.8
inner conductor or septum
inner conductor of a coaxial transmission-line system, often flat in the case of a rectangular cross-section, and which may be positioned symmetrically or asymmetrically with respect to the outer conductor

3.1.9
outer conductor or chassis
outer conductor of a coaxial transmission line system, often having a rectangular cross-section

3.1.10
characteristic impedance
for any constant phase wave-front, the magnitude of the ratio of the voltage between the inner conductor and the outer conductor to the current on either conductor and which is independent of the voltage/current magnitudes and depends only on the cross-sectional geometry of the transmission line

NOTE TEM waveguides are typically designed to have a characteristic impedance of 50 Ω. TEM waveguides with a characteristic impedance of 100 Ω are often used for transient testing.

3.1.11
anechoic material
material that exhibits the property of absorbing, or otherwise reducing, the level of electromagnetic energy reflected from that material

3.1.12
broadband transmission-line termination
broadband line termination
termination which combines a low-frequency discrete-component load, to match the characteristic impedance of the TEM waveguides (typically 50 Ω), and a volume of high-frequency anechoic material

3.1.13
correlation algorithm
mathematical routine for converting TEM waveguide voltage measurements to open-area test sites (OATS), semi-anechoic chamber (SAC), or free space field strength levels

3.1.14
EUT type
grouping of products with sufficient similarity in electromagnetic characteristics to allow testing with the same test installation and the same test protocol

3.1.15
exit cable
cable that connects the EUT to equipment external to the TEM waveguide or cable exiting the usable test volume

NOTE The test volume is specified in 5.2.1.

3.1.16
interconnecting cable
cable that connects subcomponents of the EUT within the test volume but does not exit the test volume

3.1.17
test set-up support
non-reflecting, non-conducting, low-permittivity support and positioning reference that allows for precise rotations of the EUT as required by a correlation algorithm or test protocol

NOTE A typical material is foamed polystyrene. Wooden supports are not recommended (see [4]).

3.1.18
ortho-angle
angle that the diagonal of a cube makes to each side face at the trihedral corners of the cube; assuming that the cube is aligned with the TEM waveguide Cartesian coordinate system, the azimuth and elevation angles of the projection of the cube diagonal are 45°, and the angles to the face edges are 54,7°

NOTE 1 Figure A.2a shows a diagram of the ortho-angle.

NOTE 2 When associated with the EUT, this angle is usually referred to as the ortho-axis.

3.1.19
primary (field) component
electric field component aligned with the intended test polarization

NOTE In conventional two-port TEM cells, the septum is parallel to the horizontal floor, and the primary mode electric field vector is vertical at the transverse centre of the TEM cell.

3.1.20
secondary (field) component
in a cartesian coordinate system, either of the two electric field components orthogonal to the primary field component and orthogonal to each other

3.1.21
resultant field (amplitude)
root-sum-squared values in V/m of the primary and the two secondary field components

3.1.22
manipulator
any type of manual or automatic non-metallic test set-up support similar to a turntable, and capable of supporting an affixed EUT throughout numerous positions as required by a correlation algorithm or test protocol

NOTE An example of a manipulator design is shown in Figure A.2.

3.1.23
Test field strength E_{test}
the field strength of the primary field component in V/m that is used for immunity testing.

NOTE Different levels of E_{test} are given in Annex B.

3.1.24
Verification field strength $E_{verification}$
The field strength that is used for the verification of the uniform area. This field strength should be the field strength at which the field probe has been calibrated in order to reduce uncertainties due to the non linearity of the field probe.

3.1.25
Forward power P_{fwd}
Power that is applied to the port of the waveguide.

3.1.26
Forward power for immunity testing P_{test}
forward power required to establish the test field strength E_{test} during immunity testing.

NOTE See equation (14)/(15) for the constant forward power/field strength method.

3.1.27
hyper-rotated TEM waveguide
TEM waveguide that has been reoriented such that its ortho-axis is normal to the surface of the Earth

NOTE Additional details are given in [6].

3.2 Abbreviations

BALUN	balanced-to-unbalanced
DFT	discrete Fourier transform
EUT	equipment under test
FFT	fast Fourier transform
FAR	fully anechoic room
FSOATS	free space open-area test site
GTEM	gigahertz transverse electromagnetic
HEMP	high-altitude electromagnetic pulse
IEMI	intentional electromagnetic interference
OATS	open-area test site
PoE	points of entry
RF	radio frequency

SAC	semi-anechoic chamber
SPD	surge protective device
TDR	time-domain reflectometer
TE	transverse electric (mode), (H-mode)
TEM	transverse electromagnetic
TM	transverse magnetic (mode), (E-mode)
VSWR	voltage standing wave ratio

4 General

This standard describes basic characteristics and limitations of TEM waveguides, namely test volume, field uniformity, purity of the TEM mode, and frequency ranges. Various general properties of TEM waveguides are described in Annex D.

Radiated emission measurements in a TEM waveguide are usually correlated with the open- area test site (OATS) and semi-anechoic chamber (SAC) methods, which provide valid and repeatable measurement results of disturbance field strength from equipment. In this case so-called correlation algorithms are used to convert TEM waveguide measurement results to OATS-equivalent data, as described in Annex A.

TEM waveguides can also be used as field generators for testing the immunity of equipment to electromagnetic fields. Details are given in Annex B. Immunity testing in TEM waveguides is cited in several other standards listed in the Bibliography. Field generation properties can also be used for measuring field strength, see other publications listed in the Bibliography.

TEM waveguide tests are not restricted to radiated measurements on fully assembled equipment. They may also be applied to the testing of components, integrated circuits, and the shielding effectiveness of gasket materials and cables. For further information see the bibliography.

5 TEM waveguide requirements

5.1 General

TEM waveguides can be used for emission and immunity tests when certain requirements are met. For the validation of a TEM waveguide the following methods shall be applied.

This clause focuses on general validation aspects such as the dominant TEM mode and field homogeneity. Specific validation requirements for emission, immunity, and transient testing are given in the Annex A, Annex B, and Annex C, respectively.

5.2 General requirements for the use of TEM waveguides

5.2.1 Test volume and maximum EUT size

The maximum size of an EUT is related to the size of the "usable test volume" in the TEM waveguide. The usable test volume of the TEM waveguide depends on the size, geometry, and the spatial distribution of the electromagnetic fields.

The usable test volume of a TEM waveguide (see Figures D.7 to D.11) depends on the "uniform area" as defined in 5.2.2. The propagation direction of the waveguide TEM mode (typically z-axis) is perpendicular to a uniform area (transverse plane, typically xy-plane). In the xy-plane the entire cross-section of the usable test volume has to fulfil the requirements of the uniform area defined in 5.2.3. The minimum value for the distance h_{EUT} between EUT and each conductor or absorber of the waveguide (see Figures D.7 to D.11) is given by the distance between the boundary of the uniform area (see 5.2.3) and the conductor. However, h_{EUT} should not be zero, in order to avoid the possible change of the EUT operational condition by the close coupling between EUT and conductors of the waveguide (recommended: h_{EUT} should be larger than 0,05 h). Along the z-axis (propagation direction) the usable test volume is limited by $z_{\mathrm{min}} \le z \le z_{\mathrm{max}}$. The length of the test volume is $L = z_{\mathrm{max}} - z_{\mathrm{min}}$. The requirements of a uniform area shall be validated for cross-sections at each z with $z_{\mathrm{min}} \le z \le z_{\mathrm{max}}$. It can be assumed that the TEM mode requirements are fulfilled for $z_{\mathrm{min}} \le z \le z_{\mathrm{max}}$ under the following conditions:

- if TEM mode requirements are fulfilled at the position z_{max}, and the geometry of the waveguide is similar to one of the types shown in Figures D.6 to D.11 with a constant aspect ratio of h to w (inherent shape) for $0 < z < z_{\mathrm{max}}$, or,
- if TEM mode requirements are fulfilled at the positions z_{min} and z_{max}, and the waveguide cross-section is constant or uniformly tapered for $z_{\mathrm{min}} < z < z_{\mathrm{max}}$ and the derivatives dh/dz and dw/dz are a smooth function for $z_{\mathrm{min}} < z < z_{\mathrm{max}}$ (no kinks or steps in the conductor geometries).

The maximum size of an EUT is related to the size of the usable test volume. The EUT shall be verified not to be larger than 0,6 w times 0,6 L (see Figures A.6 to A.9).

NOTE 1 The ISO 11452 series recommends an EUT size of 0,33 $w \times$ 0,6 L, and MIL-STD 462F recommends 0,5 $w \times$ 0,5 L.

The maximum usable EUT height is recommended to be 0,33 h, with h equal to the distance between the inner and outer conductors (conductor spacing) at the centre of the EUT in the test volume (for example, between septum and floor in a TEM cell). For all TEM waveguides, the EUT shall fit within the usable test volume for all rotation positions.

NOTE 2 Most standards restrict EUT size to 0,33 h. Most data sheets from TEM cell suppliers limit the EUT height to a maximum of 0,5 h. Except for highly accurate calibration, such as for field probes and sensors, the EUT height can exceed 0,33 h, but it should not exceed the manufacturer's recommendations. The maximum usable EUT height can be higher than 0,33 h if the manufacturer provides information about the measurement uncertainty for larger EUTs. More information about loaded waveguide effects is given in [37,38].

5.2.2 Validation of usable test volume

5.2.2.1 General considerations

This subclause uses the concept of a "uniform area" which is a hypothetical area in which variations of the field magnitude are acceptably small (see [18]). The TEM waveguide dimensions determine the size of this uniform area (plane), unless the EUT can be fully illuminated in a smaller surface. The maximum size of an EUT is related to the size of the usable test volume (see 5.2.1).

NOTE 1 In general the exact form and the location of the uniform area are not specified, but are determined using the procedures of this standard.

NOTE 2 If no other definition is given, the uniform area should be a vertical plane orthogonal to the propagation direction of the field. It should be one plane face area in front of the EUT.

NOTE 3 The vertical plane assumes that the direction of TEM mode propagation is near horizontal (aligned to the z-axis) and plane wave propagation is given. If the TEM mode propagation direction is in some other direction, the uniform area plane may be re-orientated accordingly.

The use of a transmission line set-up avoids perturbation due to ground-reflected fields as in a semi-anechoic chamber set-up; thus, uniform fields may be established in the vicinity of the inner and outer conductors (in the normal direction only).

In principle, the uniform area may be located at any distance from the input port; the location will depend on the specific waveguide geometry. The uniform area is valid only for that distance from the input port at which it is calibrated. To allow EUT rotation, the uniform area shall be spaced a distance at least greater than the largest case dimension away from the end of the usable test volume z_{max} defined in 5.2.1.

The uniform area is validated in the empty enclosure. The frequency range is from the lowest to the highest frequency of intended use of the TEM waveguide. The first frequency step shall not exceed 1% of the fundamental frequency and thereafter 1% of the preceding frequency in the frequency range from 80 MHz to 1000 MHz, 5% below 80 MHz and above 1000 MHz. One constraint on the sweep speed is the response time of the field probe. The validation of the usable test volume is performed with a non-modulated signal.

NOTE 4 The TEM field is the dominant mode and the cavities are low Q values, therefore resonances are not expected to be narrow. For this reason the use of logarithmic frequencies is acceptable for the validation of the usable test volume.

Depending on the size of the uniform area, it is validated at least with 5 measurement points (4 at the corners and one at the centre). The spacing between two test points has to be less than or equal to 50 cm.

NOTE 5 Choosing a bigger number of measurement points will result in a better outcome of the testing of the field homogeneity. This is due to the big number of measurement points on the outer boundary of the uniform area for small numbers of points. The better outcome is no drawback, because more measurement points result also in a more accurate estimation of the overall field homogeneity.

5.2.2.2 Field uniformity verification

The field uniformity can be verified by the constant power method and the constant field strength method. With the constant forward power method the forward power is kept constant for all grid points and all test frequencies. With the constant field strength method, the primary component of the electric field strength is kept constant for all grid points and all test frequencies. While the constant field strength method is more laborious it is also more accurate, since the linearity of the power meter is usually better than the linearity of the field probe and the field probe is always operated at the field strength it has been calibrated for.

5.2.2.2.1 Constant forward power method

The field is taken into account as sufficient homogeneous, if statistically at least 75% of the measured primary electric field components E_i are within a 6 dB range. A primary electric field component tolerance greater than 6 dB yet smaller than 10 dB is allowed for a maximum of 5% of the test frequencies (at least one frequency), provided that the actual tolerance and frequencies are stated in the test reports. The statistical approach is based on the assumption of normal distribution and the calculation of the mean value and the standard deviation of the primary field component.

At test point i the measured primary field component is given as E_i. The mean value $\overline{E}$ and the standard deviation σ_E are calculated for N test points in logarithmical values.

$$\overline{E} = \frac{1}{N}\sum_{(N)} E_i \tag{1}$$

$$\sigma_\mathrm{E} = \sqrt{\frac{1}{N-1}\sum_{(N)}\left(E_i - \overline{E}\right)^2} \tag{2}$$

In the statistical sense N = 5 reflects a very small quantity but nevertheless a normal distribution for the measurements E_i can be assumed. For the probability that 75% of the measurement results will fall in the range

$$\overline{E} - k\cdot\sigma_\mathrm{E} \le E_i \le \overline{E} + k\cdot\sigma_\mathrm{E} \tag{3}$$

where the factor K is chosen to be 1,15.

Table 1 – Values K for expanded uncertainty with normal distribution

Factor K	1	1,15	1,3	1,5	2	3
Probability %	68,3	75,0	80,6	86,6	95,5	99,7

In case of immunity measurements it is not sufficient to prove the field is homogeneous. It is also requested, that a given percentage of the measurement points result in a field strength that is bigger or equal to the test-field strength E_test. The combination of these claims results in Equation (4).

$$E_\mathrm{test} \le E_i \le E_\mathrm{test} + E_\mathrm{Margin} \tag{4}$$

Comparing the band in Equation (4) with Equation (3) gives Equation (5) with the requirement for field homogeneity.

$$E_\mathrm{test} \le E_i \le E_\mathrm{test} + 2\cdot k\cdot\sigma_\mathrm{E} \tag{5a}$$

$$\sigma_{\mathrm{E}} \leq \frac{\mathrm{Margin}}{2 \cdot k} \tag{5b}$$

For 75% (k=1,15) and a margin of 6 dB the standard deviation shall be $\sigma_{\mathrm{E}} \leq \frac{6\,\mathrm{dB}}{2 \cdot 1{,}15} = 2{,}61\,\mathrm{dB}$.

For 75% (k=1,15) and a margin of 10 dB the standard deviation shall be $\sigma_{\mathrm{E}} \leq \frac{10\,\mathrm{dB}}{2 \cdot 1{,}15} = 4{,}34\,\mathrm{dB}$.

5.2.2.2.2 Constant field strength method

At test point i the measured forward power is given as $P_{\mathrm{fwd};i}$. The mean value $\overline{P}_{\mathrm{fwd}}$ and the standard deviation σ_{P} are calculated for N test points in logarithmical values.

$$\overline{P}_{\mathrm{fwd}} = \frac{1}{N} \sum_{(N)} P_{\mathrm{fwd},i} \tag{6}$$

$$\sigma_{\mathrm{P}} = \sqrt{\frac{1}{N\text{-}1} \sum_{(N)} \left(P_{\mathrm{fwd},i} - \overline{P}_{\mathrm{fwd}}\right)^2} \tag{7}$$

In the statistical sense N=5 reflects a very small quantity but nevertheless a normal distribution for the measurements $P_{\mathrm{fwd};i}$ can be assumed. For the probability, the measurement results of $P_{\mathrm{fwd};i}$ will fall in the range

$$\overline{P}_{\mathrm{fwd}} - k \cdot \sigma_{\mathrm{P}} \leq P_{\mathrm{fwd},i} \leq \overline{P}_{\mathrm{fwd}} + k \cdot \sigma_{\mathrm{P}} \tag{8}$$

where, the factor k is chosen to be 1,15 with the 75% of measurement results (See Table 1).

The field is taken into account as sufficient homogeneous in the constant field strength method, if statistically at least 75% of the measured forward power $P_{\mathrm{fwd};i}$ are within the tolerance of -6 dB to +0 dB. This results in Equation (9).

$$-6\,\mathrm{dB} \leq P_{\mathrm{fwd},i} \leq 0\,\mathrm{dB} \tag{9}$$

Comparing the band in Equation (9) with Equation (8) gives Equation (10) with the requirement for field homogeneity.

$$2 \cdot k \cdot \sigma_{\mathrm{P}} \leq 6\,\mathrm{dB} \tag{10a}$$

$$\sigma_{\mathrm{P}} \leq \frac{6\,\mathrm{dB}}{2 \cdot k} \tag{10b}$$

A forward power tolerance greater than 6 dB yet smaller than 10 dB is allowed for a maximum of 5% of the test frequencies (at least one frequency), provided that the actual tolerance and frequencies are stated in the test reports.

The statistical approach is based on the assumption of normal distribution and the calculation of the mean value and the standard deviation of the forward power.

For 75% (k=1,15) and a margin of 6 dB the standard deviation shall be $\sigma_{\mathrm{p}} \leq \frac{6\,\mathrm{dB}}{2 \cdot 1{,}15} = 2{,}61\,\mathrm{dB}$.

For 75% (k=1,15) and a margin of 10 dB the standard deviation shall be $\sigma_{\mathrm{P}} \leq \frac{10\,\mathrm{dB}}{2 \cdot 1{,}15} = 4{,}34\,\mathrm{dB}$.

5.2.2.3 TEM mode verification

TEM waveguides may exhibit resonances above a certain cut-off frequency determined by the cross-sectional dimensions and/or the waveguide length. For practical use, the field in a TEM waveguide is considered to propagate in a TEM mode when the following requirements are met. This verification of the TEM mode applies to waveguides used either for immunity or emissions testing. The TEM mode behaviour shall be confirmed at regular intervals (see 5.2.2.4).

NOTE 1 Generally, a TEM waveguide manufacturer should verify and document the TEM mode behaviour over the desired frequency range and include verification data with the system documentation.

The TEM mode is taken into account as dominant, if statistically at least 75% of the measured secondary (unintended) electric field components are at least 6 dB smaller than the primary component of the electric field. A secondary electric field component level up to -2 dB of the primary field component is allowed for a maximum of 5% of the test frequencies (at least one frequency), provided that the actual tolerance and frequencies are stated in the test reports.

NOTE 2 The 6 dB criterion from 5.2.2.3 specifies the dominant TEM mode and not the field uniformity, and is separated from and not to be confused with the field uniformity requirements from 5.2.2.2.

The statistical description of the ratio of secondary and primary electric field component is based on the assumption of a Rayleigh distribution. For a Rayleigh distributed measurand the 75% quantile $Q_{75\%}$ can be calculated analytically. It can be assumed, that 75% of the measurement points have a ratio lower than the quantile $Q_{75\%}$.
At test point i the measured primary field component is given as $E_{\mathrm{Prim},i}$ and the secondary field component as $E_{\mathrm{Sec},i}$. Both values are to be expressed for N test points in linear values. Using Equation (6) the parameter s of the Rayleigh distribution can be estimated from the measured field components.

$$s \approx \sqrt{\frac{1}{2 \cdot N} \sum_{(N)} \left(\frac{E_{\mathrm{Sec},i}}{E_{\mathrm{Prim},i}} \right)^2} \tag{11}$$

The P-quantile of the Rayleigh distribution can be calculated by Equation (7).

$$Q_{\mathrm{P}} = \sqrt{-2 \cdot s^2 \cdot \ln(1-P)} \tag{12}$$

For P=0,75 the 75% quantile $Q_{75\%}$ is determined as:

$$Q_{75\%} = \sqrt{-2 \cdot s^2 \cdot \ln(1-0{,}75)} = s \cdot 1{,}6651 \tag{13}$$

For $Q_{75\%}$ < 0,5 it can be assumed, that statistically 75% of the measurement points have a secondary field component that is at least 6 dB smaller than the primary field component. For $Q_{75\%}$ < 0,794 it can be assumed that statistically 75% of the measurement points have a secondary field component that is at least 2 dB smaller than the primary field component.

5.2.2.4 Field uniformity and TEM mode measurement procedure

5.2.2.4.1 Constant forward power method

The procedure for carrying out the validation is known as the “constant forward power” method and is as follows:

a) position the isotropic 3-axis probe at one of the points in the grid;

b) apply a forward power P_{fwd} to the TEM waveguide input port so that the primary component of electric field strength is to be $E_{\mathrm{Verification}}$ through the frequency range with the frequency steps specified in 5.2.2.1, and record all the forward power, primary and secondary components field strength readings;

c) with the same forward power, measure and record the primary and secondary field strengths at the other grid points;

d) calculate the standard deviation σ_{E} according to Equation (2). All measurement results are expressed in dB(V/m);

e) calculate the 75% quantile $Q_{75\%}$ of the ratio of the secondary to the primary field component according to Equation (13). The calculation has to be performed in linear values;

f) the standard deviation σ_{E} shall be smaller than 2,61 dB. It may be in the range of 2,61 dB < σ_{E} < 4,34 dB for a maximum of 5% of the test frequencies (at least one frequency), provided that the actual values and frequencies are stated in the test reports;

g) the 75% quantile $Q_{75\%}$ has to be smaller than 0,5. It may be in the range of 0,5 < $Q_{75\%}$ < 0,794 for a maximum of 5% of the test frequencies (at least one frequency), provided that the actual values and frequencies are stated in the test reports;

h) knowing the forward power P_{fwd}, the mean value of the primary field component and the standard deviation of the primary field component, the required forward power P_{test} for immunity testing (see Annex B) with the test field strength E_{test} can be calculated using Equation (14). The calculation has to be performed in linear values. The coverage factor k has to be chosen according to Table 1. In general, k shall be 1,15. The forward power shall be recorded;

$$P_{\text{test}} = \frac{E_{\text{test}}^2}{\left(\overline{E} - k \cdot \sigma_{\text{E}}\right)^2} \cdot P_{\text{fwd}} \tag{14}$$

i) confirm that the test system (e.g. the power amplifier) is not in saturation. Assuming that E_{Test} has been chosen as 1,8 times a required test level of electric field strength, perform the following procedure in the frequency range:

a. Decrease the output from the signal generator by 5,1 dB from the level needed to establish a forward power of P_{Test}, as determined in the above steps;

b. Record the new forward power delivered to the TEM waveguide;

c. Subtract the forward power measured in step b. from P_{Test}. If the difference in power is between 3,1 and 5,1 dB, then the amplifier is not saturated and is adequate for use. If the difference is less than 3,1 dB, then the amplifier is saturated and is not suitable for use.

A flowchart of the procedure is shown in Fig.1

EXAMPLE If at a given point, 81 W gives a denominator in Equation (14) of 9 V/m, then 9 W is needed for a test field strength of 3 V/m.

5.2.2.4.2 Constant field strength method

The procedure for carrying out the validation is known as the “constant field strength” method and is as follows:

a) position the isotropic 3-axis probe at one of the points in the grid;

b) apply a forward power P_{fwd} to the TEM waveguide input port so that the primary component of electric field strength is to be $E_{\text{Verification}}$ through the frequency range with the frequency steps specified in 5.2.2.1, and record the readings of all the forward powers and primary and secondary components of the field strengths;

c) with the same field strength $E_{\text{Verification}}$, measure and record the readings of all the forward powers and the primary and secondary field components of the field strengths at the other grid points;

d) For field uniformity verification, calculate the standard deviation σ_{P} for all the forward powers measured at the points according to Equation (7) of 5.2.2.2. All measurement results are expressed in dBm;

e) the standard deviation σ_{P} shall be smaller than 2,61 dB;

It is allowed that a maximum of 5% of the test frequencies (at least one frequency) is in the range of 2,61 dB < σ_{P} < 4,34 dB. The actual values and frequencies shall be stated in the test reports;

f) for TEM mode verification, calculate the 75% quantile $Q_{75\%}$ of the ratio of the secondary to the primary field component according to Equation (13). The calculation has to be performed in linear values;

g) the 75% quantile $Q_{75\%}$ has to be smaller than 0,5. It may be in the range of 0,5 < $Q_{75\%}$ < 0,794 for a maximum of 5% of the test frequencies (at least one frequency), provided that the actual values and frequencies are stated in the test reports;

h) for immunity tests (see Annex B), knowing the forward power and the field strength $E_{\text{Verification}}$, the necessary forward power P_{Test} for the required test-field strength E_{Test} can be calculated using Equation (15). The forward power shall be recorded;

$$P_{\text{test}} = \left(\frac{E_{\text{test}}}{E_{\text{Verification}}}\right)^2 \cdot \left(\overline{P}_{\text{fwd}} + k \cdot \sigma_{\text{P}}\right) \tag{15}$$

i) confirm that the test system (e.g. the power amplifier) is not in saturation. Assuming that E_{Test} has been chosen as 1,8 times a required test level of electric field strength, perform the following procedure in the frequency range:

a. decrease the output from the signal generator by 5,1 dB from the level needed to establish a forward power of P_{Test}, as determined in the above steps;

b. record the new forward power delivered to the TEM waveguide;

c. subtract the forward power measured in step b from P_{Test}. If the difference in power is between 3,1 and 5,1 dB, then the amplifier is not saturated and is adequate for use. If the difference is less than 3,1 dB, then the amplifier is saturated and is not suitable for use.

A Flowchart of the procedure is shown in Fig. 2.

The uniformity validation is applicable for all EUTs whose individual faces (including any cabling) can be fully enclosed by the ”uniform area“. It is intended that the full uniform area validation be carried out annually or when changes have been made to the enclosure configuration (e.g. TEM cell or stripline within a shielded enclosure).

5.3 Special requirements and recommendations for certain types of TEM waveguides

5.3.1 Set-up of open TEM waveguides

To minimize ambient effects, open TEM waveguides should be installed inside a shielded room.

NOTE 1 The permitted ambient signal levels are defined in Annexes A, B, and C and strongly depend on the test objectives.

A minimum distance of one plate spacing h from the open TEM waveguide to the shielded-room floor, walls, and ceiling is recommended. Additional anechoic material can be placed appropriately in the shielded room to minimize reflections. These distances are given for guidance only. Note that it is possible to construct an open TEM waveguide where one plate consists of the floor of the shielded room and the other is an installed septum.

NOTE 2 MIL-STD 461F requires open TEM waveguides to be positioned in a shielded room. The required minimum distance to walls should be set in relation to the size of the waveguide. MIL-STD 462F RS105 requires a distance of two times h from the closest metallic ground including ceiling, shielded room walls, and so forth, where h is the maximum vertical separation of the plates. CISPR 20 requires a minimum distance of 800 mm from walls, floor, and ceiling, corresponding to one h.

5.3.2 Alternative TEM mode verification for a two-port TEM waveguide

As an alternative to the provisions in 5.2.1, the useful frequency range of a two-port TEM waveguide can be established using the following verification method.

Before testing the EUT, the TEM waveguide resonances shall be determined for two-port TEM devices with the test set-up and EUT installed, with EUT power off. In this case, the transmission loss of the TEM waveguide in the useful frequency range shall fulfil

$$A_{\mathrm{tloss}} = \left| 10 \cdot \lg\left(\frac{P_{\mathrm{refl}}}{P_{\mathrm{fwd}}} - \frac{P_{\mathrm{output}}}{P_{\mathrm{fwd}}} \right) \right| \quad \leq \quad 1\,\mathrm{dB} \tag{8}$$

where

A_{tloss} is the transmission loss of the loaded waveguide, in dB;

P_{refl} is the reflected power measured at the input port, in W;

P_{fwd} is the forward power measured at the input port, in W;

P_{output} is the output power measured at the second (output) port, in W.

NOTE 1 The reflected, forward and backward (output) power is measured with respect to the characteristic impedance of the TEM waveguide. An impedance transformer is not used. It is measured "in line" only. Equation (8) is valid for characteristic impedance of 50 Ω.

NOTE 2 This is an alternative verification method for a two-port TEM waveguide of the type described in ISO 11452-3, and is based on the assumption that resonating higher order modes will extract energy from the TEM mode.

5.3.3 TEM mode generation for a four-port TEM waveguide

In order to generate a TEM mode, input signals shall be applied into ports 1 and 2 with the same amplitude and reversed phase as is shown in Figure D.6. Ports 3 and 4 shall be terminated with lumped loads, which should be well matched to 50 Ω in a test frequency range (see [59], [36]).

6 Overview of EUT types

6.1 General

An EUT type is a group of products with sufficient similarity in electromagnetic characteristics or mechanical dimensions that testing with the same test installation and the same test protocol is allowable. The EUT type and its configuration are valid for immunity and emission testing to allow a uniform arrangement in the test volume.

6.2 Small EUT

An EUT is defined as a small EUT if the largest dimension of the case is smaller than one wavelength at the highest test frequency (for example, at 1 GHz λ = 300 mm), and if no cables are connected to the EUT. All other EUTs are defined as large EUTs.

6.3 Large EUT

An EUT is defined as a large EUT if it is

- an EUT with one or more exit cables,
- an EUT with one or more connected non-exit cables,
- an EUT with or without cable(s) which has a dimension larger than one wavelength at the highest test frequency,
- a group of small EUTs arranged in a test set-up with interconnecting non-exit cables, and with or without exit cables.

However, a single EUT with interconnecting cables being part of that EUT, and a cable routing that is not changed during the test, is considered to be a small EUT if the overall EUT dimensions meet the requirement specified in 6.2.

7 Laboratory test conditions

7.1 General

In order to minimize the effect of environmental parameters on test results, the test shall be carried out in climatic and electromagnetic reference conditions as specified in 7.2 and 7.3.

7.2 Climatic conditions

Unless otherwise specified by the committee responsible for the generic or product standard, the climatic conditions in the laboratory shall be within any limits specified for the operation of the EUT and the test equipment by their respective manufacturers.

Tests shall not be performed if the relative humidity is so high as to cause condensation on the EUT or the test equipment.

NOTE Where there is evidence that the measurements covered by this standard are influenced by climatic conditions, this should be noted in the test report.

7.3 Electromagnetic conditions

The electromagnetic conditions of the laboratory shall be such as to guarantee the correct operation of the EUT in order not to influence the test results.

8 Evaluation and reporting of test results

Testing 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.

The test report shall contain all the information necessary to reproduce the test. In particular, the following shall be recorded:

– the items specified in the test plan;
– identification of the EUT and any associated equipment, for example, brand name, product type, serial number;
– identification of the test equipment, for example, brand name, product type, serial number;
– any special environmental conditions in which the test was performed;

– any specific conditions necessary to enable the test to be performed;

– performance level defined by the manufacturer, requestor or purchaser;

– for immunity, performance criterion specified in the generic, product or product-family standard;

– any effects on the EUT observed during or after the application of the test disturbance, and the duration for which these effects persist;

– for immunity, the rationale for the pass/fail decision (based on the performance criterion specified in the generic, product or product-family standard, or agreed between the manufacturer and the purchaser);

– any specific conditions of use, for example cable length or type, shielding or grounding, or EUT operating conditions, which are required to achieve compliance;

– drawing and/or pictures of the test set-up and EUT arrangement.

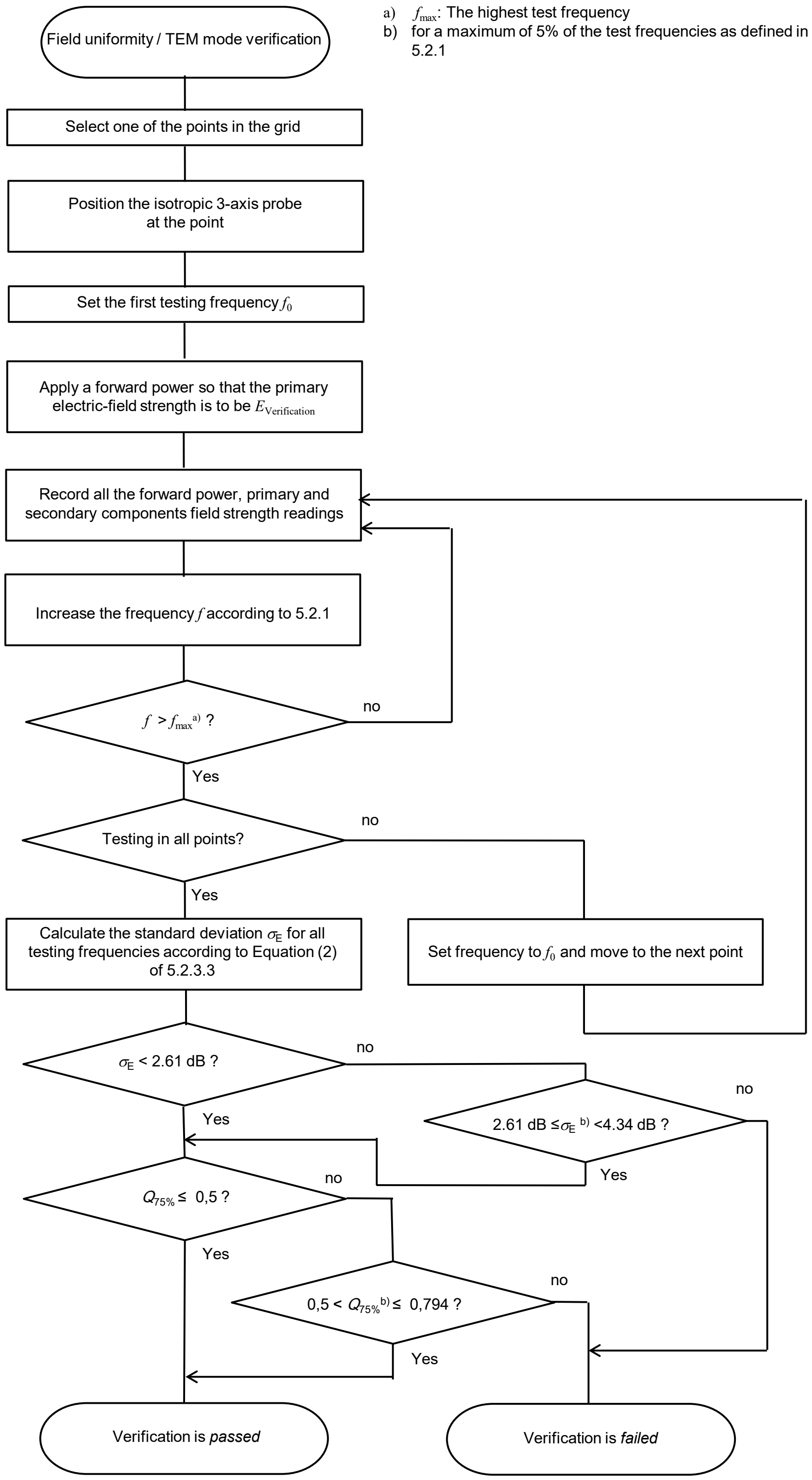


Fig.1 Flowchart of TEM mode/field uniformity verification procedure with the “constant forward power” method

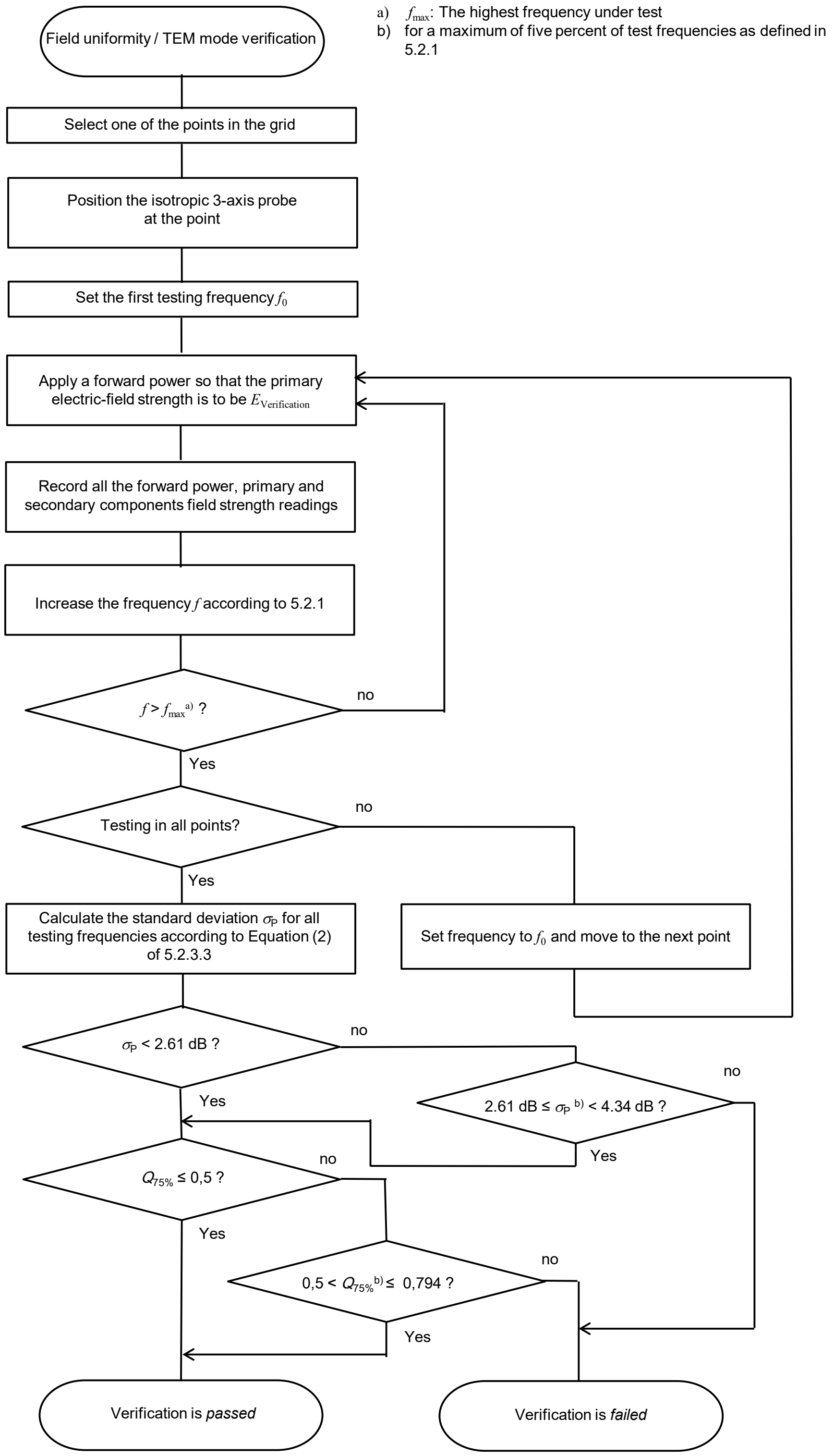


Fig.2 Flowchart of TEM mode/field uniformity verification procedure with the “constant field strength” method

Annex A
(normative)

Emission testing in TEM waveguides

A.1 Overview

This annex describes emission testing in TEM waveguides.

Emission tests made in TEM waveguides may be compared with limits derived in one of two ways:

- **TEM waveguide-based limits**

  This approach has been applied to specific product families (for example, procedures for integrated circuits, military devices, vehicle components and modules, etc.), as described in the references of the Bibliography. In this case, TEM waveguide test results are used and compared directly to an independent disturbance limit or guideline, usually developed specifically for one type of TEM waveguide. In some cases, the TEM waveguide limits may be derived from limit values used in other test facilities (see [50]).

- **OATS-based limits**

  This approach is applicable for EUTs which have to comply with disturbance limits given in terms of field strength at an OATS. A correlation algorithm is used to derive the OATS field strength from TEM waveguide tests.

Only the second case is described in detail in this annex. Emission testing using TEM waveguides requires a validation in order to demonstrate the suitability of the TEM waveguide being used. For each EUT type a validation procedure shall be carried out as described in Clause 5. In cases where only relative comparison will be made within the same EUT product family, correlation to OATS or other test sites is not required. In that case, product committees shall supply specific limits to determine the compliance of the test data.

Correlation algorithms are described in Clause A.3. Correlation algorithms use TEM waveguide voltage measurements to estimate equivalent OATS field strengths. Free space field strengths may also be estimated. These field strengths, along with test results from the EUT type validation procedure, may then be compared to the requirements in standards.

NOTE The test procedures typically require that the EUT be rotated about all three axes. If a hyper-rotated TEM waveguide is used (see [6]), the TEM waveguide is re-oriented so that its ortho-axis is normal to the surface of the Earth. The EUT is rotated by ±120° about its vertical axis (which is its ortho-axis). The EUT needs not be rotated around its horizontal axis.

A.2 Test equipment

The test equipment shall comply with the relevant requirements of CISPR 16-1-1.

NOTE An isotropic field sensor can be seen as an antenna (see CISPR 16-1-4 for antenna requirements). The calibration procedures of isotropic field probes and their specifications are described in [34].

A.3 Correlating TEM waveguide voltages to E-field data

A.3.1 General remarks

This procedure is intended to establish an alternative to OATS emissions test methods. The TEM waveguide results are converted to equivalent OATS E-field data. This subclause describes an algorithm based on the assumption that the radiated power, as derived from a TEM waveguide measurement, will be radiated by a dipole positioned above a perfectly conducting ground plane.

Correlation routines include the distance between the EUT and each conductor, h_{EUT}, and the conductor spacing h (or plate separation) at the centre of the EUT (see Figures A.6b) and A.7b) in the calculation. The voltages measured with the EUT placed in the TEM waveguide are generated by the EUT emissions. After rotation (repositioning) of the EUT according to the requirements of the correlation routine, further voltage measurements are taken until all required positions have been tested. The correlation routine then uses these data to simulate an OATS test.

NOTE Information about correlation and correlation data for emission measurements can be found in [5], [9], [22], [30], [48], [50], [55] and [56].

The following subclause describes an algorithm based on a three-position test. Other algorithms have been proposed and may be useful for some EUTs (see [45] and [56]).

A.3.2 Correlation algorithms

A.3.2.1 General

Subclauses A.3.2.2 and A.3.2.3 show independent correlation approaches. Subclause A.3.2.2 describes the basic approach of correlation routines for the “multipole model,” and uses a set of waveguide tests in order to determine the equivalent multipole moments. Subclause A.3.2.3 describes another correlation routine which uses three voltage measurements. This latter procedure is often referred to as the “total radiated power method”.

A.3.2.2 Multipole model

Any radiation source of finite size may be replaced by an equivalent multipole expansion which gives the same radiation pattern outside a volume encompassing the source. If the source is electrically small (characteristic dimensions less than 0,1 times the wavelength), then the initial multipole expansion terms, effectively electric and magnetic dipoles, will yield an accurate simulation of the source. The above statement holds for an arbitrary source. If the source itself consists of electric and magnetic dipole-like elements only, then the size restriction with respect to the wavelength may be relaxed.

The basic approach of correlation algorithms between TEM waveguides and open-area test site or free space data is to use a set of TEM waveguide tests in order to determine the multipole moments. Usually three complex-valued orthogonal dipole moments are used, requiring six or more measurements. With the basic three-orientation method, radiated power is estimated, but not the individual multipole moments. Once the radiated power is estimated, radiated fields either in free space or over an infinite ground plane may be derived numerically. In this way, it is possible to simulate the various source-to-receiver antenna configurations required by OATS emission standards.

For two-port TEM waveguides, measurements at both ports yield both amplitude and relative phase information (see [17], [42], [44], [49] and [52]). In this manner both the magnitude and the phase of the multipole moments may be determined and the radiation pattern accurately simulated, including possible nulls due to phase cancellation. For one-port TEM waveguides no relative phase information is available; thus, it is only possible to determine the magnitudes of the multipole moments (see [50], [55] and [56]). Because relative phase information is not known, one-port TEM waveguide correlation routines assume that all of the multipole moments radiate in phase. This yields an upper bound estimate only (see [13], [41] and [53]). Detailed radiation patterns cannot be simulated. The upper bound estimate is valid for comparison to standards limits. In [45] and [46] it was shown that cross-polar coupling does occur in TEM waveguides. The influences on emission tests have been shown there.

A.3.2.3 One-port TEM waveguide correlation algorithm

A.3.2.3.1 General

The one-port correlation algorithm is based on three voltage measurements made in a TEM waveguide from which the total radiated power of the EUT may be calculated. The individual dipole moments are not separately determined. The total radiated power is then used to simulate the maximum EUT fields over a ground plane based on a model of parallel dipoles (source and receive dipole) transmitting the same total power.

A.3.2.3.2 TEM waveguide voltage measurements

The voltages are measured for three orientations of the EUT that are specified as follows. An (x,y,z) axis system is assigned to the TEM cell. A standard choice is to align the z-axis in the direction of propagation, the y-axis parallel to the E-field (vertical) and the x-axis parallel to the H-field. The centre of the EUT is placed at (x = 0, y, z) with x = 0 in the middle of the septum. A local "primed" coordinate system (x', y', z') is assigned to the EUT. Position *a* aligns x' with x, y' with y, and z' with z, as indicated in Figure A.3. Position *b* is obtained by simply permuting the primed EUT axes: x' to y, y' to z, and z' to x. This is equivalent to two 90° rotations of the EUT. Position *c* is obtained by a further permutation: x' to z, y' to x, z' to y. Designating the three voltage measurements by V_{p1}, V_{p2}, V_{p3}, it can be shown (see [45] and [56]) that the total radiated power $\boldsymbol{P_0}$ due to the EUT is given by

$$P_0 = \frac{\eta_0}{3\pi} \cdot \frac{k_0^2}{e_{0_y}^2 Z_C} \cdot S^2 \text{, in W} \qquad \text{(A.1)}$$

where

$$S=\sqrt{V_{p1}^2+V_{p2}^2+V_{p3}^2}\text{, with } V_p \text{ in V} \qquad \text{(A.2a)}$$

$$S=\sqrt{10^{\frac{V_{p1}|_{dB}-120}{10}}+10^{\frac{V_{p2}|_{dB}-120}{10}}+10^{\frac{V_{p3}|_{dB}-120}{10}}}\text{, with } V_p|_{dB} \text{ in dB}(\mu\text{V}) \qquad \text{(A.2b)}$$

and

V_{p1}, V_{p2}, V_{p3}	are the voltage measurements from three EUT positions;
S	is the root-sum-square of measured voltages, in V;
$k_0=\frac{2\pi}{\lambda}$	is the wave number, k_0 in $\frac{1}{\text{m}}$;
$\eta_0=\sqrt{\frac{\mu_0}{\varepsilon_0}}$ = 120 π Ω ≈ 377 Ω	is the free space wave impedance in Ω;
Z_C	is the characteristic impedance of the TEM waveguide in Ω (typically 50 Ω);
e_{0_y}	is the TEM mode field factor: the normalized y-component of the electric field at the EUT location (for Equation (A.1): (x = 0, y, z)), in $\frac{\sqrt{\Omega}}{\text{m}}$.

NOTE For some EUTs, it may be necessary to test three orthogonal orientations at each of four start orientations (start orientations a1, a2, a3 and a4 in Figure A.4) for a total of 12 canonical orientations. The maximum voltage measurement and the voltage measurements from the two corresponding orthogonal orientations are then used in the usual three-orientations method [29].

A.3.2.3.3 Determining the field factor

General

The algorithm described here requires the primary y-component TEM mode electric field. Higher order field modes are not directly coupled to the voltage at the port. The field factor e_{0y} is the normalized y-component of the electric field of the TEM mode at a given test location of the EUT. Two possible procedures to derive the field factor e_{0_y} are as follows.

The e_{0_y} field factor for each specific type and size of TEM waveguide shall be provided by the manufacturer.

Experimental procedure

The field factor can be determined experimentally via a measurement of the y-component of the electric field E_y in V/m (for an empty cell) at the location (x, y, z) of the EUT centre with a known input power P_i in watts

$$e_{0_y}=\frac{E_y(x,y)}{\sqrt{P_i}} \quad \text{in } \frac{\sqrt{\Omega}}{\text{m}} \qquad \text{(A.3)}$$

Analytical procedure

For a TEM cell with a rectangular cross-section as shown in [56] the normalized TEM mode component can be analytically approximated with the equation

$$e_{0_y}=\frac{4}{a}\sqrt{Z_c}\cdot\sum_{m=1,3,5\cdots}^{\infty}\left(\frac{\cosh(M\cdot y)}{\sinh(M\cdot h)}\cdot\cos(M\cdot x)\cdot\sin\left(M\frac{a}{2}\right)\cdot J_0(M\cdot g)\right) \quad \text{in } \frac{\sqrt{\Omega}}{\text{m}} \qquad \text{(A.4)}$$

where

$\boldsymbol{M} = \boldsymbol{m}\frac{\pi}{\boldsymbol{a}}$, m = 1, 3, 5,...,∞ , in 1/m;

a is the cell width (see Figures D.7 to D.11) at z, in m;

h is the septum height at z, in m;

g is the gap width at z, in m;

x,y,z is the location of the EUT centre, in m;

J_0 is the zero-order Bessel function, dimensionless.

Only a few terms of this series need to be retained for a good approximation of e_{0_y}. Field factor results for a variety of geometries are given in [41].

A.3.2.4 Correlation to OATS

EUT emissions over an OATS are simulated by assuming that the EUT's total radiated power, as estimated by the TEM waveguide tests, is the same as that emitted by a dipole (replacing the EUT) over an ideal perfectly conducting half-space.

The equations for the fields from a dipole are well known and the ideal ground plane is accounted for by introducing an image dipole. The fields are calculated over the equivalent height scan of the receiving antenna as required by the OATS method. The simulated maximum received signal for two polarizations (horizontal, vertical) then gives the estimated maximum field strength $E_{\max}$. Using the geometry factor $g_{\max}$ determined by the height-scan of the receiving dipole, $E_{\max}$ is given by

$$E_{\max} = g_{\max} \cdot \sqrt{\frac{3\eta_0}{4\pi} P_0}\text{, in } \frac{\mathbf{V}}{\mathbf{m}} \qquad \text{(A.5)}$$

$$E_{\max} = g_{\max} \cdot \frac{\eta_0 k_0}{2\pi \cdot e_{0y}} \cdot \frac{S}{\sqrt{Z_C}}\text{, in } \frac{\mathbf{V}}{\mathbf{m}} \qquad \text{(A.6)}$$

where

S is defined by Equation (A.2), in V;

$k_0 = \dfrac{2\pi}{\lambda}$ is the wave number in $\dfrac{\mathbf{1}}{\mathbf{m}}$;

$\eta_0 = \sqrt{\dfrac{\mu_0}{\varepsilon_0}} = 120\pi\Omega \approx 377\ \Omega$ is the free-space impedance in Ω;

Z_c is the characteristic impedance in Ω;

e_{0_y} is the TEM-mode field factor in $\dfrac{\sqrt{\Omega}}{\mathbf{m}}$

and

$$g_{\max} = \begin{cases} \left|\dfrac{e^{-jk_0 r_1}}{r_1} - \dfrac{e^{-jk_0 r_2}}{r_2}\right|_{\max} = \left|\dfrac{1}{r_1 r_2}\left[r_2^2 + r_1^2 - 2r_1 r_2 \cos k_0(r_2 - r_1)\right]^{1/2}\right|_{\max} & \textbf{horizontal polarization} \\ \left|\dfrac{s^2}{r_1^2}\dfrac{e^{-jk_0 r_1}}{r_1} + \dfrac{s^2}{r_2^2}\dfrac{e^{-jk_0 r_2}}{r_2}\right|_{\max} = \left|\dfrac{s^2}{r_1^3 r_2^3}\left[r_2^6 + r_1^6 + 2r_1^3 r_2^3 \cos k_0(r_2 - r_1)\right]^{1/2}\right|_{\max} & \textbf{vertical polarization} \end{cases}$$

$$g_{\max} \text{ in } \frac{\mathbf{1}}{\mathbf{m}} \qquad \text{(A.7)}$$

with the following parameters as shown in Figure A.5:

$r_1 = \sqrt{s^2 + (R_H - h_g)^2}$ distance source dipole to receiving dipole, in m;

$r_2 = \sqrt{s^2 + (R_H + h_g)^2}$ distance image dipole to receiving dipole, in m;

s receiving dipole to source dipole horizontal distance as designated in normative standards. Normally this value is 30 m, 10 m or 3 m, in m;

h_g height of EUT above ground plane, in m;

R_H height of receiving dipole above ground plane, in m. Normally this parameter is varied over the range 1 m to 4 m.

NOTE 1 The maximum free-space, far-zone electric field at a distance r is given by $E_{\mathrm{max}} = \frac{1}{r}\sqrt{\frac{\eta_0}{4\pi} D_{\mathrm{max}} P_0}$, where D_{max} is the maximum directivity of the antenna. Equation (A.5) follows from setting D_{max} equal to 3 and accounting for the image antenna and distance r via the geometry factor g_{max}. The value 3 is an upper limit for an electrically small antenna and follows from the presence of an electric and a magnetic dipole both orientated and phased for maximum directivity. For an electric or magnetic dipole alone D_{max} = 1,5. This is the more likely case for an unintentional radiator since one source type should be dominant. In this sense, Equation (A.5) may be viewed as the “worst case”.

Generally, the directivity D is given by either an assumed value, or a value known *a priori*, or the measured directivity of the EUT. The one-port TEM waveguide correlation algorithm has always assumed a “worst-case” estimate based on a) total radiated power versus the OATS scanning volume or cone and b) the implicit worst-case directivity choice. For comparison with other total radiated power emissions test methods, for example, reverberation chambers, directivities of D = 1, 5 or D = 1,7 may be used. For the purposes of this standard, it has been agreed to use a “worst-case” small-EUT directivity of D = 3.

NOTE 2 This correlation is valid for small EUTs as defined in 6.2.

NOTE 3 For product classes having approximately the same size (form factor) and functionality, a full TEM waveguide to OATS comparison is made using a representative product from that class. This comparison forms a reference so that only TEM waveguide testing is needed for other products within that specific product class.

NOTE 4 Another correlation is to free space. For the free space case, or an equivalent fully anechoic chamber, the reflection terms caused by the ground plane (terms with subscript 2 in Equation (A.7)) are omitted.

Alternately, E_{max} may be expressed in terms of dB(μV/m) as

$$E_{\mathrm{max}} = 20 \cdot \log_{10}\left(\frac{g_{\mathrm{max}}}{\mathrm{m}^{-1}}\right) + 10 \cdot \log_{10}\left(\frac{P_0}{1\,\mathrm{W}}\right) + 139{,}5 \text{, in dB}(\mu\text{V/m}) \qquad \text{(A.8)}$$

The factor $20 \cdot \log_{10}\left(g_{\mathrm{max}} \cdot 1\,\mathrm{m}\right)$ may be calculated each time, or interpolated from pre-calculated look-up tables for standard geometries.

E_{max} can also be expressed as a function of the measured voltages. The insertion of P_0 from Equation (A.1) and S from Equation (A.2) into Equation (A.5) and conversion to dB(μV/m) leads to

$$E_{\mathrm{max}} = 20 \cdot \log_{10}\left(\frac{g_{\mathrm{max}}}{\mathrm{m}^{-1}}\right) + 20 \cdot \log_{10}\left(\left|\frac{\eta_0 k_0}{2\pi \cdot e_{0y} \cdot \sqrt{\Omega}}\right|\right) + 10 \cdot \log_{10}\left(\frac{S^2}{Z_C \cdot 1\,\mathrm{W}}\right) + 120 \text{, in dB}(\mu\text{V/m}) \qquad \text{(A.9)}$$

A.4 Emission test correction factors

A.4.1 Reference emission sources

Correction factors can be determined using a set of reference emission sources with well-characterized OATS-method emission responses. The reference sources are selected on the basis of the types of EUTs that will be tested in the TEM waveguide. Five types of reference sources are recommended to represent general EMC applications. These represent variations of table-top equipment as defined in CISPR 22.

a) A battery-powered comb generator with a broadband antenna, which is an example of a small EUT. The largest dimension of the comb generator should be smaller than 0,1 h, where h is the conductor spacing. If there is no comb generator available on the market that fulfils the size requirement, a comb generator up to 0,35 h may be used. In this case the size and type of the used comb generator and the regularly allowed size (0,1 h) are stated at the same position of the test protocol and are marked specially. The EUT case should be smaller than one wavelength at the highest frequency tested (see 6.2).

b) A battery-powered comb generator with a wire attached, which is an example of a large EUT without exit cables (see 6.3). The attached wire should extend to the edge of, but remain within, the usable test volume.

c) A battery-powered comb generator with an attached exit cable, which is an example of a large EUT with exit cables. The attached wire runs to and through a ferrite clamp.

d) A (480 mm) case with a built-in comb generator, with at least two exit cables, intended to be an example of a large EUT with exit cables.

e) As in terms a) to d), with a built in broadband noise source.

For examples a) to d), the comb generator should produce spectral lines every 10 MHz or less over the entire frequency range of interest. For example e), the broadband source should cover the entire frequency range of interest.

The output spectrum should be stable with variations of less than 1 dB during the test duration.

NOTE If the largest dimension of the source is smaller than 0,1 h, minimal perturbation of the TEM mode can be assumed.

For manufacturers of specific TEM waveguide types and sizes, it is recommended that emission tests be performed using the examples of EUTs in four or more TEM waveguides of the same type and size, and four or more different OATS. The results are valid for all TEM waveguides of the same type and size. An identical EUT arrangement, receiver detector function, dwell time, and bandwidth should be used at all frequencies and at each test site. The three-orientation correlation algorithm should be applied to convert the TEM waveguide-measured voltages into OATS field strength values.

A.4.2 Arrangement of small EUTs

Tests are performed using a specific test sequence with an example of a small EUT in a TEM waveguide. The EUT is placed in the centre of the test volume, for example on a test set-up support, and turned to a minimum of three orthogonal orientations around the ortho-axis (see Figure A.2). In some cases, the use of a non-conductive cube to enclose the affixed EUT, or use of a manipulator, may assist with the rotations.

A.4.3 Calculation of the small EUT correction factor

In the case of the example of a small EUT, a statistical correction factor has been seen to improve the agreement between OATS and three-orientation correlation algorithm TEM waveguide field strengths.

NOTE 1 The emission measurement in TEM waveguides is based on the total radiated power method. Therefore, all possible orientations are considered. When comparing OATS data with TEM waveguide measurements, the operator should select the orientation of the EUT on the OATS with the maximum emission.

The correction factor calculation is based on the differences of the average and standard deviation of both the TEM waveguide-correlated and the OATS-measured field strengths at each frequency. An additional radiation pattern correction factor has also been seen to improve agreement between OATS and TEM waveguide results for the example small EUT. The correction factor c_f at each frequency f is calculated using

$$c_f = \bar{x}_f - d_{s,f} - t \text{, in } \frac{\mathrm{V}}{\mathrm{m}} \qquad \text{(A.10)}$$

where

$\bar{x}_f$ is the average difference between the TEM waveguide and the OATS field strengths, in $\frac{\mathrm{V}}{\mathrm{m}}$;

$d_{s,f}$ is the difference of standard deviations of multiple TEM waveguide and OATS readings (Equation (A.12)), in $\frac{\mathrm{V}}{\mathrm{m}}$;

t is the radiation pattern uncertainty factor (Equation (A.18)), in $\frac{\mathrm{V}}{\mathrm{m}}$.

NOTE 2 Even a small EUT may not have an omnidirectional radiation pattern. This difference should be taken into account by the factor t in Equation (A.10). Measurements on different OATS and in different TEM waveguides may result in deviations also. This is taken into account by $d_{s,f}$ in Equation (A.10). The typical order of magnitude of t and $d_{s,f}$ is 1 dB.

The difference of averages of the field strengths at each frequency is given by

$$\bar{x}_f = \left(\frac{1}{n} \sum_{i=1}^{n} g_{i,f} - \frac{1}{m} \sum_{k=1}^{m} o_{k,f} \right) \text{ in } \frac{\mathrm{V}}{\mathrm{m}} \qquad \text{(A.11)}$$

where

$g_{i,f}$	is the TEM waveguide electric field strength correlated with free space (A.3.2.4), in $\frac{\mathrm{V}}{\mathrm{m}}$;
$i = 1 \cdots n$	n is the number of TEM waveguide measurements;
$o_{k,f}$	is the OATS electric field strength, in $\frac{\mathrm{V}}{\mathrm{m}}$;
$k = 1 \cdots m$	m is the number of OATS measurements;
f	is the frequency, in Hz;
$g_{i,f}$	are the correlated field strengths from $i = 1 \cdots n$ measurements using one or more TEM waveguides of a specific type and size, and
$o_{k,f}$	are the results from $k = 1 \cdots m$ measurements using one or more different OATS.

NOTE 3 The quantities g_{if} and o_{kf} follow a log-normal distribution and therefore the Equation (A.11) can be expressed in logarithmic scale in this case.

The difference of the standard deviations of the multiple TEM waveguide and OATS readings is given by

$$d_{s,f} = s_{\mathrm{TEM},f} - s_{\mathrm{OATS},f}, \text{ in } \frac{\mathrm{V}}{\mathrm{m}}. \qquad \text{(A.12)}$$

Here $s_{\mathrm{TEM},f}$ is the standard deviation of the TEM waveguide multiple field strength values, given by

$$s_{\mathrm{TEM},f} = \sqrt{\frac{\sum_{i=1}^{n} \left(g_{i,f} - \bar{g}_f \right)^2}{n-1}}, \text{ in } \frac{\mathrm{V}}{\mathrm{m}}, \qquad \text{(A.13)}$$

and $s_{\mathrm{OATS,f}}$ is the standard deviation of the results from one or multiple OATS, given by

$$s_{\mathrm{OATS},f} = \sqrt{\frac{\sum_{k=1}^{m} \left(o_{k,f} - \bar{o}_f \right)^2}{m-1}}, \text{ in } \frac{\mathrm{V}}{\mathrm{m}} \qquad \text{(A.14)}$$

In these standard deviation equations, the mean of each TEM waveguide and the OATS levels are given by

TEM waveguide: $$\bar{g}_f = \frac{1}{n} \sum_{i=1}^{n} g_{i,f}, \text{ in } \frac{\mathrm{V}}{\mathrm{m}} \qquad \text{(A.15)}$$

OATS: $$\bar{o}_f = \frac{1}{m} \sum_{k=1}^{m} o_{k,f}, \ o_{k,f} \text{ in } \frac{\mathrm{V}}{\mathrm{m}} \qquad \text{(A.16)}$$

NOTE 4 If the TEM waveguide is unique (n = 1), for example, built for scientific use in a single laboratory, then $s_{\mathrm{TEM},f} = 0$ for the determination of the correction factor of this specific waveguide. Therefore, these results cannot be used for the validation of any other TEM waveguide, even of the same type and size.

For each specific TEM waveguide, the radiation pattern uncertainty factor t is derived from a series of three-position correlation tests made at eight starting positions of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°, for example. For instance, for the start position of Figure A.4.a1 (*xx'yy'zz'*), the EUT is rotated to these angles around the y-axis. At each start position, the three-position correlation method is used to yield, in sum, a series of eight correlated field strength values designated E_α(8 × 3 = 24 voltage readings). $\bar{E}_\alpha$ is the mean value of the electric field, specifically, $\bar{E}_{0^\circ} = (E_{0^\circ} + E_{90^\circ})/2$, ... $\bar{E}_{225^\circ} = (E_{225^\circ} + E_{315^\circ})/2$. A maximum field strength, $E_{\alpha,\max}$, is obtained as the highest field strength for each pair of values separated by 90°. Specifically, $E_{0^\circ,\max} = \max(E_{0^\circ}, E_{90^\circ})$,.... $E_{225^\circ,\max} = \max(E_{225^\circ}, E_{315^\circ})$. A standard deviation factor is calculated using the following equation.

$$t_{90^\circ,f} = \sqrt{\frac{\sum_{\alpha=0^\circ \cap 90^\circ}^{225^\circ \cap 315^\circ} \left(E_{\alpha,\max} - \bar{E}_\alpha\right)^2}{l-1}}, \text{ in } \frac{\text{V}}{\text{m}} \tag{A.17}$$

where l is the number of start positions (eight in the above example).

The final radiation pattern uncertainty factor t is obtained as the average of these, or

$$t = \frac{1}{n}\sum_{i=1}^{n}\left(t_{90^\circ,f}\right)_i, \text{ in } \frac{\text{V}}{\text{m}}. \tag{A.18}$$

NOTE 5 An alternative to the t-factor (radiation pattern uncertainty factor) may be the six-position method of [40], or the 12-position method (“enhanced three-position”) of [51]. The important issue is that EUT total radiated power should be captured. Comparison data are shown in [28] and [29].

A.5 Emission test procedures in TEM waveguides

A.5.1 EUT types

A.5.1.1 Small EUTs

A small EUT shall be tested using two start orientations in the TEM waveguide. The first start orientation is arbitrary, while the second start orientation is the first start orientation rotated as shown in Figure A.4. For each start orientation, the applicable correlation algorithm EUT rotations are performed. For example, the three-orientation method of A.3.2.3.2 requires that three orientations be tested. This procedure shall be carried out with start orientation a1 and a3, or a2 and a4 of Figure A.4 (a total of 2 × 3 = 6 orientations). The highest correlated field strength from these two data sets shall be reported at each frequency.

NOTE The frequency range is determined by the applicable limit or test objective, usually 30 MHz to 1 GHz for small EUTs. The usable frequency range is determined in the TEM mode verification tests (see 5.2.1, 5.3.2).

A.5.1.2 Large EUTs

A.5.1.3 Large EUTs may be tested using 12 orientations, as depicted in Figure A.4. For each EUT orientation, exit cables shall be aligned as closely as possible with the primary TEM mode electric field component (e.g., the y-axis in Fig. D.7) until the outer wall is reached. They then shall be routed along the outer wall to the exit point. Interconnecting non-exit cables shall be arranged in a manner consistent with typical EUT usage.

The maximum received voltage over the 12 orientations shall be found and converted to an electric field strength $E_{\max,TL}$ using an equivalent antenna factor for the TEM waveguide AF_{TL} given by

$$E_{\max,\mathrm{TL}} = V_{\max}\, AF_{\mathrm{TL}}, \text{ where } AF_{\mathrm{TL}} = \frac{\eta_0}{Z_\mathrm{c}} \frac{h}{r_{\mathrm{TL}}} \frac{1}{\lambda}$$

where r_{TL} is the distance from the TEM guide measurement port to the EUT position.

This TEM waveguide maximum electric field can be compared to OATS based limits $E_{\max}$ (see Section A.1) by normalizing it to the OATS test separation distance s as follows

$$E_{\max} = E_{\max,\mathrm{TL}}\, 2\frac{r_{\mathrm{TL}}}{s}$$

A.5.2 EUT arrangement

The following information is given for guidance purposes.

The EUT is placed in the centre of the usable test volume (5.2.2) on a manipulator (3.1.21 and Figures A.1, A.2b and A.2c or on a test set-up support (3.1.16).

EUTs without any cables should be fixed in the rotation centre of the manipulator. Using the manipulator, the EUT is rotated around its electrical centre (which can be assumed to be identical with the geometrical centre of the EUT).

For EUTs with cable(s) the following cable routing applies. Long cables should be bundled according to the rules stated in 7.2.5.2 of CISPR 16-2-3:2006.The interconnecting cable(s) should be routed perpendicularly from each case. In order to obtain repeatable measurement results, the relative positions of the interconnecting cable(s) and of the EUT should not change throughout the three-orientation correlation algorithm. If the cable(s) are too long, the interconnecting cable(s) can be bundled according to 7.2.5.2 of CISPR 16-2-3:2006.

The exit cable(s) should be routed perpendicularly from each EUT case to the boundary of the usable test volume. The cable is then routed along the border of the usable test volume to the corner at the ortho-angle and the lower edge of the test volume (Figure A.1). Using a positioner as shown in Figure A.2b, the exit cable(s) should be routed along the ortho-axis. The cable position should be restrained, for example, by non-conductive clamps. The exit cable(s) are routed from the lower corner of the usable test volume at the ortho-angle to the absorbing clamp(s) at the waveguide ground plane. Multiple cables should be separated by approximately 100 mm. At the waveguide ground plane, each cable is to be terminated by separate absorbing clamps or by clip-on ferrites (see [1]). The insertion loss of the clamp (or clip-on ferrite) should be greater than 15 dB for the frequency range of 30 MHz to 1 000 MHz. The connection cable should not touch the inner or outer conductor of the TEM waveguide before the cable is terminated by the absorbing clamp or clip-on ferrite. Up to 1,3 m of cable are to precede the clamp location. If the cable is shorter than 1,3 m, then all of the cable precedes the clamp location. If the cable is longer than 1,3 m then at least 1,3 m of cable should precede the clamp location (see Figure A.1). Exit cables are routed from the absorbing clamps to connectors on the floor or wall, and then connected to associated equipment outside the TEM waveguide.

A.6 Test report

The report shall include both the corrected (E) and uncorrected (E_{max}) field strength results, as determined according to

$$E = E_{\mathrm{max}} - c_f, \text{ in } \frac{\mathrm{V}}{\mathrm{m}} \qquad \text{(A.19a)}$$

with E_{max} in V/m from Equation (A.5) and c_f in V/m from Equation (A.10), or

$$E\big|_{\mathrm{dB}} = E_{\mathrm{max}}\big|_{\mathrm{dB}} - 20 \cdot \log_{10}\left(\frac{c_f}{1\,\mathrm{V/m}}\right) - 120, \text{ in dB}(\mu\mathrm{V/m}) \qquad \text{(A.19b)}$$

with $E_{\mathrm{max}}|_{\mathrm{dB}}$ in dB(μV/m) from Equation (A.8) and c_f in V/m from Equation (A.10).

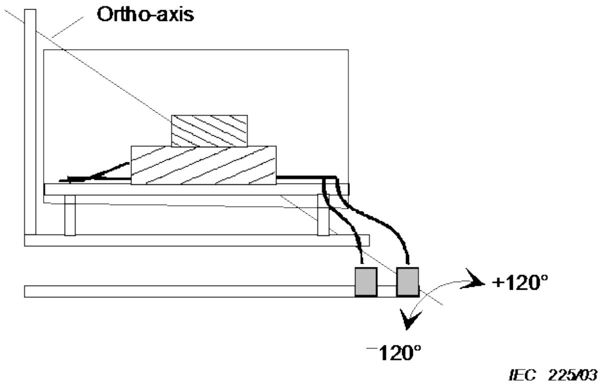


Figure A.1a – Side view

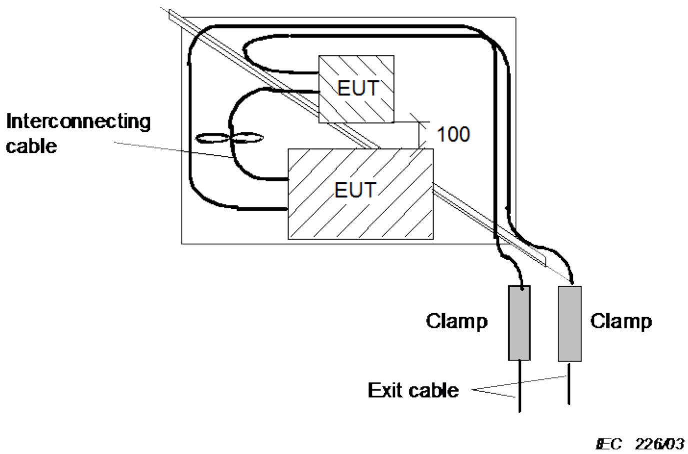


Figure A.1b – Top view

The length of the connection cable between the EUT case and the termination shall be approximately 1,3 m.

Figure A.1 – Routing the exit cable to the corner at the ortho-angle and the lower edge of the test volume

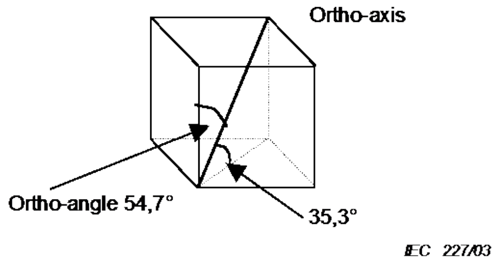


Figure A.2a – The ortho-axis and the ortho-angle

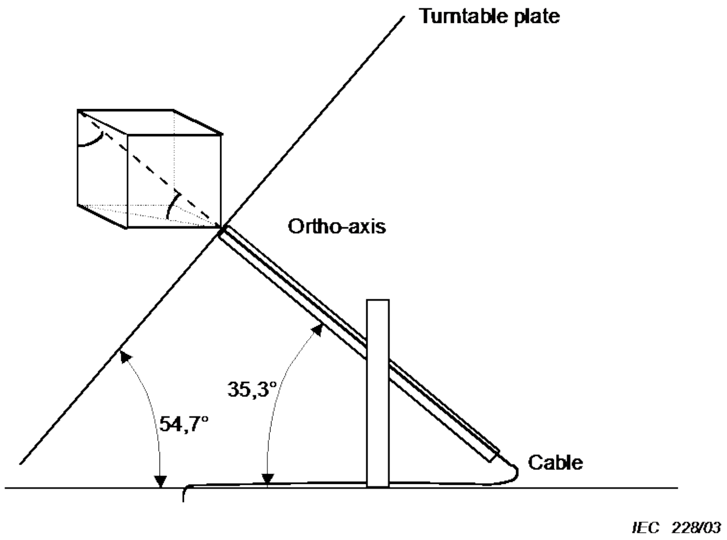


Figure A.2b – Side view (see 3.1.21 and A.5.1.2)

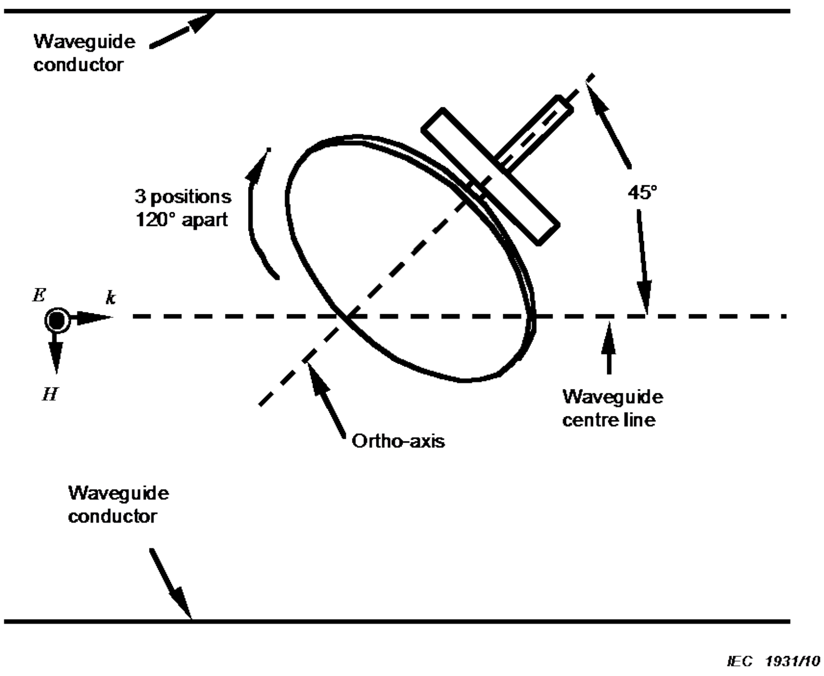
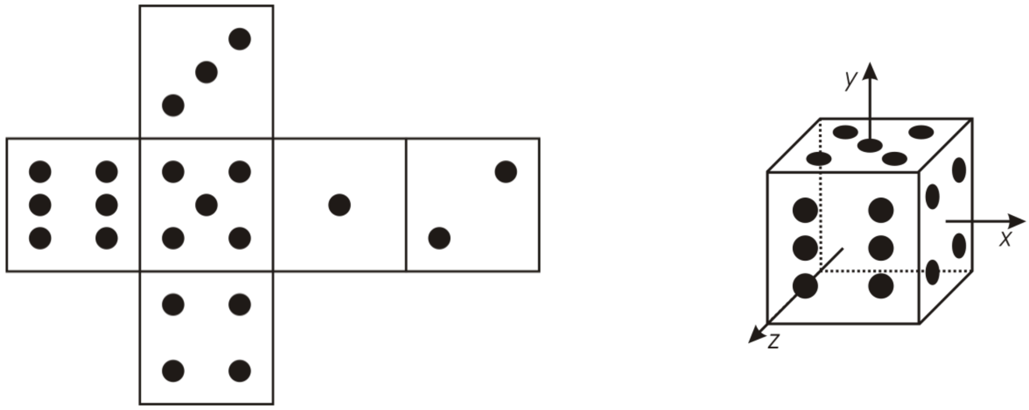


Figure A.2c – Top view (see 3.1.21 and A.5.1.2)

NOTE Analogous to the set-up of Figure A.1, this positioner gives three orthogonal positions by means of three 120° rotations around the ortho-axis.

Figure A.2 – Basic ortho-axis positioner or manipulator

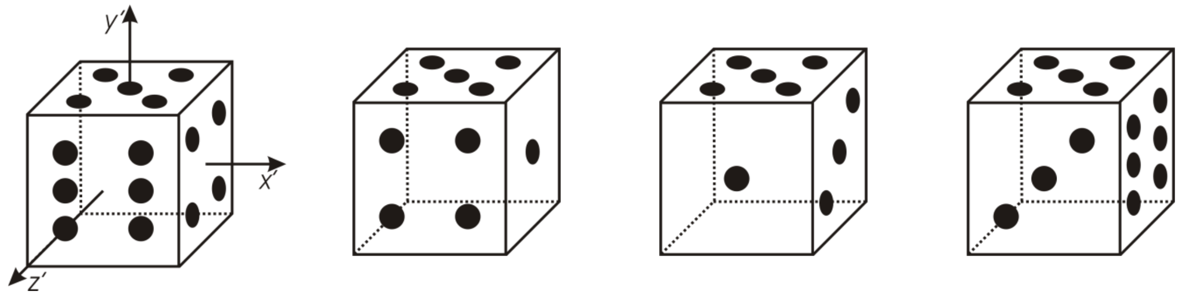


a) Dice net for the EUT. b) Axis alignment in position 65.

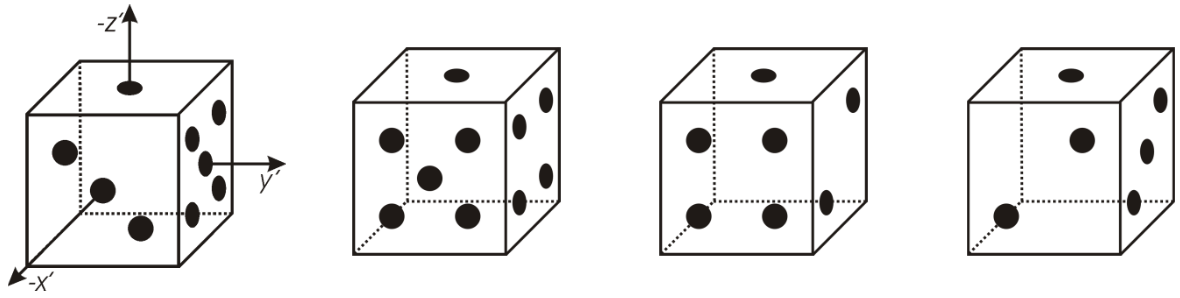
NOTE 1 The axes x, y, z refer to the TEM-waveguides coordinate axes, where z is the direction of propagation and the field is polarized along the y-axis. Each EUT position consists of two numbers: The number in positive z-direction and the number in positive y-direction. Therefor figure b) displays the EUT in position 65.

NOTE 2 For most EUTs the position 65 is redundant to the position 62. Or, generally speaking, each position has a redundant position for which the sum of the second digit of the positions name is seven (e.g. 46 and 41, 64 and 63).

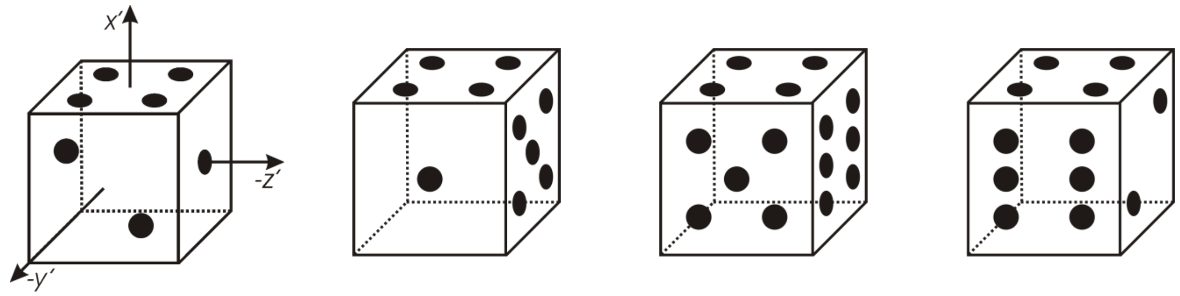
Figure A.3 – Dice net and axis alignment for the dice representing the EUT [26].



Position 65	Position 45	Position 15	Position 35
xx'yy'zz'	*x(-z')yy'zx'*	*x(-x')yy'z(-z')*	*xz'yy'z(-x')*



Position 31	Position 51	Position 41	Position 21
xy'y(-z')z(-x')	*xx'y(-z')zy'*	*x(-y')y(-z')zx'*	*x(-x')y(-z')z(-y')*



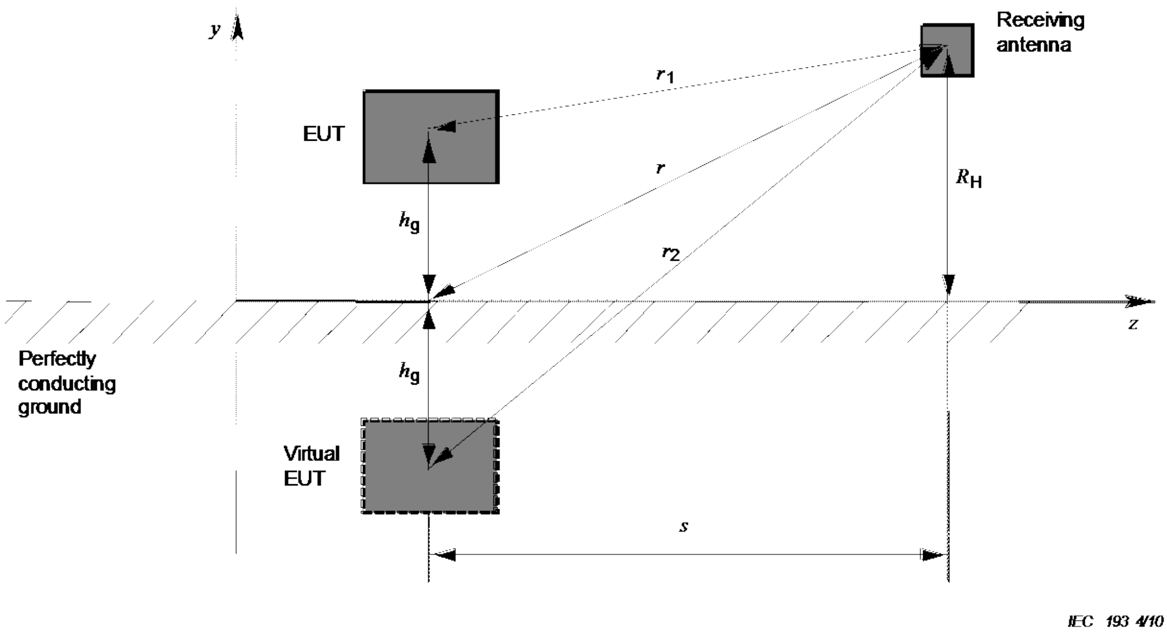
Position 24	Position 14	Position 54	Position 64
x(-z')yx'z(-y')	*xy'yx'z(-z')*	*xz'yx'zy'*	*x(-y')yx'zz'*

NOTE 1 In this figure x, y, z refer to the TEM waveguide coordinate axes, x', y', z' are the EUT coordinate axes and the field is polarized along the y-axis and propagating along the z-axis. The virtual (or geometric or phase) center of the EUT should remain at the same position relative to the TEM waveguide conductors.

NOTE 2 These 12 positions can be obtained by rotating the EUT three times by -90 degrees around the y-axis of the TEM waveguide (65, 45 15, 35), then tilting the EUT by -90 degrees around the z-axis of the TEM waveguide. Another three rotations around the y-axis (31, 51, 41, 21), followed by another tilt around the z-axis and the last three rotations around the y-axis (24, 14, 54, 64) results in the required 12 non redundant measurement positions.

NOTE 3 The triples (65, 41, 24), (45, 21, 14), (15, 31, 54) and (35, 51, 64) form a set of three orthogonal orientations that can be used for the three-orientation correlation algorithm. Similarly, in an immunity test, the minimum eight faces are given by, for example, the two sets of four orientations (24, 14 54, 64) and (65, 45, 15, 35) in the first and the third row of the figure.

Figure A.4 – Non redundant twelve-face and axis orientations for a typical EUT [26].



NOTE The *z*-axis is horizontal like the ground plane and aligned with the propagation direction. This is consistent with the coordinate system of TEM waveguides, where the *z*-axis is parallel to the conductor and aligned with the propagation direction.

Figure A.5 – Open-area test site (OATS) geometry

Annex B
(normative)

Immunity testing in TEM waveguides

B.1 Overview

This annex describes immunity testing in TEM waveguides. The intention is to enable the testing of electrical and electronic equipment for immunity to an incident electromagnetic field.

The test is performed with a specific arrangement of the EUT. This requires that the test set-up and the test limits or levels are defined by specific product or product family standards.

B.2 Test equipment

B.2.1 General

The following types of test equipment are recommended:

– TEM waveguide: of a size adequate to maintain a uniform field of sufficient dimensions to contain the intended equipment under test (EUT);

– electromagnetic interference (EMI) filters;

– RF signal generator(s): It is often useful to monitor the forward and backward power into the TEM waveguide when establishing field levels. A directional coupler along with a RF voltmeter or power meter allows the measurement of actual forward power to a TEM waveguide (as opposed to nominal power of the RF signal generator). Both shall cover the intended bandwidth.

– power amplifiers;

– field sensors, capable of separately monitoring the electric field along all three orthogonal axes. Any probe-head and opto-electronics circuitry shall have adequate immunity to the field strength to be measured and a fibre-optic link to the indicator outside the TEM waveguide. An adequately filtered signal line may also be used. TEM waveguides 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, it shall be repositioned to measure each field component separately;

– associated equipment to record the power levels.

B.2.2 Description of the test facility

NOTE A TEM cell acts itself as a shielded enclosure. In the case of a stripline (open), the stripline should be located in a larger shielded enclosure to ensure isolation. This shielding enclosure may require an appropriate amount of absorbing material in order for the stripline to fulfil uniform area requirements.

For TEM waveguides, the TEM mode is equivalent to an incident plane wave for the purposes of immunity testing. Whereas an ideal plane wave is invariant over any constant phase front, the TEM mode fields in a transmission line will vary over a constant phase front in accordance with the particulars of the cross-section geometry. Both the anechoic chamber and TEM waveguide methods are based on a plane wave field distribution before the EUT is inserted. A TEM mode-field pattern is more similar to vertical polarization in an anechoic chamber, while in a chamber the field pattern in horizontal polarization is more prone to distortion caused by ground plane reflections.

B.3 Field uniformity area calibration

Areas not listed in Table B.1 shall be calibrated using a grid number defined by the smallest 0,5 m grid fully containing the proposed area. Grid spacing shall be uniform along each side. In the test set-up, the EUT shall have its face illuminated coincident with this plane (see Figure B.2).

Table B.1 – Uniform area calibration points

Dimensions	Layout and number of measurement points
1,5 m × 1,5 m	4 × 4 = 16
1,0 m × 1,5 m	3 × 4 = 12
1,0 m × 1,0 m	3 × 3 = 9
0,5 m × 1,0 m	2 × 3 = 6
0,5 m × 0,5 m	4 + 1 (centre) = 5
0,25 m × 0,25 m	4 + 1 (centre) = 5

EXAMPLE 1 A 20 cm × 20 cm area using 4 + 1 [centre] = 5 points, a 80 cm × 80 cm area using 3 × 3 = 9 points, and a 1,2 m × 0,6 m area using 4 × 3 = 12 points.

EXAMPLE 2 A 1,2 m × 0,6 m uniform area shall use a 0,4 m × 0,3 m basic cell size.

The requirement of a uniform area is based on the TEM mode verification method of 5.2.2.3. In principle, the field uniformity is verified in terms of the primary TEM mode field component. If the resultant field strength is used instead, all above-mentioned requirements have to be fulfilled, and it shall be shown that the requirements on the secondary components of 5.2.2.3 are fulfilled. Further information about field homogeneity is given in [22].

B.4 Test levels

The test levels are given for guidance in Table B.2.

Table B.2 – Test levels

Test level	Test-field strength V/m
1	1
2	3
3	10
X	Special
NOTE X is an open test level. This level may be given in the product specification.	

B.5 Test set-up

B.5.1 Arrangement of table-top equipment

For TEM waveguides, rather than using a 0,8 m high non-conducting table as typical for some immunity test set-ups, the equipment is placed on a test set-up support (see 3.1.17) or manipulator (see 3.1.22) of a proper shape and size such that the front face lies within the uniform field area in each position. A typical EUT set-up is shown in Figure B.1.

B.5.2 Arrangement of floor-standing equipment

For TEM waveguides, the equipment is placed on a test set-up support in such a way that the front face lies within the uniform field area. The use of non-conducting test set-up support prevents accidental earthing (grounding) of the EUT and distortion of the field. The test set-up support shall be bulk non-conducting, rather than an insulating coating on a metallic structure.

B.5.3 Arrangement of wiring

Wiring is left exposed to the electromagnetic field for a distance of 1 m from the EUT and is routed above the floor, at either EUT level or along a diagonal in the xy-plane, to the exit point in the TEM waveguide outer conductor (TEM cell: wall, floor). Routing cable in the z-direction along the outer or inner conductor shall be avoided. Cables routed parallel to the inner or outer conductor of the TEM waveguide shall be spaced a minimum of 0,1 m away from the conductor. Exit cables are terminated by absorbing clamps (see A.5.1.22). The termination of the exit cable is placed at the borderline of the uniform area. For guidance on absorbing clamp characteristics, see the descriptions in CISPR 16-1-4.

B.6 Test procedures

The test shall normally be performed with each of the four sides of the EUT facing the generator port.

For TEM waveguides, the electric field is polarized in a single direction (typically vertically). Thus, to ensure that the EUT is fully exposed to the equivalent of both the horizontal and vertical polarization it is necessary to rotate the EUT. For example, for a vertically polarized electric field the equivalent horizontal polarization exposures are achieved by first rotating the EUT 90° around the axis perpendicular to the uniform area (direction of TEM mode propagation) to reorient the first EUT face, followed by three rotations about the horizontal axis aligned with the uniform area to expose the other EUT faces (Figure B.1). This may preclude the testing in some TEM waveguides of an EUT which is orientation dependent.

Alternatively, the TEM waveguide may be rotated around the EUT or a multiple-polarization TEM waveguide (see Figure D.10) may be used in such a manner as to achieve the same polarization.

The frequency step size shall be 1% of the previous frequency. The dwell time at each frequency shall not be less than the time necessary for the EUT to be exercised and to respond, but shall in no case be less than 0,5 s. However, a dwell time of 1 s is advisable.

NOTE If an EUT consists of several components, care should be taken that the relative component positions are preserved during rotations. This may require careful restraint of the EUT and the fastening of its components and cables to a test set-up support or manipulator.

The frequency ranges to be considered are to be covered in frequency steps, according to the above requirement, with the signal 80% amplitude modulated with a 1 kHz sine wave, pausing to adjust the RF signal level or to switch oscillators as necessary.

B.7 Test results and test report

In addition to the usual radiated immunity report contents, details about the TEM waveguide size, type, and verification methods shall be reported.

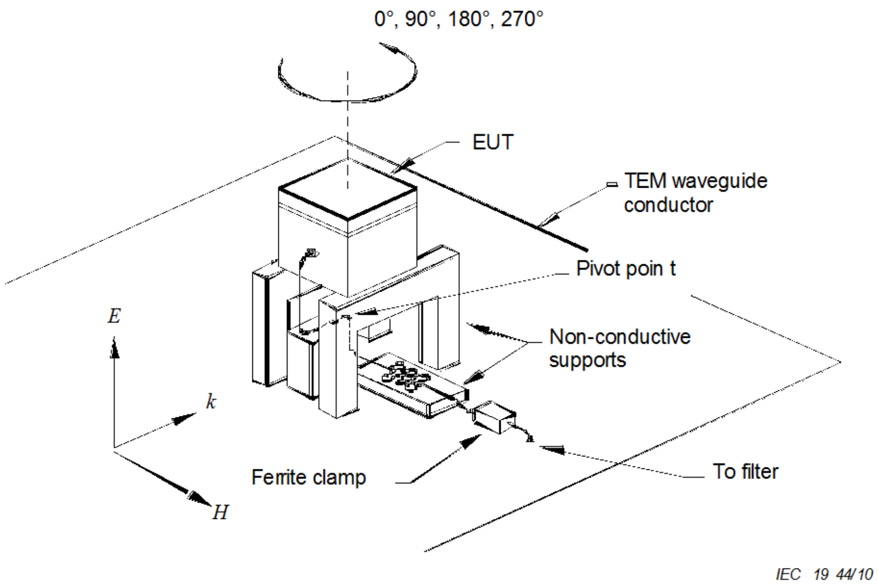


Figure B.1a – Vertical polarization

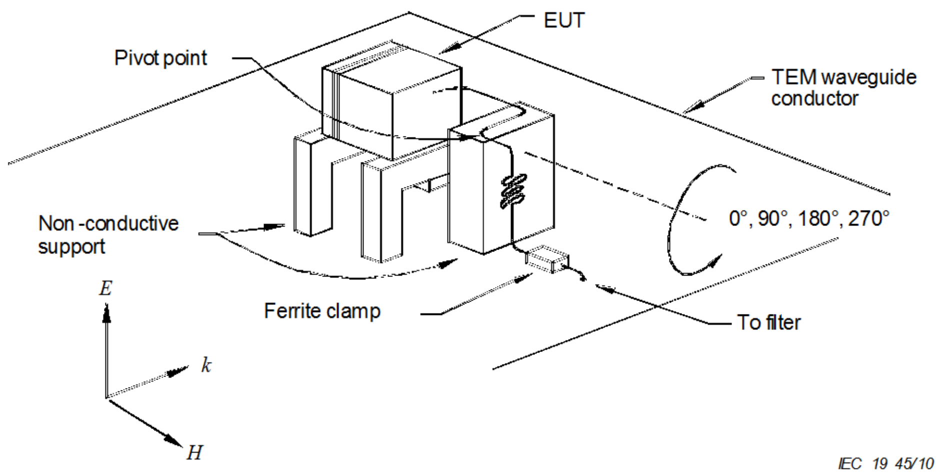


Figure B.1b – Horizontal polarization

Key: *E* Primary electric field component
H Magnetic field
k Propagation direction (wave vector)

The cable layout on the filter side of the pivot point shall remain stationary. The test set-up supports (3.1.17) may be repositioned as necessary during rotations. The test set-up supports should be 0,1 m thick. Multiple-unit EUTs shall be affixed to a test set-up support or an equivalent platform and rotated in the same manner. Manipulators and rotatable (see [6]) or multiple-polarization TEM waveguides (Figure D.10) which achieve the same set of EUT to incident field polarizations may be used.

Figure B.1 – Example of test set-up for single-polarization TEM waveguides

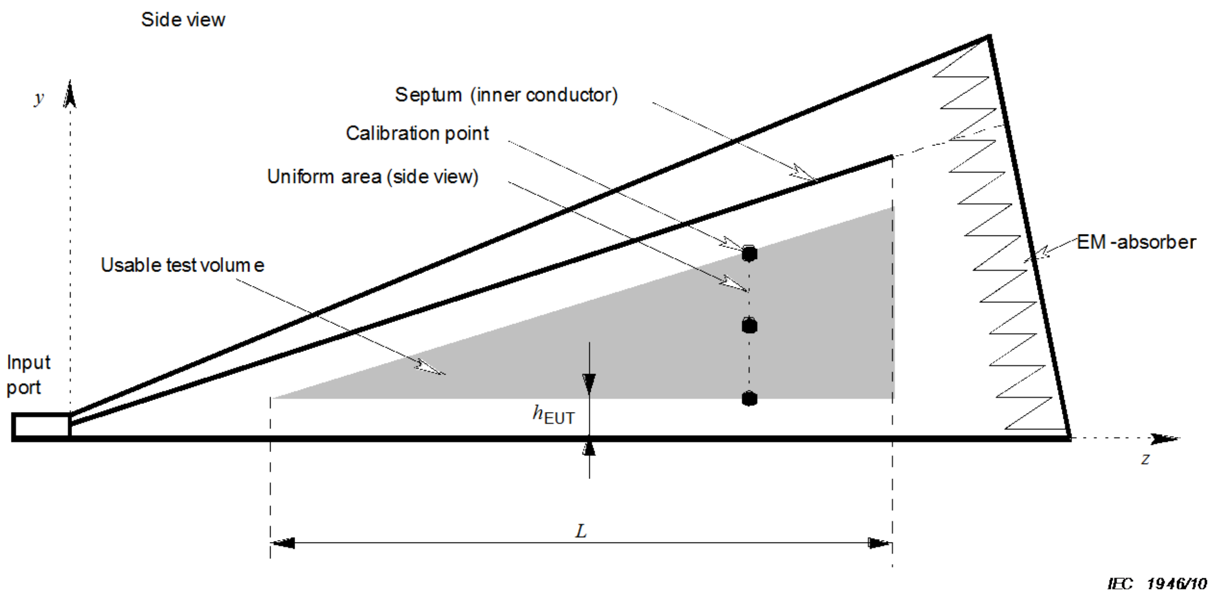


Figure B.2a – Side view

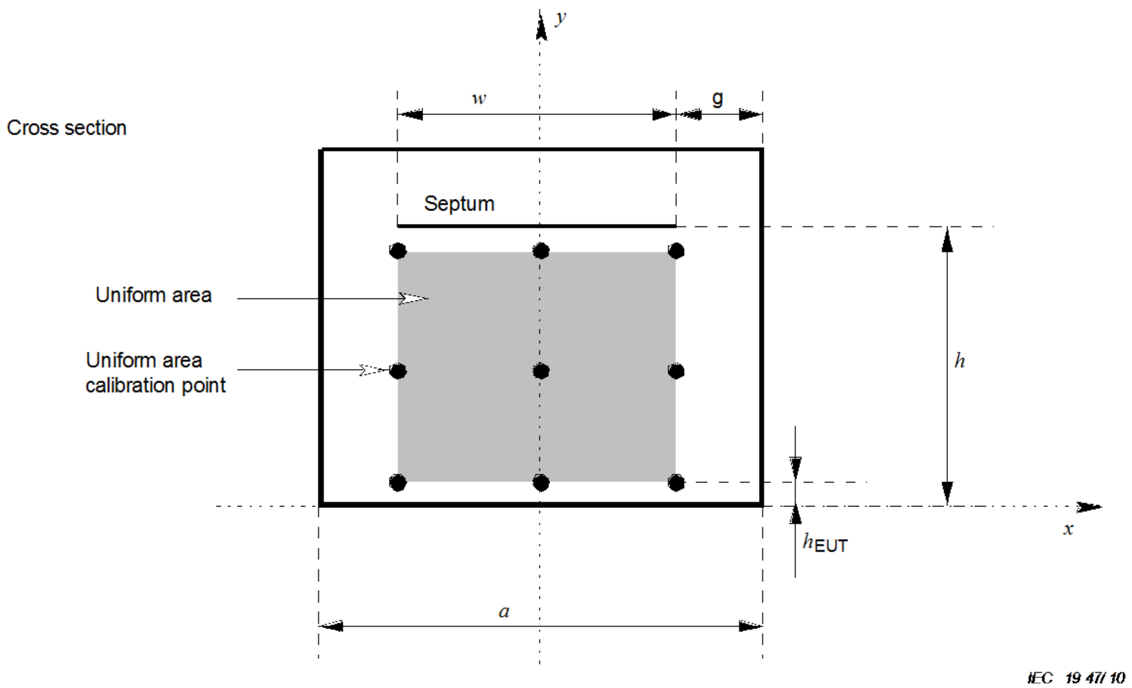


Figure B.2b – Cross-section view

NOTE Example for a uniform area with 3 × 3 calibration points in a GTEM cell according to 5.2.2.3. Figure B.2b shows the maximum possible size of the uniform area. The boundary of the uniform area (plane) is given by the outer calibration points. The calibration points cannot be outside the usable test volume (see 5.2.1 and Figures D.7 to D.11).

Figure B.2 – Uniform area calibration points in TEM waveguide

Annex C
(normative)

HEMP transient testing in TEM waveguides

C.1 Overview

This annex has been developed to specify the high-altitude electromagnetic pulse (HEMP) immunity test for electrical or electronic equipment and systems. The intent is to allow manufacturers to qualify equipment and small systems and to use many of the same IEC laboratory immunity tests that are already prescribed for other EMC purposes.

It should be noted that in the HEMP community the term "simulator" is often used to describe many different types of test facilities that can generate the correct incident HEMP environment (see IEC 61000-4-32). In this annex, the term is understood to refer only to TEM waveguides that produce a HEMP waveform.

While this annex is intended to describe the HEMP testing requirements in TEM waveguides in a consistent fashion with other types of testing performed in TEM waveguides, this annex covers transient testing which by its nature differs from continuous wave testing in important ways. When HEMP test requirements in this annex differ from those described in the main body of this standard, the HEMP requirements shall supersede all others.

C.2 Immunity tests

C.2.1 General

HEMP immunity tests consist of two major types: radiated immunity tests and conducted immunity tests. For the purpose of this standard, the term "electronic equipment" denotes an apparatus that performs a specific function. This could be a small computer or a telephone. Some equipment (for example, a computer connected to additional peripherals such as control boards to monitor processes in a factory) may be considered as part of a larger system. Often, electronic equipment is relatively small – of the order of 1 m × 1 m × 1 m or smaller. It is expected that most of the tests on such small equipment will be performed in laboratories using current injection simulators and TEM waveguides.

In the absence of an object in the simulator, the electric field in the test volume is a wave comparable to a plane wave, with a double exponential pulse time history described by a 2,5/25 ns wave, i.e. a unipolar wave with a 10% to 90% rise time of 2,5 ns and a pulse width equal to 25 ns. This waveform is given by the Equation (C.1).

$$E(t) = E_{\text{peak}} \cdot k\,(e^{-\beta t} - e^{-at}) \quad \text{in } \frac{\mathbf{V}}{\mathbf{m}} \qquad \text{(C.1)}$$

where

α = 6,0 × 10⁸ s⁻¹;

β = 4,0 × 10⁷ s⁻¹;

k = 1,3;

E is the primary component of the electric field, in V/m;

E_{peak} is the peak value of the electric field, in V/m;

t is the time, in s;

E_{peak} is the severity test level selected from Table C.1.

The frequency-domain spectral magnitude for Equation (C.1) is given by Equation (C.2)

$$\left|E(f)\right| = \frac{E_{\text{peak}} \cdot k \cdot (\alpha - \beta)}{\sqrt{\left((2\pi f)^2 + \alpha^2\right) \cdot \left((2\pi f)^2 + \beta^2\right)}} \quad \text{in } \frac{\mathbf{V}}{\mathbf{m}} \frac{\mathbf{1}}{\mathbf{Hz}} \qquad \text{(C.2)}$$

where f is the frequency, in Hz.

For the waveform parameters given above, the frequency-domain spectral magnitude of Equation (C.2) is shown in Figure C.1.

NOTE For additional details see [33].

C.2.2 Radiated test facilities

Small test facilities can more easily meet the desired field specifications with smaller tolerances in parameter variations than large simulators. These small facilities will be used primarily to test relatively small equipment. Tolerances for the early-time HEMP pulse waveform over the entire test volume of the small test facility shall be as follows:

- the ratio of peak electric field to the peak magnetic field shall be equal to η_0 = 377 Ω ± 50 Ω;
- the rise time between 10% to 90% of the peak value shall be 2,25 ns ± 0,25 ns;
- the electric field shall be continuously increasing during the 10% to 90% rise time;
- the pulse width (the time duration between points on the leading and trailing edges of the pulse at 50% of $E_{\mathbf{peak}}$) shall be 27,5 ns ± 2,5 ns;
- the magnitude of any pre-pulse of the electric field shall be equal to, or less than, 7% of the magnitude of the peak field;
- electric field reflections from the terminator of the simulator shall be less than 10% of the magnitude of the peak field;
- fluctuations in the smoothed frequency spectrum of the electric field at the centre of the test volume shall not be larger than ±3 dB compared to the theoretical spectrum in the bandwidth between 100 kHz and 300 MHz;
- at the time of the peak value of the primary field, other secondary electromagnetic components (see 3.1.19) shall be smaller than 10% of the peak value of the primary field. It is recognized that this requirement is more severe than that given in 5.2.1;
- the peak electric field shall be uniform in the test volume to within the following criteria: the peak electric field within the test volume shall be within the range of E_{peak} and 2 E_{peak} in the time domain;
- to evaluate the field tolerances, electric and magnetic field measurements at the centre and the eight corners of the test volume shall be performed in the absence of the EUT.

C.2.3 Frequency domain spectrum requirements

In addition to the requirements on the transient fields of the HEMP simulator, the following requirements shall be placed on the frequency domain spectrum of the simulator fields:

a) the frequency spectrum shall be computed using a uniformly sampled transient waveform having 4096 samples between the starting time of 0 μs and the ending time of 2 μs. A 4096-point complex-valued frequency spectrum shall be calculated using an FFT (fast Fourier transform) or a discrete Fourier transform (DFT) with a frequency sampling interval of 0,5 MHz, and a maximum frequency of 1,0 GHz;

b) the frequency domain spectrum shall be smoothed using a five-point windowing average (i.e. the spectrum is to be averaged over a 2 MHz window);

c) the resulting magnitude of the smoothed spectrum shall lie within the specified dB level of the spectrum of the specified waveform of Equation (C.2) and shown in Figure C.1.

NOTE Most measured frequency spectra have occasional nulls (or "drop-outs"), which do not significantly alter the overall behaviour of the transient waveform. The requirement that the smoothed frequency domain spectrum of the small and large simulators lie within ±3 dB and ±10 dB, respectively, is made in recognition of this fact, and with the aim of permitting an occasional null in the spectrum. The spectral limits of ±3 dB and ±10 dB are different because the smaller simulators generally have higher tolerances and accuracy of the simulated fields.

C.3 Test equipment

The measurement method shall involve the use of a fibre optic transmission link that permits signals to be measured and transmitted to a data processing system without disturbing the ambient EM field. The measurement system shall be intrinsically insensitive to electromagnetic radiation emitted by the simulator. The purposes of the measurement system are

- to provide reference field measurements,
- to synchronize the simulated HEMP with the operational modes of the equipment under test as required by the user, and
- to provide EUT current and voltage measurements, as required by the user.

The required overall measurement system accuracy shall be within ±3,0 dB over a frequency range of 50 kHz to 500 MHz, and its overall instantaneous dynamic range shall be at least 40 dB.

It is recommended that the measurement system have the following characteristics:

- the data transmission system should have a minimum 3 dB bandwidth of 50 kHz to 1 GHz;
- the digitizer or oscilloscope should have a minimum bandwidth of 500 MHz and a minimum sampling rate of 2 gigasamples per second with a minimum data resolution of 8 bits;
- the electric and magnetic field sensors should have a minimum 3 dB bandwidth of 50 kHz to 1 GHz. See IEC 61000-4-23 for further information concerning appropriate sensor designs.

The reference field measurement shall consist of the three orthogonal electric and three orthogonal magnetic field components to permit an assessment of the electric to magnetic field ratio, as well as the spurious electromagnetic field components. The user may also specify other field measurements in the test volume.

C.4 Test set-up

The test volume of a simulator depends on its physical size and on the characteristics of the TEM waveguide structure. It is defined as the volume in which the incident electromagnetic fields meet, or exceed, the strength and uniformity requirements, as specified for a simulated HEMP test. If the equipment under test is too large in relation to the test volume, the induced response will deviate from that of an incident plane wave illumination, and the results of the test will be questionable.

To ensure the accuracy of the simulation, it is necessary to minimize the EUT-simulator interaction by locating the equipment under test far enough from the radiating or wave-guiding elements of the simulator. The equipment under test shall be located no closer than 0,3 times its overall transverse dimension to the conductors of the TEM waveguide. If the EUT is to be tested while resting on a ground plane, it shall be located no closer than 0,6 times its transverse dimension to the septum.

The EUT is described generally as a finite volume with dimensions determined by its greatest orthogonal dimensions in height, width and length. The EUT shall fit within the simulator test volume as defined above. If “short” external conductors that are associated with the EUT can be illuminated in a realistic manner by the simulator, then those cables shall also be used in determining the volume of the EUT. If the EUT is to be tested in a free-space mode, that is to say, not resting on a ground plane, then it shall be placed on a dielectric stand within the simulator.

C.5 Test procedure

C.5.1 General

Tests for conducted and radiated disturbance immunity may be performed separately. There are no requirements for testing both types of stresses simultaneously.

If the entire system including all “short” external conductors can be illuminated in a realistic manner in a radiated test, then the early-time conducted tests may not be required on those cables. Moreover, conducted tests may not be necessary for antenna ports, if the antenna can be tested to the simulated HEMP stress with the antenna oriented for a maximum response. However, all ports connected to power, telecom, or other long lines shall have conducted immunity tests.

HEMP immunity tests shall be conducted in accordance with a test plan that describes the equipment to be tested, the severity test level and waveforms, climatic conditions, major operational modes, and the criteria for passing the immunity requirements. The ambient environment (both climatic and electromagnetic) of the laboratory or HEMP test facility shall not influence the test results. During the testing it is important to monitor the equipment to classify its performance as specified. If equipment receives and sends data to other equipment in a system, an effort shall be made to send and receive the same or simulated data to the equipment being tested. This shall allow an evaluation of the equipment performance during the test.

If the EUT does not pass the test requirements and if diagnostic measurements were made within the system or equipment, these probes and cables shall be removed, and the test shall be performed again to ensure that the added instrumentation is not the cause of the test failure. The test report shall clearly identify the presence of all external cables connected to the EUT, whether they are part of the equipment or are part of a measurement system.

The EUT shall be tested in each major operational mode that is specified in the test plan. For conducted immunity tests, both positive and negative waveforms shall be used. For radiated immunity tests, only one polarity of the waveform is required.

Laboratory tests shall be conducted with the ambient environmental conditions identified in 7.2. On-site tests are not suitable for immunity acceptance tests, but these tests may be used to verify installed equipment immunity as well as system immunity. For on-site tests, ambient conditions described in 7.2 are desirable, but not required.

C.5.2 Severity level and test exposures

It is important to perform some test exposures below the voltage protection level of surge protective devices (SPDs) and also at a voltage level low enough to avoid arcing within the system, since damage may occur. Thus, each severity level shall consist of three actual test amplitudes, starting two levels below the specified severity level, which is assumed to be below the voltage protection level provided by SPDs and the arcing threshold. Each test pulse shall use the same waveform as that of the specified severity level.

For radiated immunity tests, a severity level shall be specified. At least two test exposures shall be performed at each of the three test amplitudes for each orientation (see Clause B.6) and major operational mode of the EUT. If a test facility is available that includes the capability of hyper-rotation (see [6]) for the EUT, the facility may be used for HEMP testing.

C.5.3 Test procedure

C.5.3.1 Test parameter measurements

The climate parameters defined in 7.2 shall be measured by the test operator and documented. The characteristics of the test facility consisting of a series of measurements of the electromagnetic field waveforms within the test volume without the EUT present shall be made available to the test operator. This information shall also include an evaluation that indicates that the requirements for the field uniformity and waveform characteristics stated in C.2.2 and C.2.3 have been met. A reference electric field measurement shall be recorded for each pulse of field illumination.

C.5.3.2 Radiated test procedure

A small radiated test facility can be used to test equipment; however, conducted immunity tests on all cable ports are also required. A small system may be tested in a large HEMP simulator and possibly meet the conducted immunity requirements for many cable ports. However, long lines such as AC power and telecommunication lines cannot be adequately tested in any HEMP simulator. Consequently, conducted immunity tests are always required for these ports.

It is recognized that the large HEMP simulator is better suited for performing system-level tests where multiple pieces of equipment may be operating together. However, it is not a requirement of this International Standard that system level testing be performed in such a simulator.

Each immunity test at a specified severity level consists of exposures at three exposure levels: the specified severity level and the next two lower levels. If only one lower level is defined by this International Standard, then only one level shall be used. If the lowest severity level is specified, then only that level of exposure is necessary for the immunity test. A minimum of two pulses of the field illumination shall be performed for each exposure level.

C.5.3.3 Small radiated test facility

The basic approach used in this procedure is to test equipment and small systems in a laboratory test facility, such as a TEM waveguide. The EUT shall be placed on a dielectric stand at a height of 0,1 m ± 0,01 m above the ground plane within the test volume, and all equipment cables shall be used in manner consistent with the normal operation of the equipment. A ground connection shall be made between the ground plane and the EUT, according to the manufacturer's specifications. It is necessary to control and document the lengths and positions of the cables associated with the EUT. Orientate the cabling for minimum coupling to the electric and magnetic field components in the test facility.

Additional conducted immunity tests shall be performed separately to account for the coupling to these cables.

The EUT shall be rotated to expose all sides (typically six sides) to the incident pulsed fields, although practical considerations may limit the number of rotations. In addition, both polarizations shall be applied.

If the method of monitoring involves measurements within the EUT, the probes and cables involved shall be carefully positioned, so as to minimize adverse effects on the measurements. In particular, fibre optic cables without metal material are recommended for such measurements.

C.5.4 Test execution

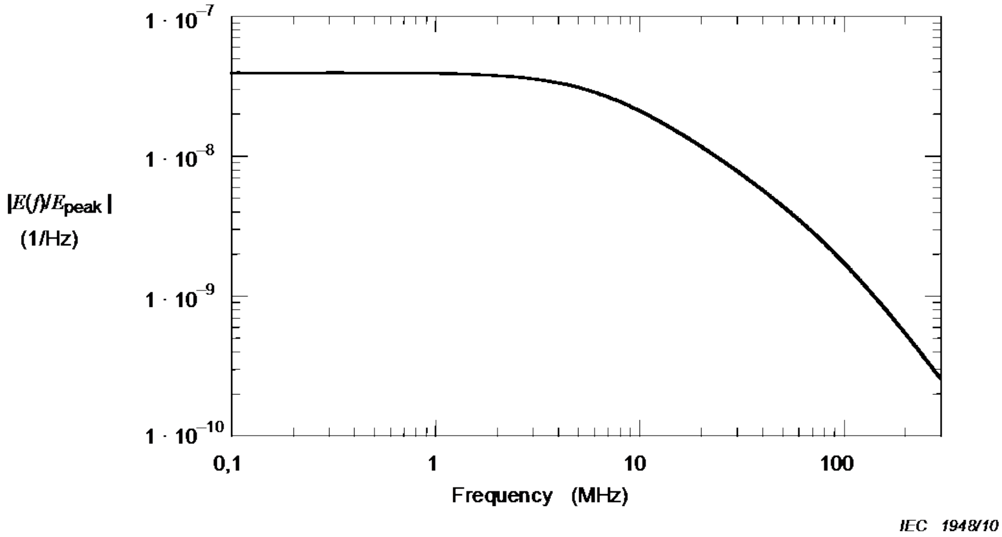
The test shall be performed in accordance with a test plan. Test exposures shall be applied when the EUT is in each of its major operating modes under normal operating condition, as defined in the test plan. For each test exposure level, the pulses shall be applied with sufficient time between pulses to check for system degradation or damage. After each exposure level, the operational performance of the EUT shall be determined.

C.5.5 Execution of the radiated immunity test

The radiated immunity test shall be carried out on the basis of a test plan, including the verification of the performances of the EUT, as defined in the product standard, or in its absence, by the technical specification.

The EUT shall be in the normal operating condition. A test configuration matrix consisting of the EUT operational configurations, major functional states, and orientations relative to the direction of wave propagation shall be developed. For each test configuration, the test plan shall specify:

- test exposure levels: the selected severity level, plus the next two lower levels;
- the number of exposures at each level (at least two are required);
- the points of entry (PoEs) or ports to be evaluated;
- a description of positions of the cables and measurements to be made;
- the required auxiliary equipment;
- the polarity and angle of incidence of the simulated fields;
- the details of the test set-up, whenever it is different from that specified in Clause C.4 of this document;
- the pass/fail criteria.



NOTE Spectral magnitude is determined using parameters listed after Equation (C.1) in Equation (C.2).

Figure C.1 – Frequency domain spectral magnitude between 100 kHz and 300 MHz

Table C.1 – Radiated immunity test levels defined in the present standard

Test level	**Test required for equipment and systems with the following protection** [a]	**E-field peak value** E_{peak} [b] kV/m
R1	Concept 4	0,5
R2	Intermediate value	1
R3	Intermediate value	2
R4	Concepts 2A, 2B, 3	5
R5	Intermediate value	10
R6	Intermediate value	20
R7	Concepts 1A, 1B	50
RX	Special applications	X

[a] The protection concepts are described in IEC 61000-5-3.

[b] According to IEC 61000-2-11, Table 2.

Annex D
(informative)

TEM waveguide characterization

D.1 Overview

This annex describes the basic characteristics of a TEM wave, including the propagation and polarization aspects. The different categories of TEM waveguides are also presented, along with the limitations with respect to test volumes and frequencies of operation.

D.2 Distinction between wave impedance and characteristic impedance

A TEM waveguide is a transmission line. The wave and characteristic impedances of a loss-less transmission line are defined as follows in [47].

The wave impedance η is defined as the ratio of the transverse field components, which can be calculated assuming an $e^{-\mathrm{j}\beta z}$ dependence to give

$$\eta = \frac{E_{\tilde{\mathrm{n}}}}{H_{\phi}} = \frac{\omega\mu}{\beta} = \sqrt{\frac{\mu}{\varepsilon}} \tag{D.1}$$

where

η is the wave impedance;

E_{ρ} is the transverse component of the electric field;

H_{ϕ} is the transverse component of the magnetic field;

μ is the permeability of the transmission line dielectric (typically air);

ε is the permittivity of the transmission line dielectric (typically air);

β is the propagation constant (real part);

ω is the radiant frequency.

This wave impedance is then seen to be identical to the intrinsic impedance of the medium and is a general result for TEM transmission lines.

The characteristic impedance of a circular-cylindrical coaxial line is defined as

$$z_{\mathrm{c}} = \frac{V_0}{I_0} = \frac{E_{\rho} \ln\frac{2h}{a}}{2\pi H_{\varphi}} = \eta \cdot \frac{\ln\frac{2h}{a}}{2\pi} = \sqrt{\frac{\mu}{\varepsilon}} \cdot \frac{\ln\frac{2h}{a}}{2\pi} \tag{D.2}$$

where

Z_{c} is the characteristic impedance of the coaxial line;

V_0 is the voltage of the coaxial line;

I_0 is the current of the coaxial line;

E_{ρ} is the transverse component of the electric field;

H_{ϕ} is the transverse component of the magnetic field;

h $2h = r_{\mathrm{i}}$, r_{i}: radius of inner conductor;

a $a = r_{\mathrm{a}}$, r_{a}: radius of outer conductor.

where the forms for $E_{\tilde{\mathrm{n}}}$ and H_{ϕ} from [8] have been used. The characteristic impedance is geometry-dependent, and it will be different for other transmission line configurations.

Equations (D.1) and (D.2) show that in general the wave and characteristic impedances are not equal. Since TEM and gigahertz TEM cells and two- and three-plate striplines are basically two-conductor TEM-mode transmission lines, in general the wave and characteristic impedances in those devices will also not be equal.

D.3 TEM wave

D.3.1 General

TEM waves are most easily described in terms of their behaviour in free space. The following two subclauses present several equations and criteria for both the free-space and waveguide cases.

D.3.2 Free-space TEM mode

In a TEM mode both the electric and magnetic field vectors are entirely transverse to the direction of energy propagation (Poynting vector $\vec{S}$). There is no component of either $\vec{E}$ or $\vec{H}$ in the direction of transmission.

$$\vec{S} = \vec{E} \times \vec{H} \tag{D.3}$$

For "free space" the ratio between $|\vec{E}|$ and $|\vec{H}|$ is given by

$$\eta_0 = \frac{|\vec{E}|}{|\vec{H}|} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi\ \Omega \tag{D.4}$$

The essential properties of the TEM mode are

- no field component in the direction of transmission;
- the ratio between $|\vec{E}|$ and $|\vec{H}|$ is nearly $120\pi\ \Omega$.

NOTE Far away from a transmitting antenna, the situation above is observed. Therefore, the TEM mode is often called the "far-field condition" of an antenna.

D.3.3 Waveguide

A classical waveguide for RF applications consists of only one closed conducting surface. It can be shown that a TEM mode cannot propagate within such a waveguide (see Figure D.1). Only TE and/or TM modes are possible. Because TE or TM modes have a specific cut-off frequency, wave propagation is possible only above this frequency. A double- or multi-connected cross-section is necessary to propagate a TEM mode within a waveguide (multi-conductor transmission line, like TEM cell, stripline or open TEM waveguide). Each pair of two conductors creates a system for a possible specific TEM-mode propagation. For the example shown in Figure D.2, propagation of two separate TEM modes is possible. Each of these TEM modes has the same properties as the free-space TEM mode.

NOTE Each pair of conductors forms a TEM-mode transmission system. Inside a coaxial line the signal energy is transported via the TEM mode.

D.4 Wave propagation

D.4.1 General

Wave propagation describes the shape of the equiphase lines and surfaces of the field.

D.4.2 Spherical propagation

This type of propagation is the most common one in free space far field. Normally it is caused by a point source like a single antenna. The field amplitude decreases with increasing distance to the source.

D.4.3 Plane wave propagation in free space

Very far away from an antenna, the wave front can be considered as planar. This kind of propagation will be observed within a parallel plate waveguide where the field amplitude is constant and independent of the distance to the source.

D.4.4 Velocity of propagation

The phase velocity of the TEM mode for propagation in free space and TEM waveguides is always equal to speed of light c_0. It only depends on the permittivity ε and of the permeability μ of the space.

D.5 Polarization

D.5.1 Polarization vector

The electric field vector direction represents the polarization vector.

D.5.2 Linear and elliptic polarization

In general, the direction of the polarization vector changes with time. The curve traced out by the tip of the polarization vector, shown in Figure D.3, defines the type of polarization.

From [8] the shape of the polarization curve can be calculated by the following procedure. The transverse electric field vector is given by

$$\vec{E}_{tr}(t) = \mathrm{Re}\left\{\sum_{i=0}^{\infty} \underline{V}_i \cdot \vec{e}_{\mathrm{tr},i} \cdot e^{\mathrm{j}\omega t}\right\} \tag{D.5}$$

The first term of the series represents the TEM mode, so a complex phasor can be written as

$$\underline{\vec{A}}_{\mathrm{TEM}} = \underline{V}_1 \cdot \vec{e}_{\mathrm{tr},i} = \underline{V}_{\mathrm{TEM}} \cdot \vec{e}_{\mathrm{tr,TEM}} \tag{D.6}$$

The phasor can be separated into its real and imaginary parts

$$\underline{\vec{A}}_{\mathrm{TEM}} = \vec{a}_{\mathrm{r}} + \mathrm{j}\vec{a}_{\mathrm{i}} \tag{D.7}$$

The vectors $\vec{a}_{\mathrm{r}}$ and $\vec{a}_{\mathrm{i}}$ define a fixed plane. In general the tip of vector $\vec{E}$ moves in an ellipse. If $\vec{a}_{\mathrm{r}}$ and $\vec{a}_{\mathrm{i}}$ are parallel, $\vec{E}$ moves on a fixed line. This case is called linearly polarized. Any individual modes are inherently linearly polarized. Only superposition with other modes results in circular polarization. The intentional TEM mode for testing purposes in TEM waveguides is usually linearly polarized.

D.6 Types of TEM waveguides

D.6.1 General

The simplest version of a TEM waveguide is a two-conductor transmission line as shown in Figure D.6.

The complete transmission line may be divided into three sections.

a) Feed section

   This is the port where a signal generator or receiver is connected to the TEM-waveguide.

b) TEM-waveguide section

   Usually contains the test volume.

c) Termination section

   Normally the termination represents an actual or equivalent resistor which is equal to the characteristic impedance of the transmission line (= TEM waveguide).

For most two-port TEM waveguides, the feed and termination sections are geometrically identical and therefore interchangeable. A coaxial connector is used at both ports. Some TEM waveguides are based on a balanced transmission-line system, in which case a BALUN transformer is needed.

Firstly, TEM waveguides can be classified into closed and open geometries. A TEM waveguide structure is called "closed" when one conductor fully surrounds the other conductor. In these cases, the outer conductor also acts as an electromagnetic shield.

Secondly, there are one-, two- and four-port waveguides (Figures D.5 – D.11). This classification defines the termination of a TEM waveguide. Normally the TEM waveguide is used under matched termination conditions. The simplest way to match a two-port or a four-port TEM waveguide is to put a lumped termination equal to the characteristic impedance at one port. In this case, it is assumed that the TEM line geometry close to the ports (tapered section) is well designed for wide-band matching.

For a one-port TEM waveguide, the termination is made with distributed resistors and/or a combination of anechoic absorbers. This type of termination can be used up to several GHz in some geometries. Rather than a wide frequency range, a two-port TEM waveguide has the advantage of allowing measurements of reflected and transmitted powers at either port.

Septum conductors can either be single or multiple wires connected in parallel or single or multiple plates connected in parallel. For multiple conductor systems, the excitation amplitude and phase can be intentionally changed to vary the dominant polarization within the test volume.

The septum can be installed either symmetrically or asymmetrically with respect to the outer conductor. The advantage of an asymmetrical TEM waveguide is a larger test volume.

D.6.2 Open TEM waveguides (striplines, etc.)

A simple open TEM waveguide can be built using a plate installed over a conducting ground plane. A generator or receiver (typical impedance 50 Ω) is connected at one port, and the other port is matched to the transmission line characteristic impedance. A constant voltage/current distribution along the structure is achieved with proper impedance matching. This geometry is called an open two-port TEM waveguide.

The main disadvantage of open waveguides is energy lost to radiation. This unwanted radiation can cause interference to the test equipment system. Particularly for continuous-wave immunity testing, a shielded room for the open waveguide is absolutely necessary.

D.6.3 Closed TEM waveguides (TEM cells)

The main advantage of the closed TEM waveguide configurations is the inherent shielding. All immunity tests can be performed without generating any disturbance to the environment. Another advantage is that the cell is an unbalanced system, so a BALUN is not needed. Lastly, in general a TEM waveguide has no low-frequency limit. For that reason, transient tests can be performed with closed TEM waveguides.

NOTE For a symmetrical-feed TEM waveguide, a low-frequency limitation may be introduced by the BALUN.

D.7 Frequency limitations

The operation of a TEM waveguide is predicated on the assumption that the TEM mode has an identical field structure to that of a plane wave in free space over a defined portion of the cross-section of the cell. Therefore, using a TEM waveguide in emission or immunity tests requires the propagation of the TEM mode over the useable frequency range.

For a given frequency within the operating range of the empty waveguide, the wave will encounter a cross-section of dimension that will allow propagating modes other than TEM to be established. For a given non-TEM mode, the point along the waveguide’s length at which the mode can propagate is dependent on frequency, and moves back towards the feed point with increasing frequency. The lowest order non-TEM mode (typically TE_{10}) is able to propagate when one cross-sectional dimension of the waveguide exceeds one-half of the free-space wavelength at that frequency. Higher order modes are launched initially by mode conversion from the TEM mode. Energy conversion between two modes is caused by irregularities in the waveguide structure that can couple to both modes.

In practice, many open and closed TEM waveguides include some type of foam or ferrite anechoic absorbers to minimize or remove the higher order modes and non-propagating resonant field distributions. If installed in the proper locations with respect to the modal field distribution, TEM mode characteristics can be essentially preserved. Generally, with the proper combination of absorber loading and input/output conductor tapering, many TEM waveguides will operate in a TEM mode up to frequencies of several GHz or higher. Proper absorber placement is determined by the shapes of the input/output tapers and the test-volume section. The disadvantage for many TEM waveguides with absorber lining in the testvolume section is that the field factor e_{0y} (see A.3.2.3.3) used in the emissions correlation algorithm can no longer be calculated analytically. This may lead to higher measurement uncertainties.

For any TEM waveguide with or without absorber, the valid frequency range shall be established using the methods described in this standard (see 5.2.1 and 5.3.2).

Further information about field homogeneity and resonant frequency are given in [22,23] and [24]. For TEM waveguides without absorber, resonant frequencies depend on the geometry of the TEM waveguide. In a two-port TEM cell they occur between a certain cross-section of the feeding section and of the termination section, called cut-off positions z_c. Each higher order mode has another cut-off position, depending on the mode-type. In between port and cut-off position the field mode is not able to propagate. A resonance occurs if the distance between the two cut-off positions is a multiple of the half wavelength. For symmetrical reasons the resonant field shall have a maximum or be zero in the middle of the cell at $z = z_{\mathrm{sym}}$. The resonant frequencies of the field modes can be analytically calculated by

$$f_{\mathrm{res}} = \frac{1}{2\pi\sqrt{\varepsilon\mu}} \cdot \sqrt{\left(\frac{\frac{n+1}{2}\cdot\pi - \arctan\left(\frac{K_3}{K_4}\right)}{z_{\mathrm{sym}}}\right)^2 + k_{\mathrm{c}}^2(z_{\mathrm{sym}})} \qquad \text{(D.8)}$$

with n = 0,1,2,3,... and K_3, K_4 = f(z, a, k, k_{c}, J_{v}) and $k_{\mathrm{c}} = f(z_{\mathrm{c}}, a,$ mode).

The constants K_1 to K_4 may be solved analytically. K_1 is chosen to 1. Therefore K_2 leads to 0. K_3 and K_4 can be written as:

$$\begin{pmatrix} K_3 \\ K_4 \end{pmatrix} = \frac{1}{\sqrt{k^2 - k_c^2(z_k)}} \cdot \begin{pmatrix} \frac{\sqrt{k^2 - k_c^2(z_k)}}{1}\cos\left(z_k\sqrt{k^2 - k_c^2(z_k)}\right) & -\sin\left(z_k\sqrt{k^2 - k_c^2(z_k)}\right) \\ -\frac{\sqrt{k^2 - k_c^2(z_k)}}{1}\sin\left(z_k\sqrt{k^2 - k_c^2(z_k)}\right) & \cos\left(z_k\sqrt{k^2 - k_c^2(z_k)}\right) \end{pmatrix} \cdot \begin{pmatrix} \sqrt{a' z_k} \cdot J_\nu(kz_k) \\ \frac{a' - 2\nu a'}{2\sqrt{a' z_k}} \cdot J_\nu(kz_k) + \sqrt{a' z_k} \cdot J_{\nu-1}(kz_k) \end{pmatrix}. \qquad \text{(D.9)}$$

For details see [24].

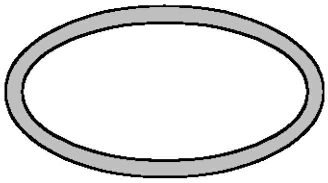


Figure D.1 – Simple waveguide (no TEM mode)

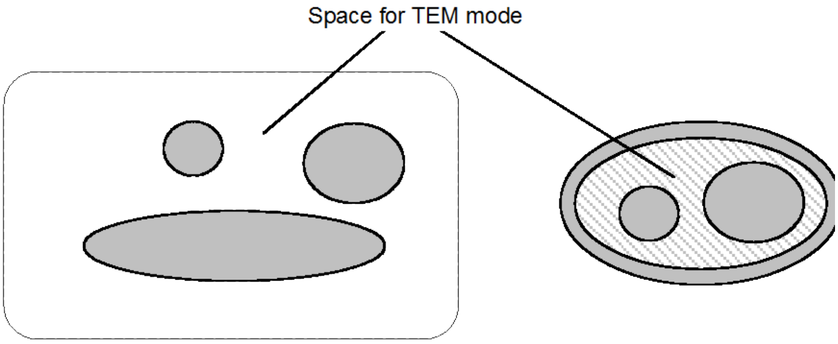


Figure D.2 – Example waveguides for TEM-mode propagation

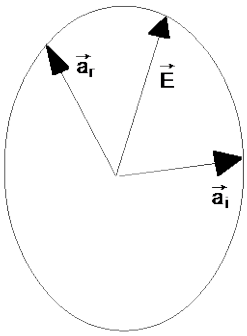


Figure D.3 – Polarization vector

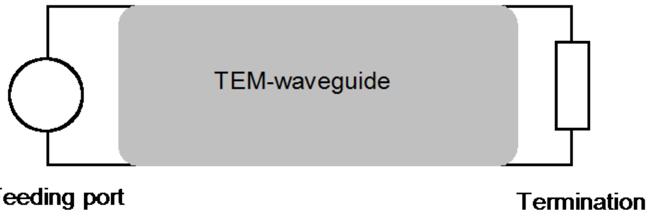


Figure D.4 – Transmission line model for TEM propagation

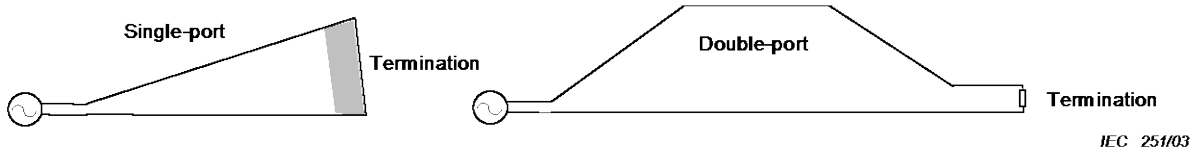


Figure D.5 – One- and two-port TEM waveguides

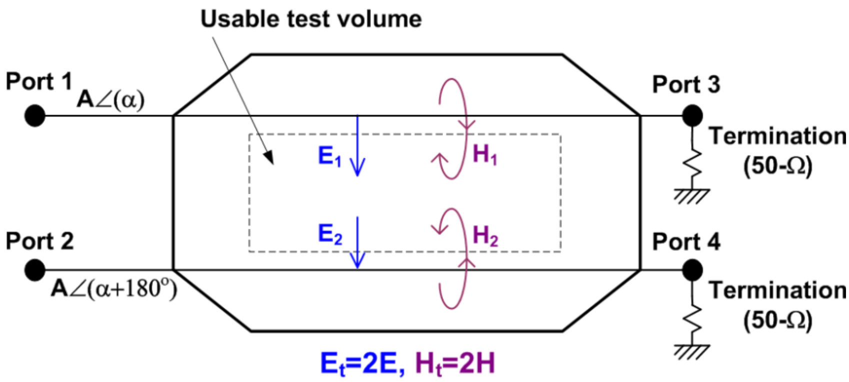


Figure D.6 – Operation of four-port TEM waveguides

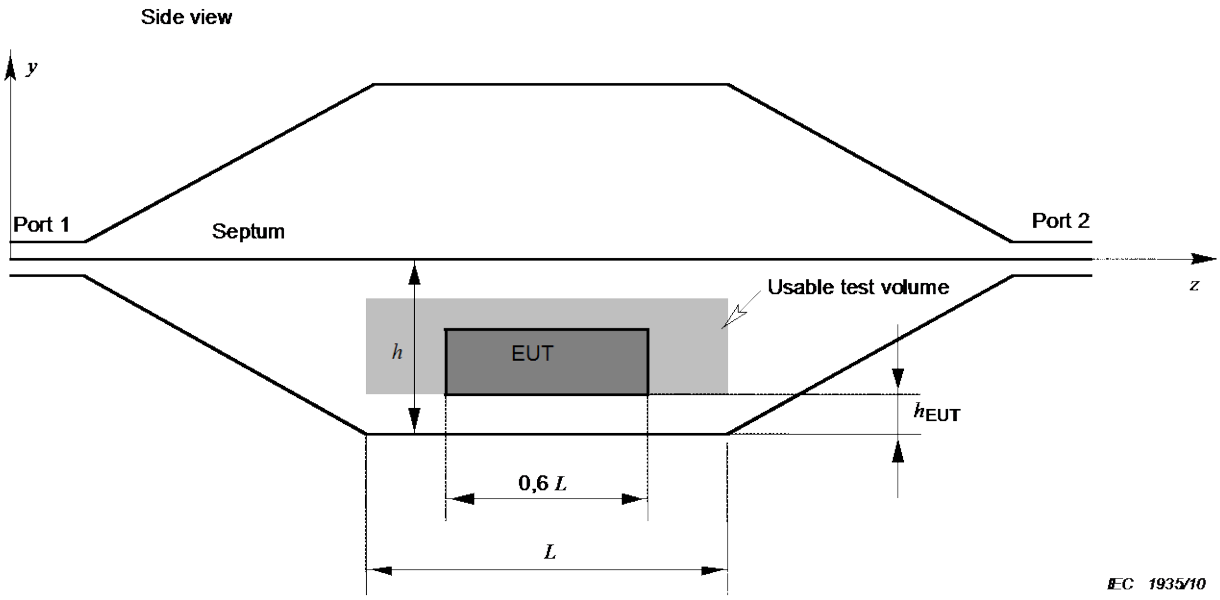


Figure D.7a – Side view

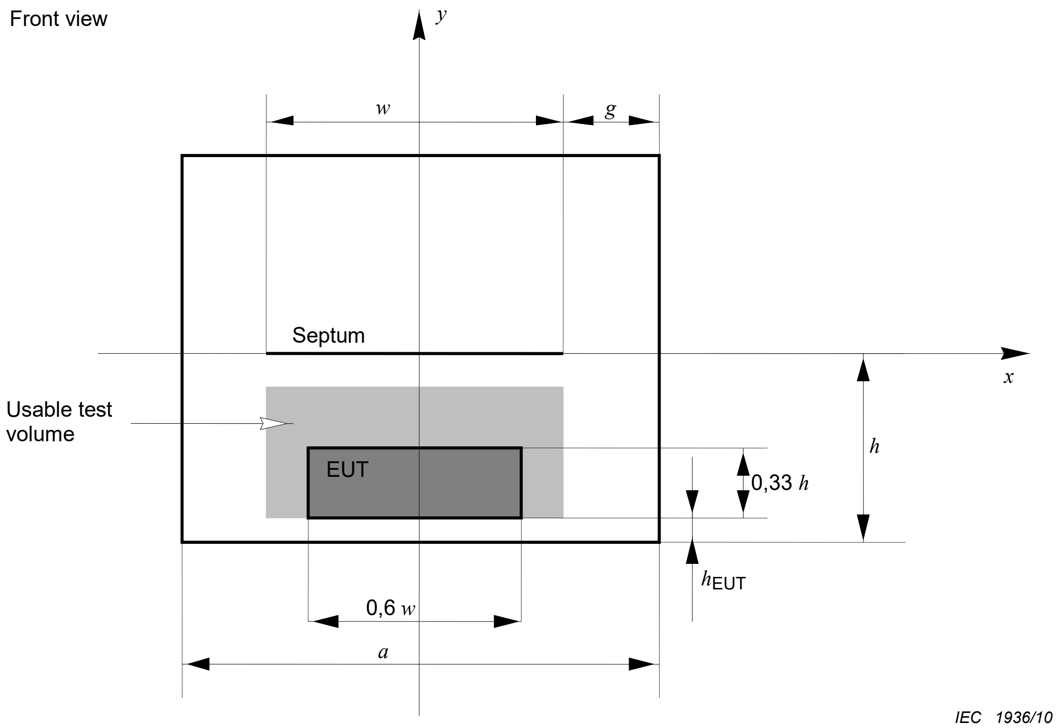


Figure D.7b – Cross-section view

NOTE h_{EUT} is the minimum distance between the EUT and each conductor or absorber of the waveguide

Figure D.7 – Two-port TEM cell (symmetric septum)

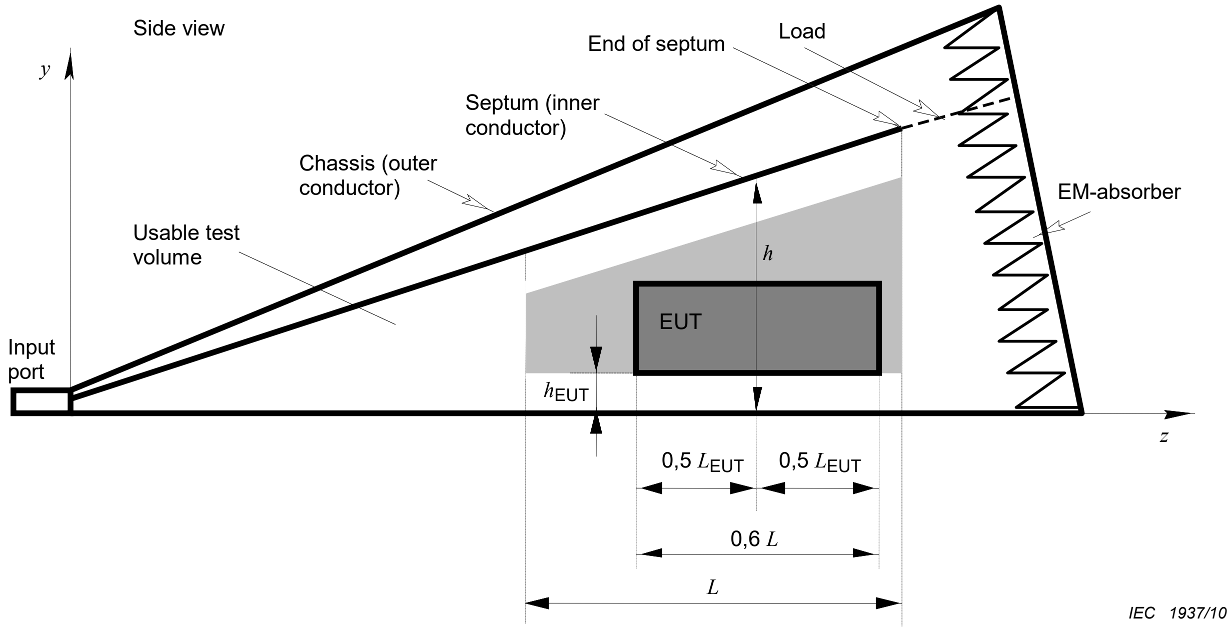


Figure D.8a – Side view

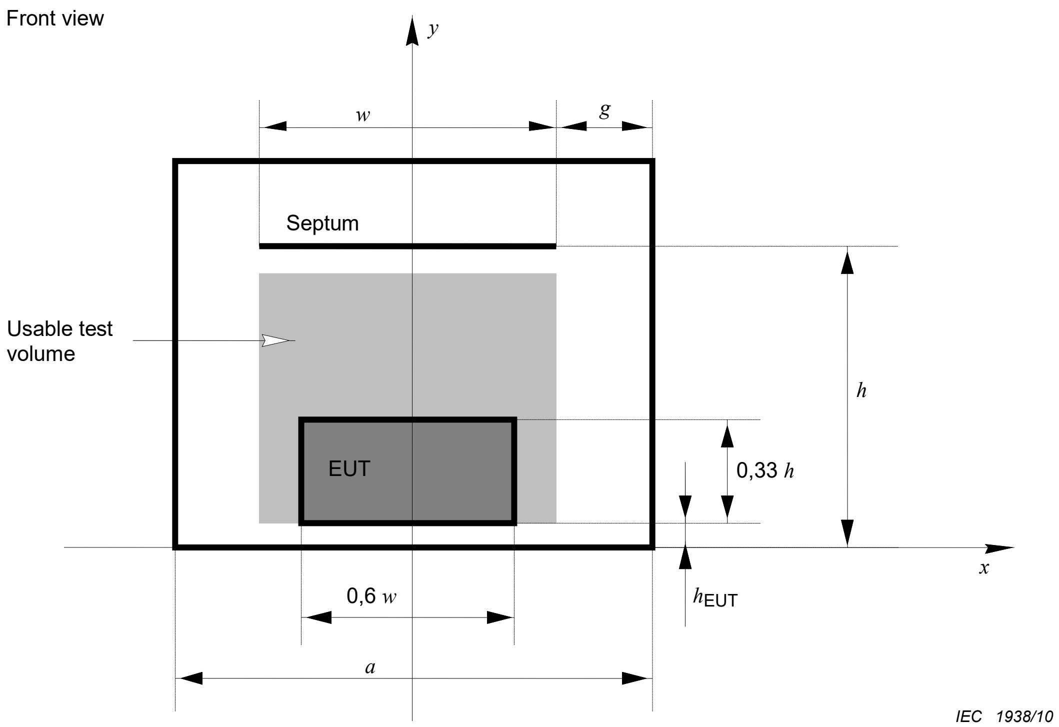


Figure D.8b – Cross-section view

NOTE h_{EUT} is the minimum distance between the EUT and each conductor or absorber of the waveguide

Figure D.8 – One-port TEM cell (asymmetric septum)

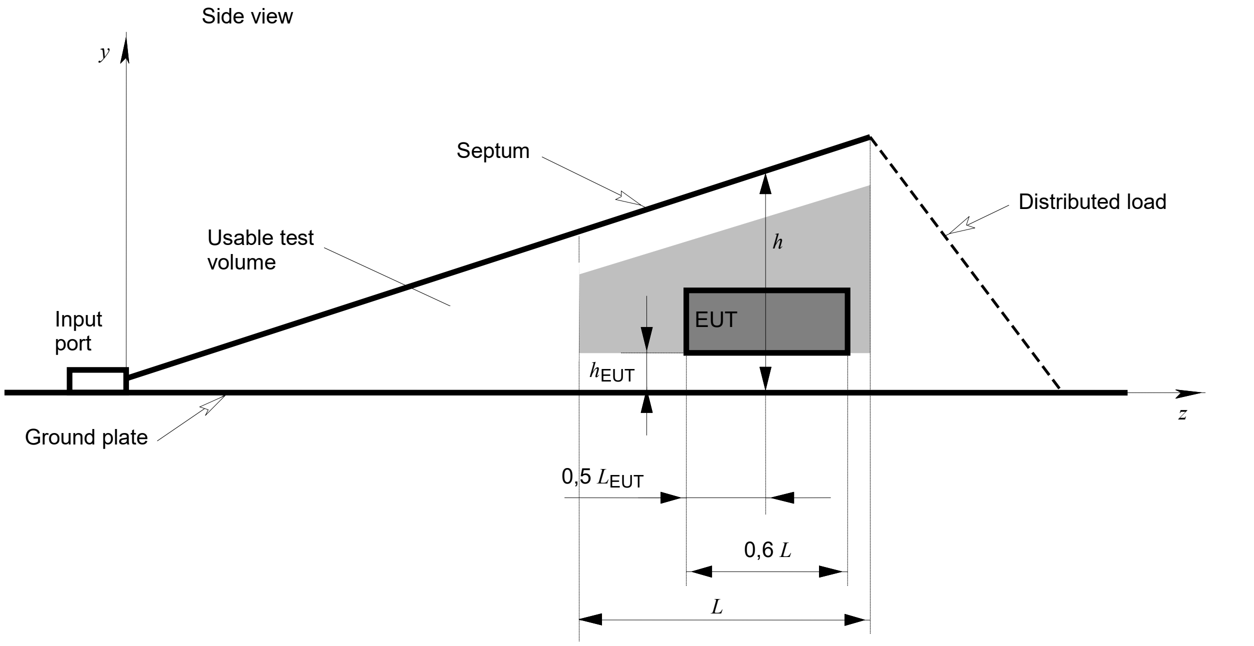


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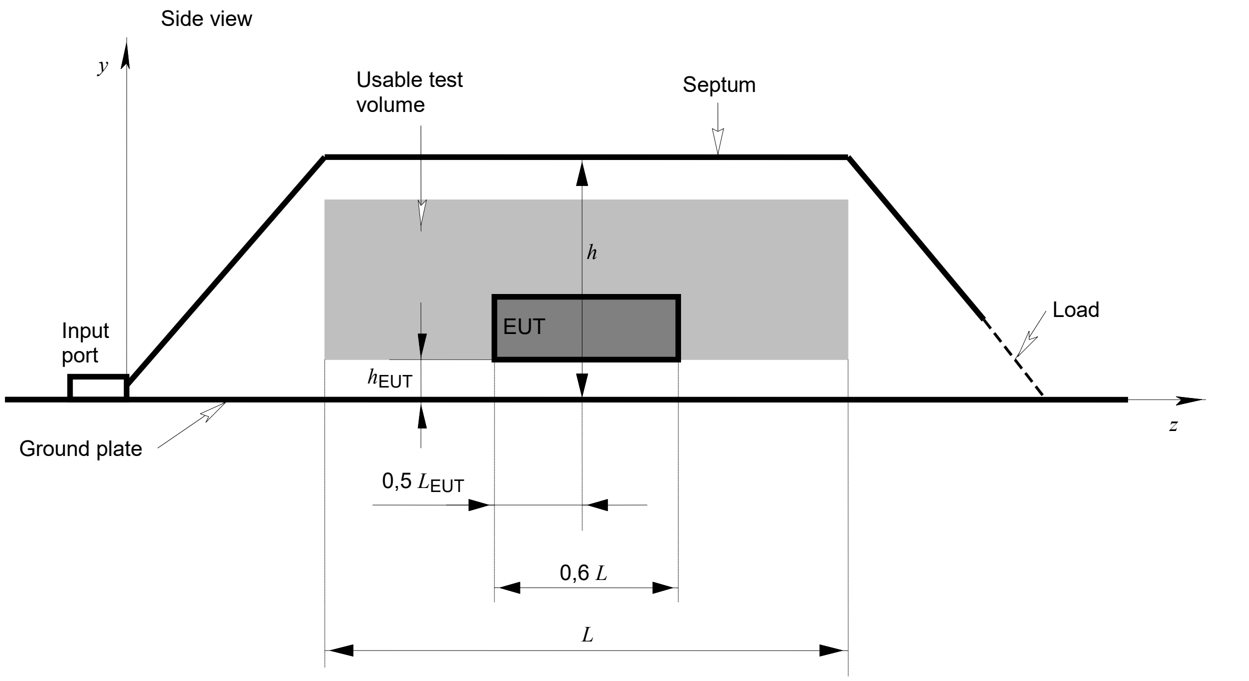
Figure D.9a – Side view (one-port)



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NOTE A tri-plate stripline with centre-line side view the same as that of Figure A.6a is obtained using this geometry and image theory.

Figure D.9b – Side view (basically similar to a two-port TEM waveguide, but some versions have a distributed load at the output port)

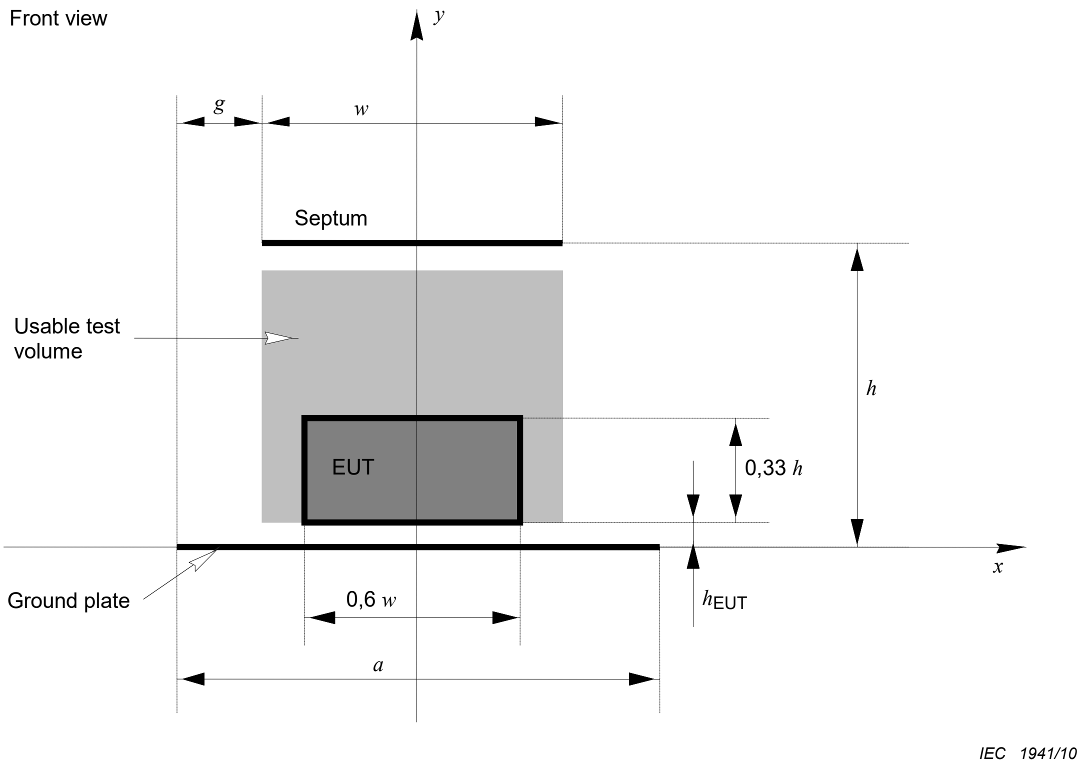


Figure D.9c – Cross-section view

NOTE h_{EUT} is the minimum distance between the EUT and each conductor or absorber of the waveguide

Figure D.9 – Stripline (two plates)

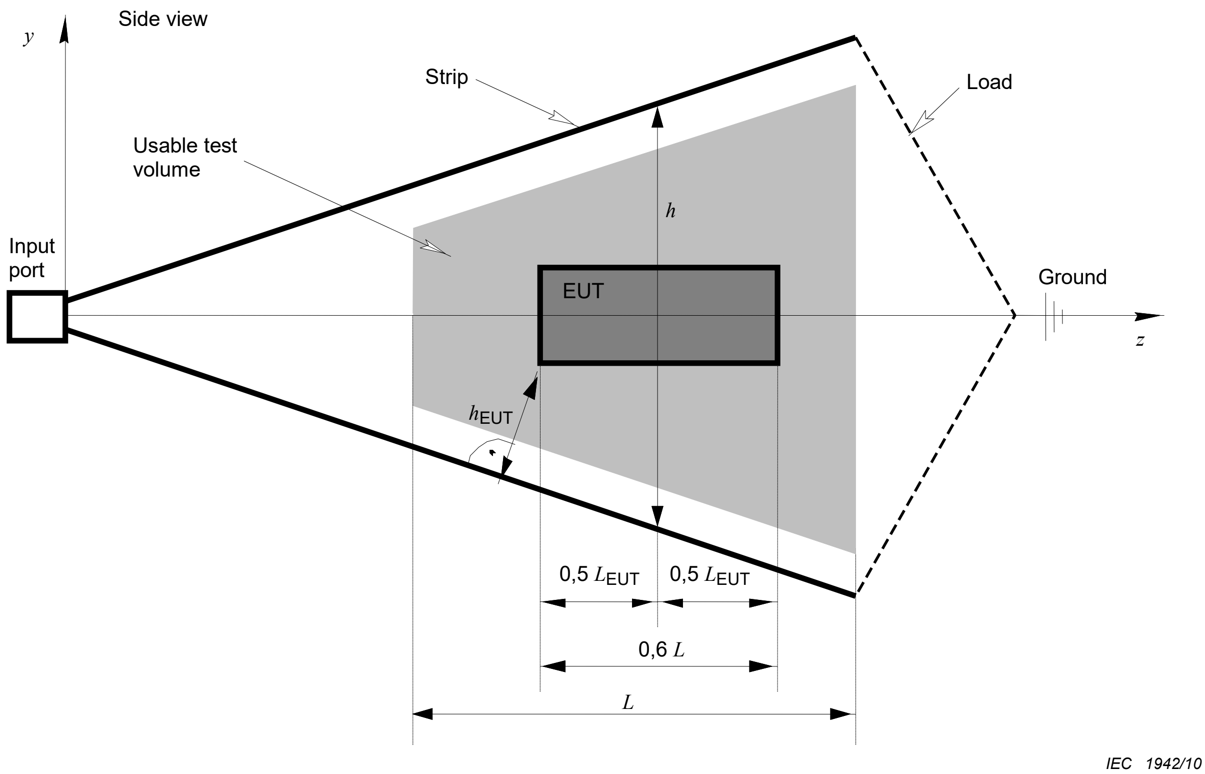


Figure D.10a – Side view

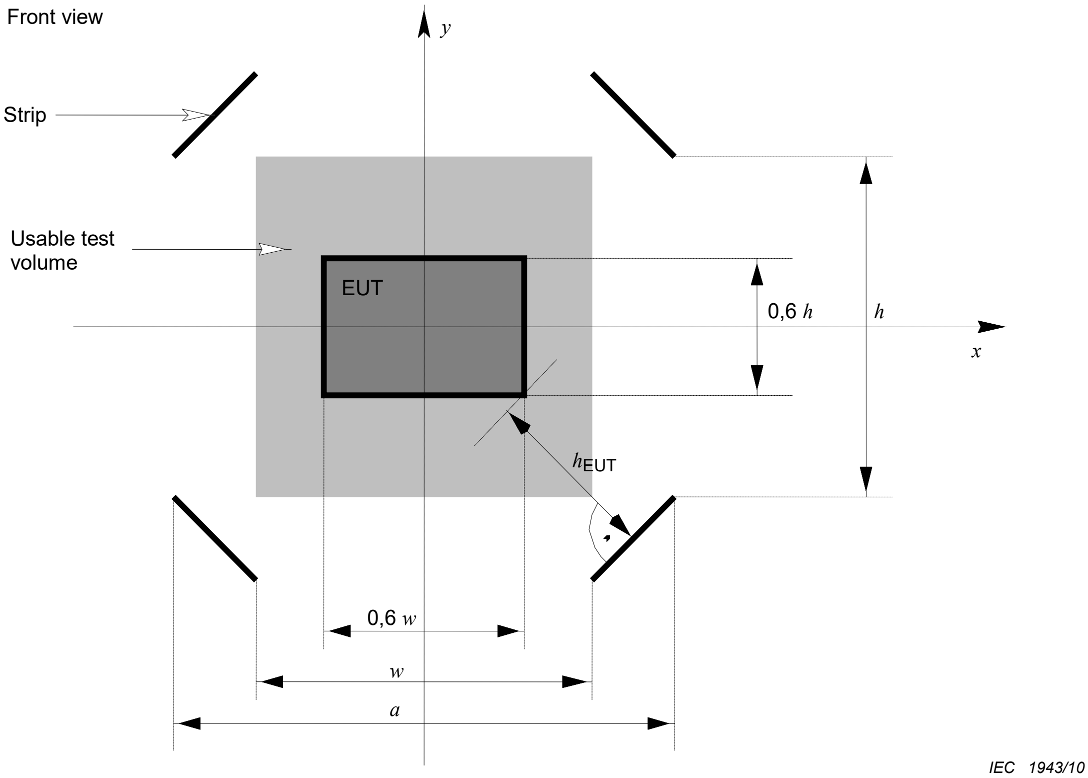


Figure D.10b – Cross-section view

NOTE The entire TEM waveguide configuration is surrounded by a fully anechoic enclosure. For symmetry purposes reasons the restriction of the maximum usable EUT height changes from 0,33 h to 0,6 h (see 5.2.2).

Figure D.10 – Stripline (four plates, balanced feeding)

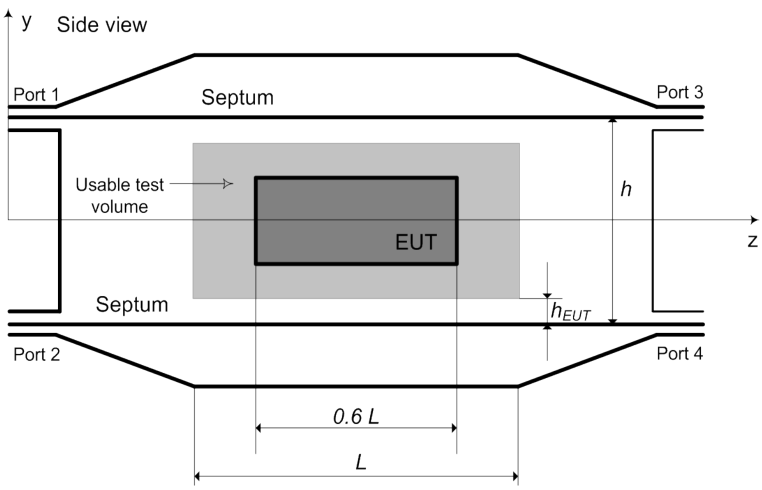


Figure D.11a – Side view

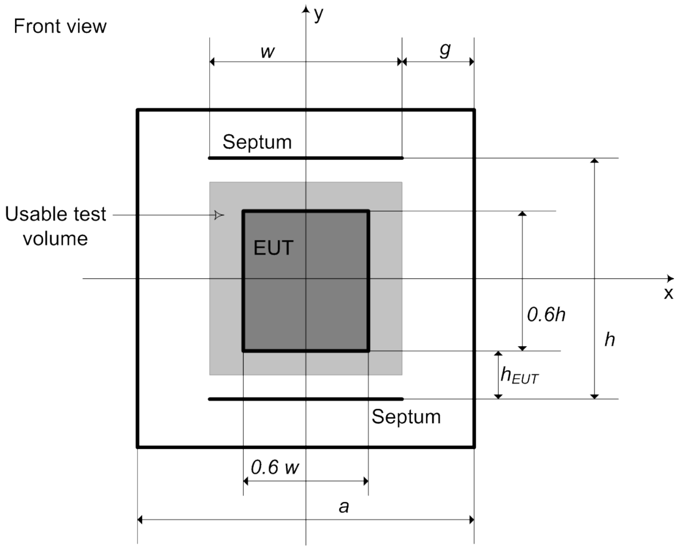


Figure D.11b – Cross-section view

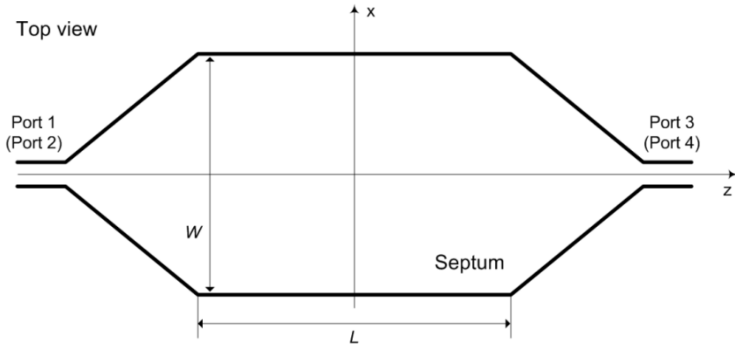


Figure D.11c – Top view of septum

NOTE h_{EUT} is the minimum distance between the EUT and each conductor or absorber of the waveguide

Figure D.11 – Four-port TEM waveguide (symmetric parallel septa)

Annex E
(informative)

Calibration method for E-field probes in TEM waveguides

E.1 Overview

E-field probes with broad frequency range and large dynamic response are extensively used in the field uniformity validation procedures in accordance with this standard. Among other aspects, the quality of the field probe calibration directly impacts the uncertainty budget of a radiated immunity test.

Generally, depending on the radiated immunity test performed, probes may be subject to field up to 200 V/m or even more, during the field uniformity validation in accordance with this standard. Therefore a calibration of the E-field probes used within this standard should take the intended frequency and dynamic ranges into consideration.

Currently probe calibration results show differences when the probe is calibrated in different calibration laboratories. Therefore, the environment and method for field probe calibration are to be specified. This annex gives the TEM waveguide validation procedures to be used for probe calibration and provides relevant information on calibration of probes to be used in this standard field uniformity measurements in order to limit these differences in validation results.

E.2 Probe calibration requirements

E.2.1 General

The calibration of E-Field probes intended to be used for uniform field area (UFA) validation procedures as defined in this standard should satisfy the following requirements. UFA is a hypothetical vertical plane of the field calibration in which variations are acceptably small.

E.2.2 Calibration frequency range

The frequency range should normally cover to the highest frequency that is specified by the size and the structure of the TEM waveguide. The largest dimension of probe head of an E-field probe, l_{pmax}, should be smaller than one quarter wavelength at the highest calibration frequency, f_{cmax}, to avoid approaching resonance. Therefore, the highest frequency is given by the dimension of the probe head as

$$f_{\mathrm{max}} \leq \frac{c_0}{4 l_{\mathrm{p\,max}}} \quad \text{(E.1)}$$

where, c_0 is the speed of the light.

For example, when the largest dimension of probe head of an E-field probe, l_{pmax}, is 2,5 cm, the highest frequency is given as 3 GHz from Equation (E.1). If the frequency exceeds the highest frequency that is determined by the TEM mode verification described in 5.2.1, the calibration is carried out up to the highest frequency determined by the TEM verification.

E.2.3 Calibration volume

The dimensions of the calibration volume, which should be as regular as possible, e.g. cubic or parallelepiped, should be smaller than 20% of the distance between the inner and outer conductors (septum height). The centre of the volume where an electric-field probe can be calibrated should be positioned in the centre of the septum height.

The validation of the volume should be performed at the grid points of the cube. A grid interval between two calibration points is selected at about 10% of the septum height. An electric-field probe or sensor for the validation should be as small as possible. The probe or the sensor need not necessarily be calibrated.

NOTE 1 When the dimensions of the calibration volume are a 20 cm cube for example, the grid interval is 10 cm and the number of the measuring points is 27 as shown in Figure E.1.

The validation procedure of the volume is as follows:

a) the electric fields are measured at all points using the constant forward power method mentioned in 5.2.3. Frequencies should be selected as mentioned in E.2.6;

b) a standard deviation for the measured electric fields is calculated;

c) the standard deviation should be smaller than about 1 dB for a one-port TEM waveguide, and 0,6 dB for a two-port TEM waveguide;

NOTE 2 The basis of these standard deviations is mentioned in [35].

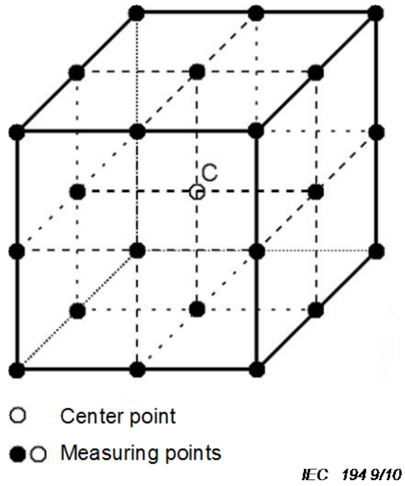


Figure E.1 – An example of the measurement points for the validation

E.2.4 Probe dimensions

The probe-head dimensions should be smaller than 10% of the distance between the inner and outer conductors (septum height), h (see 5.2.3). The probe dimensions should also be smaller than the calibration volume (see E.2.3).

E.2.5 Perturbations of a TEM waveguide due to probe

The perturbation of a TEM waveguide due to probe including the measurement apparatus should be validated with and without the probe.

NOTE The perturbation depends not only on the perturbation caused by measurement apparatus but also the linearity of the TEM waveguide.

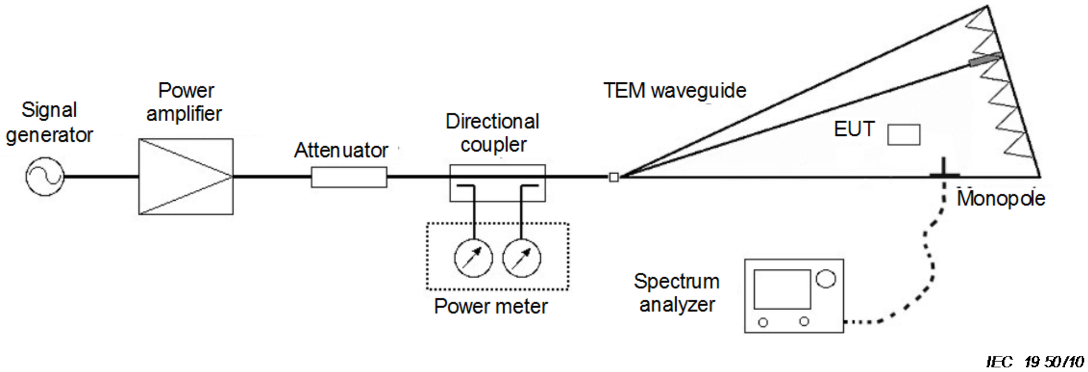


Figure E.2 – Setup for validation of perturbation

An example of the measurement setup for the validation is shown in Figure E.2. A power amplifier, a signal generator, a directional coupler, and a power meter should be connected to a TEM waveguide as in a case of the probe calibration. A monopole antenna is used for the sensing of the electric field. A small hole is made in the ground plate and then the antenna is attached to the ground plate. A less-invasive electric-field sensor, e.g. an optical electric-field sensor using $LiNbO_3$ electro-optic crystal, is also available instead of the monopole antenna. When the sensor is used, the hole is not needed. The antenna/sensor needs not necessarily be calibrated. The monopole antenna is connected to a spectrum analyzer to measure the antenna output. A metallic cube that has dimensions of the calibration volume can be used as a probe.

The validation procedure of the perturbation is as follows:

a) set a frequency without an probe and apply the forward power to a TEM waveguide;
b) measure the level of the power and the reading of the spectrum analyzer;
c) increase the power and repeat b);
d) change the frequency (see E.2.6) and repeat from a) to c);
e) when the measurement is done for all frequencies, add the probe and repeat from a) to d);
f) check the perturbation of the reading to the input power.

The difference between the perturbation with probe and that without probe should be less than the measurement uncertainty of the power meter and the spectrum analyzer.

NOTE See [7] and [54] to determine the uncertainty. Some manufacturers of measurement apparatus provide the measurement uncertainty of the apparatus.

E.2.6 Frequency steps

To be able to compare test results between different calibration laboratories, it is necessary to use fixed frequencies for the calibration, see Table E.1.

Table E.1 – Calibration frequencies

Frequency range	**Typical calibration frequencies** MHz
f_0 to 1 GHz	f_0, 50, 100, 150, 200, …, 950, 1 000
Above 1 GHz	1 000, 1 200, 1 400, …
NOTE f_0 is the lowest frequency of the probe under calibration.	

E.2.7 Field strength

The field strength at which a probe is calibrated should be based on the field strength required for the immunity test. As the preferred method for uniformity field validation is carried out at field strength of at least 1,8 times the field strength to be applied to the EUT, it is recommended that the probe calibration is carried out at twice the test field strength, as shown in Table E.2.

NOTE This also covers the 1 dB compression requirement of the power amplifier.

Table E.2 – Calibration field strength level

Calibration level	Calibration field strength V/m
1	2
2	6
3	20
4	60
X	Y
NOTE X, Y is an open calibration level. This level may be given in the product specification or by the test laboratory.	

E.3 Requirements for calibration instrumentation

E.3.1 Specifications of TEM waveguide

A TEM waveguide can be used to establish standard fields for field probe calibrations. The field at the centre of a TEM cell between the septum and the top or bottom plate is calculated from:

$$E_{\text{approx}} = \frac{\sqrt{Z_0 P_{\text{net}}}}{h} \quad \text{,in V/m} \qquad \text{(E.2)}$$

where

Z_0 is the characteristic impedance of the TEM cell (typically 50 Ω),

P_{net} is the net power in watts, determined according to E.3.4,

h is the separation distance between the septum and the top or bottom plate (in m).

NOTE 1 The field at the mid-point between two conductors is approximated by Equation (E.2).

NOTE 2 The Equation (E.2) is only valid for the TEM mode.

The VSWR of the TEM cell should be kept small, e.g. less than 1,3 to minimize the measurement uncertainties.

An alternative method of measuring P_{net} is to use a calibrated, low VSWR attenuator and power sensor connected to the output port of the TEM waveguide (two-port TEM waveguide only).

E.3.2 Harmonics and spurious signals

Any harmonics or spurious signals from power amplifiers should be at least 20 dB below the level at the carrier frequency. This is required for all field strength levels used during calibration and linearity check. Since the harmonic content of power amplifiers is usually worse at higher power levels, the harmonic measurement may be performed only at the highest calibration field strength. The harmonic measurement can be performed using a calibrated spectrum analyzer which is connected to the amplifier output through an attenuator, or through a directional coupler.

Calibration laboratories should perform a measurement to validate that the harmonic and/or spurious signals from the amplifier satisfy the requirements for all measurement setups. This may be done by connecting a spectrum analyzer to Port 3 of the directional coupler (replacing the power meter sensor with the spectrum analyzer input, see Figure E.3).

NOTE It should be assured that the power level does not exceed the maximum allowable input power of the spectrum analyzer. An attenuator may be used.

The frequency span should cover at least the third harmonic of the intended frequency. The validation measurement should be performed at the power level that will generate the highest intended field strength. Harmonic suppression filters may be used to improve the spectrum purity of the power amplifier(s).

NOTE "Intended frequency" means the maximum frequency to be calibrated.

E.3.3 Probe fixture

The probe fixture may cause reflections of electromagnetic fields during the probe calibration. The fixture should be made of a material with a relative permittivity of less than 1,2 and a dielectric loss tan δ less than 0,005.

E.3.4 Measuring net power to a transmitting device using directional couplers

Net power delivered to a transmitting device can be measured with a 4-port bi-directional coupler, or two 3-port single directional couplers connected back-to-back (forming the so-called “dual directional coupler”). A common setup using a bi-directional coupler to measure the net power to a transmitting device is shown in Figure E.3. The forward coupling and reverse coupling are defined by the following equations in case where each port is connected with a matched load and a matched source:

$$C_{\text{fwd}} = \frac{P_3}{P_1} \qquad \text{(E.3)}$$

$$C_{\text{rev}} = \frac{P_4}{P_2} \qquad \text{(E.4)}$$

where P_1, P_2, P_3, and P_4 are the respective powers at each port of the directional coupler.

The net power delivered to the transmitting device is then:

$$P_{\text{net}} = \frac{PM_1}{C_{\text{fwd}}} - \frac{PM_2}{C_{\text{rev}}} \qquad \text{(E.5)}$$

where PM_1 and PM_2 are the power meter readings in linear units.

Where the VSWR of the TEM waveguide is known, then a single three-port coupler can be used. For example, when the TEM waveguide has a VSWR of 1,5 this is equivalent to a voltage reflection coefficient (VRC) of 0,2.

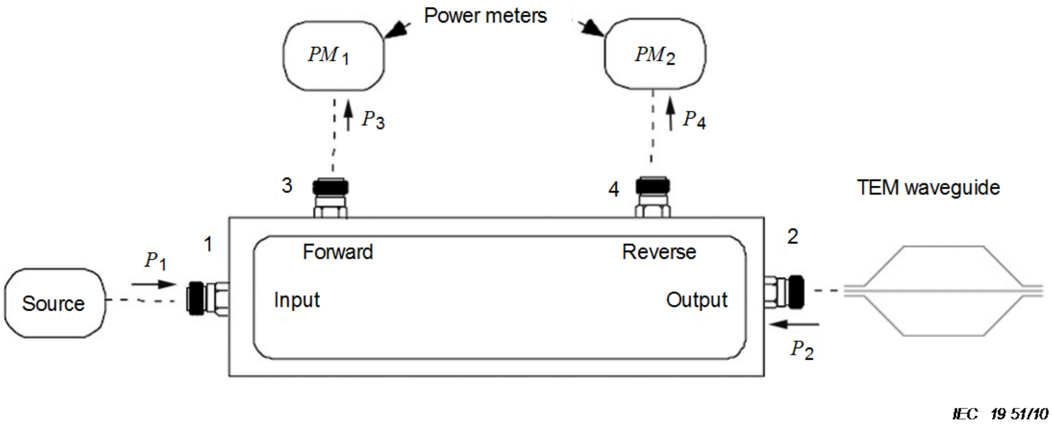


Figure E.3 – Setup for measuring net power to a transmitting device

The accuracy is affected by the directivity of the coupler. The directivity is a measure of the coupler’s ability to isolate the forward and the reverse signals. For a well-matched transmitting device, the reverse power is much smaller than the forward power. The effect of the directivity is therefore less important than in a reflectivity application. For example, when the TEM waveguide has a VSWR of 1,5, and the coupler has a directivity of 20 dB, the absolute maximum uncertainty in the net power due to the finite directivity is 0,22 dB – 0,18 dB = 0,04 dB with a U-shaped distribution (where 0,22 dB is the loss of the incident power from VSWR 1,5).

The net power delivered to the transmitting device is then:

$$P_{\text{net}} = \frac{PM_1(1 - VCR^2)}{C_{\text{fwd}}} \qquad \text{(E.6)}$$

E.4 Field probe calibration

E.4.1 Calibration methods

Although three calibration methods are provided in [54], two methods are generally employed. The standard field method using calculated field strengths is used for a two-port TEM waveguide (see E.4.2). The calibration method using the transfer standard (i.e., a field sensor or probe similar to the one being calibrated) is used for a one-port TEM waveguide.

E.4.2 Calibration procedure in a case of two-port TEM waveguide

The standard field method can be applied for the probe calibration in a case of such waveguide. Figure E.4 shows an example of the setup for the calibration of an E-field probe. If the E-field level and the forward and reverse powers are read manually, a computer needs not necessarily be used. The calibration procedure should be selected according to the type of TEM waveguide. The procedure for carrying out the calibration in a case of two-port TEM waveguide is as follows:

a) position the isotropic electric field strength sensor at the centre of septum height;

b) apply a forward power to the TEM waveguide input port so that the electric field strength of the primary field component is in the range 6 V/m to 20 V/m, through the frequency range specified in E.2.2 in frequency steps specified in E.2.6, and record all the forward and reverse powers, primary and secondary components field strength readings;

c) calculate the net power, P_{net}, with Equation (E.5) or (E.6) and the measured powers;

d) calculate the nominal primary electric-field strength with Equation (E.2) as E_{approx}.

NOTE The calibration factor may change depending on how the probe is installed. There also is a method to insert only a probe head from the upper part of TEM waveguide to remove the influence from any parts other than the probe head.

The calibration factor, F_p, can be obtained as

$$F_p = \frac{E_m}{E_{approx}}, \text{ or } F_p = E_m - E_{approx} \quad \text{in dB} \qquad \text{(E.7)}$$

where E_m is the measured primary field strength.

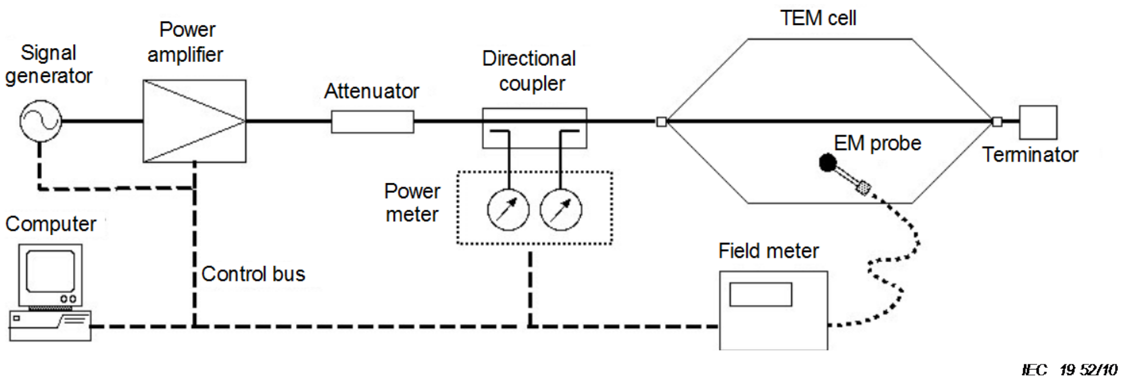


Figure E.4 – Example of setup for calibration of E-field probe

E.4.3 Calibration procedure in a case of one-port TEM waveguide

E.4.3.1 Transfer method

Generally, deviations of the measured electric field strength from the field strength given by Equation (E.2) are within ±0,5 dB for all frequencies in a case of a two-port TEM waveguide. However, the deviations may be ±3 dB or ±4 dB in a case of one-port TEM waveguide. Therefore, the calibration method mentioned in E.4.2 should not be used in the one-port TEM waveguide. In that case, the calibration can be performed by using a transfer method.

A transfer probe can be used to establish standard fields in a field-generating device (working standard device). The transfer probe response can be either determined by theoretical computations (for probes such as dipoles) or by calibrations performed according to some methods (e.g. a three antenna method in an anechoic chamber can be used). Another method is the use of a small (to allow a high upper frequency) two-port-TEM-cell. That of course requires that the transfer probe is sufficiently small. Once the transfer function of the working standard device is known, probe calibration can be performed at other power levels provided that the working standard device is linear. Possible additional errors due to the difference in calibration environments (e.g. calibration site, size, orientation) for transfer standards as well as differences in shapes between the transfer standard and the probe under calibration should be noted.

NOTE 1 Usually, any difference between the calibration environment between the reference calibration and the actual use in a calibration laboratory will introduce systematic errors. Furthermore, the transfer standard used in a calibration laboratory should ideally have the same geometry and construct as the probe that is actually to be calibrated. If this is not the case additional systematic errors will be introduced that will have to be quantified.

The procedure for carrying out the calibration by using the transfer probe is as follows:

a) position the transfer probe at the centre of septum height;

b) apply a forward power to the TEM waveguide input port through the frequency range specified in E.2.2 in frequency steps specified in E.2.6, and record all the forward and reverse powers and the primary field strength readings (or the output voltage of the transfer probe);

NOTE 2 If the output voltages are measured, these should be converted to the electric field strength.

c) calculate the net power, P_{net}, with Equation (E.5) or (E.6) and the measured powers;

d) replace the transfer probe by the isotropic electric field strength sensor to be calibrated;

e) apply a forward power so that the net power is the same as the power in b), and record the primary field strength readings.

The calibration factor, F_{p}, can be obtained as

$$F_{\mathrm{p}} = \frac{E_{\mathrm{m}}}{E_{\mathrm{T}}}, \text{ or } F_{\mathrm{p}} = E_{\mathrm{m}} - E_{\mathrm{T}} \quad \text{in dB} \tag{E.8}$$

where E_{T} is the primary field strength obtained by the transfer probe.

The transfer method is accurate if the following conditions are met:

- the setup does not change between the transfer and calibration procedures;
- the probe position during measurements is reproduced;
- the transmitted power remains the same;
- the probe under test is similar in construction (size and element design) to the transfer probe;
- the cables connecting the sensor head and readout do not disturb or pick up the field;
- the working standard device is largely anechoic.

References [20,21] and [19] have more information on this method.

E.4.3.2 Method of electric field estimation at the calibration position

If the transfer probe is not available, a probe can be calibrated by another method. A monopole antenna mentioned in E.2.5 is used (see Figure E.5). The calibration procedure is as follows:

a) position the monopole antenna at the ground plate;

b) apply the forward power to the TEM waveguide input port through the frequency range specified in E.2.2 in frequency steps specified in E.2.6, and record all the forward and reverse powers, and the spectrum analyzer readings, P_{nmono};

c) calculate the strength of the electric field at the position of the monopole, E_{mono}, using the antenna factor of the antenna;

d) calculate the net power, P_{net}, with Equation (E.5) or (E.6) and the measured powers;

e) remove the monopole, and then position the small electric field sensor (e.g. optical electric field sensor) at the place where the monopole had been positioned;

f) apply a forward power so that the net power is the same as the power in a case of b),record the primary field strength or the spectrum analyzer readings by the sensor (E_{M} or P_{M});

NOTE The small electric field sensor need not necessarily be calibrated. Although the electric field probe can be used, the probe to be calibrated should not be used.

g) position the small electric field sensor at the position to be calibrated (normally, at the centre point of the septum height);

h) apply a forward power so that the net power is the same as the power in a case of b), and record the primary field strength or the spectrum analyzer readings by the sensor (E_C or P_C).

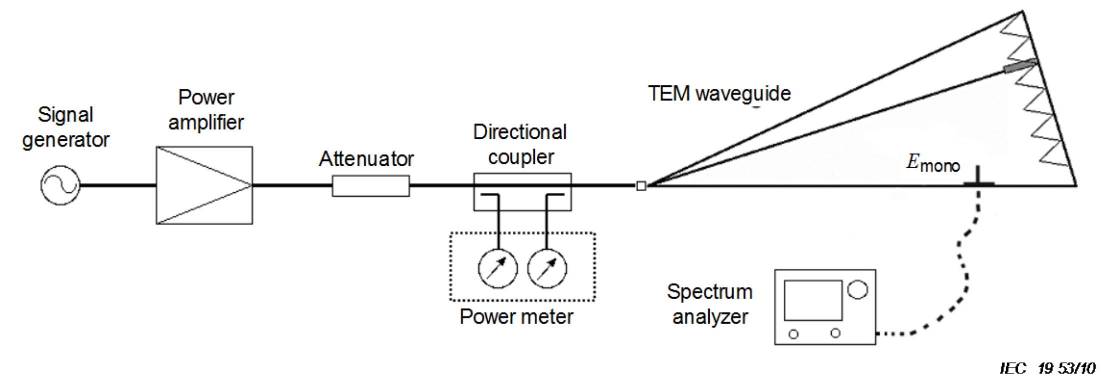


Figure E.5a – Use of a monopole antenna

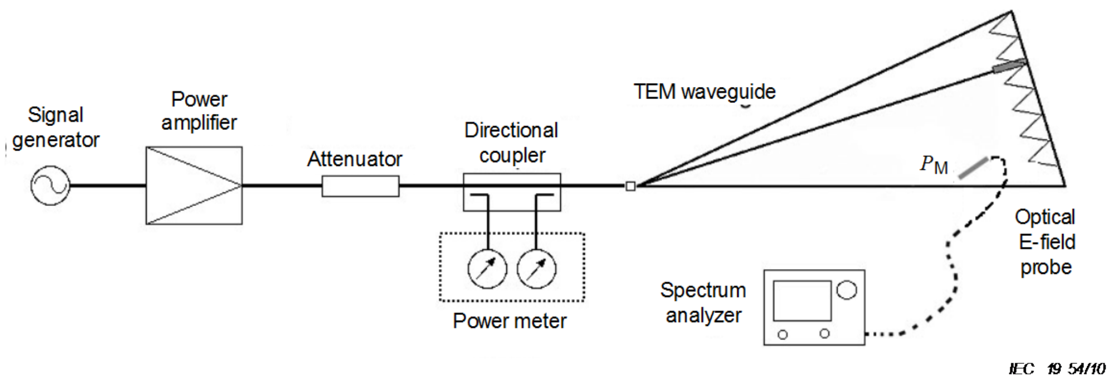


Figure E.5.b – Use of a small electric field sensor

Figure E.5 – Setup for calibration of E-field probe by another method

The reference electric field can be calculated as the following equation.

$$E_{ref} = \frac{E_{mono}\sqrt{P_C}}{\sqrt{P_M}}$$

or (E.9)

$$E_{ref} = \frac{E_{mono}E_C}{E_M}$$

The calibration factor, F_p, can be obtained as

$$F_p = \frac{E_m}{E_{ref}}, \text{ or } F_p = E_m - E_{ref} \quad \text{in dB} \qquad (E.10)$$

where E_m is the primary field strength obtained by a probe under test.

The procedure of the antenna factor of the monopole antenna is stated in E.4.3.3.

E.4.3.3 Calculation of antenna factor from antenna impedance using equivalent length

Antenna impedance can be obtained by measuring the reflection coefficient of the antenna using a network analyzer, or by a calculation using the Labus's equation [43] or other numerical methods such as the method of moments.

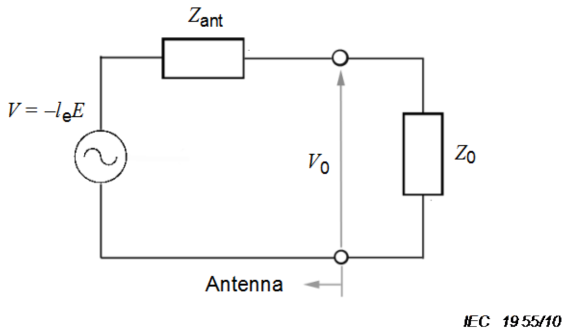


Figure E.6 – Equivalent circuit of antenna and measurement apparatus

The equivalent circuit of a receiving antenna and a measurement apparatus is shown in Figure E.6. The terminal voltage of the antenna, V_0, is obtained as follows:

$$V_0 = \frac{Z_0 V}{Z_0 + Z_{\text{ant}}} = -\frac{Z_0 l_e E}{Z_0 + Z_{\text{ant}}} \tag{E.11}$$

where Z_0 and Z_{ant} are the characteristic impedance of the apparatus and the antenna impedance, respectively; E is the electric field at the place where the element of the antenna is positioned.

l_e is the effective length of the antenna, which is calculated as follows:

$$l_e = \frac{1}{\sin\left(\frac{2\pi l}{\lambda}\right)} \int_0^l \sin\left(\frac{2\pi x}{\lambda}\right) dx = \frac{\lambda}{2\pi \sin\left(\frac{2\pi l}{\lambda}\right)} \left\{1 - \cos\left(\frac{2\pi l}{\lambda}\right)\right\} \quad \left(l \le \frac{\lambda}{4}\right) \tag{E.12}$$

$$l_e = \frac{\lambda}{2\pi}\left\{1 - \cos\left(\frac{2\pi l}{\lambda}\right)\right\} \quad \left(\frac{\lambda}{4} \le l < \frac{\lambda}{2}\right) \tag{E.13}$$

where l and λ are the element length of the antenna and the wavelength, respectively.

The antenna factor, AF, is expressed by the electric field and the terminal voltage is indicated by the following equation.

$$AF = \frac{E}{V_0} \tag{E.14}$$

The antenna factor is obtained from (E.11) and (E.14) as

$$AF = \frac{Z_0 + Z_{\text{ant}}}{Z_0 l_e} \tag{E.15}$$

Annex F
(informative)

Measurement uncertainty of emission measurements

F.1 Radiated disturbance measurements using a TEM Waveguide

F.1.1 Measurand for radiated disturbance measurements using a TEM Waveguide

E Disturbance field strength, in dB(μV/m), measured on a 10 m OATS/SAC for 30 to 1000 MHz and measured in a 3 m FAR (FSOATS) for 1 to 18 GHz

NOTE 1: It is assumed that measurement results taken in a TEM waveguide are converted to field strength for comparison with OATS-based limits at 10 m distance up to 1 GHz and to FAR-based limits at 3 m distance above 1 GHz.

F.1.2 Symbols of input quantities common to all disturbance measurements

a_c	Attenuation of the connection between the receiver and the TEM waveguide, in dB
δM	Correction for the error caused by mismatch, in dB
V_r	Receiver voltage reading, in dB(μV)
δV_{sw}	Correction for receiver sine wave voltage inaccuracy, in dB
δV_{pa}	Correction for imperfect receiver pulse amplitude response, in dB
δV_{pr}	Correction for imperfect receiver pulse repetition rate response, in dB
δV_{nf}	Correction for the effect of the receiver noise floor, in dB

F.1.3 Symbols of input quantities specific to TEM waveguide measurements

$F_{conv\ TEM}$	Conversion factor for field-strength measurements in TEM waveguide, in dB(1/m)
δS_{uni}	Correction factor for field non-uniformity in EUT volume, in dB
δS_d	Correction factor for separation distance between waveguide port and EUT, in dB
$\delta S_{EUT\ dir}$	Correction factor for the effect of EUT directivity, in dB
δS_{TT}	Correction factor for the effect of turntable/manipulator material, in dB

F.2 Input quantities to be considered for radiated disturbance measurements using a TEM waveguide

– Receiver reading
– Cable attenuation between TEM waveguide and measuring receiver
– Conversion factor for field-strength measurements using the TEM waveguide
– Receiver related input quantities
  - Sine wave voltage accuracy
  - Pulse amplitude response
  - Pulse repetition rate response
  - Noise floor proximity
– Mismatch effects between TEM waveguide receiver port and measuring receiver
– Effect of field non-uniformity
– Effect of separation distance between EUT and waveguide port
– Effect of EUT directivity
– Effect of EUT turntable/manipulator material

F.3 Uncertainty budget and rationale for the input quantities for radiated disturbance measurements using a TEM waveguide

F.3.1 Uncertainty budget for radiated disturbance measurements using a TEM waveguide

The measurand E is calculated using model equation (F.1):

$$E = V_r + a_c + F_{\mathrm{conv\,TEM}} + \delta V_{sw} + \delta V_{pa} + \delta V_{pr} + \delta V_{nf} + \delta M + \delta S_{uni} + \delta S_d + \delta S_{\mathrm{EUT\,dir}} + \delta S_{TT} \quad \text{(F.1)}$$

Table F.1 – Uncertainty budget for radiated disturbance measurements using a TEM waveguide from 30 MHz to 1000 MHz (Example)

Input quantity	X_i	Uncertainty of x_i		$c_i\,u(x_i)$[b]
		dB	Probability distribution function	dB
Receiver reading[F1)]	V_r	± 0,1	k = 1	0,10
Attenuation: TEMwg-receiver[F2)]	a_c	± 0,2	k = 2	0,10
TEM conversion factor[F7)]	$F_{\mathrm{conv\,TEM}}$	± 0,0	-	0,0
Receiver corrections:				
Sine wave voltage[F3)]	δV_{sw}	± 1,0	k = 2	0,50
Pulse amplitude response[F4)]	δV_{pa}	± 1,5	Rectangular	0,87
Pulse repetition rate response[F4)]	δV_{pr}	± 1,5	Rectangular	0,87
Noise floor proximity[F5)]	δV_{nf}	± 0,3	Rectangular	0,17
Mismatch: TEMwg-receiver[F6)]	δM	+0,64/–0,69	U-shaped	0,47
Field non-uniformity[F8)]	δS_{uni}	± 2,61	k = 1	2,61
Separation distance[F9)]	δS_d	± 0,19	Rectangular	0,11
Effect of EUT directivity[F10)]	$\delta S_{\mathrm{EUT\,dir}}$	-1,5/0	Rectangular	1,2
Effect of EUT manipulator[F11)]	δS_{TT}	± 2,0	Rectangular	1,16
[a] Superscripts (e.g. [F1)]) correspond to comments in F.4.2				
[b] All c_i = 1				
The distribution function is normal, unless otherwise expressed in the table.				

Hence, expanded uncertainty $U(E) = 2u_c(E)$ = 6,82 dB

Table F.2 – Uncertainty budget for radiated disturbance measurements using a TEM waveguide from 1 GHz to 6 GHz (Example)

Input quantity[a]	X_i	Uncertainty of x_i		$c_i u(x_i)$[b]
		dB	Probability distribution function	dB
Receiver reading[F1)]	V_r	± 0,1	k = 1	0,10
Attenuation: TEMwg-receiver[F2)]	a_c	± 0,3	k = 2	0,15
TEM conversion factor[F7)]	$F_{conv\ TEM}$	± 0,0	-	0,0
Receiver corrections:				
Sine wave voltage[F3)]	δV_{sw}	± 1,5	k = 2	0,75
Noise floor proximity[F5)]	δV_{nf}	+ 0,2/0,0	Rectangular	0,12
Mismatch: TEMwg-receiver[F6)]	δM	+0,51/–0,54	U-shaped	0,37
Field non-uniformity[F8)]	δS_{uni}	± 2,61	k = 1	2,61
Separation distance[F9)]	δS_d	± 0,19	Rectangular	0,11
Effect of EUT directivity	$\delta S_{EUT\ dir}$	-	-	0
Effect of EUT manipulator[F11)]	δS_{TT}	± 2,0	Rectangular	1,16

[a] Superscripts (e.g. [F1)]) correspond to comments in F.4.2

[b] All c_i = 1

The distribution function is normal, unless otherwise expressed in the table.

Hence, expanded uncertainty $U(E) = 2u_c(E) = 5{,}97$ dB

F.3.2 Rationale for the estimates of input quantities for radiated disturbance measurements using a TEM waveguide

NOTE 2 Comments F1) through F8) are adapted from CISPR 16-4-2 [15]

NOTE 3 General background on measurement uncertainty for radiated disturbance measurements is provided in [30].

F1) Receiver readings will vary for reasons that include measuring system instability and meter scale interpolation errors. The estimate of V_r is the mean of many readings (sample size larger than 10) of a stable signal, with a standard uncertainty given by the experimental standard deviation of the mean (k = 1).

F2) An estimate of the attenuation a_c of the connection between the receiver and the TEM waveguide is assumed to be available from a calibration report, along with an expanded uncertainty and a coverage factor.

NOTE 4 If the estimate of attenuation a_c is obtained from manufacturer's data for a cable or attenuator, a rectangular probability distribution having a half-width equal to the manufacturer's specified tolerance on the attenuation may be assumed. If the connection is a cable and attenuator in tandem, with manufacturer's data available on each, a_c has two components, each with its own rectangular probability distribution.

NOTE 5 In the frequency range below 30 MHz, the estimate of the expanded uncertainty is 0,1 dB, from 30 to 1000 MHz it is 0,2 dB, from 1 GHz to 6 GHz it is 0,3 dB and from 6 GHz to 18 GHz it is 0,6 dB with a coverage factor of 2. A lower estimate for this uncertainty contribution can be achieved using a vector network analyzer for the cable calibration.

F3) An estimate of the correction δV_{sw} for receiver sine-wave voltage accuracy is assumed to be available from a calibration report, along with an expanded uncertainty and a coverage factor.

NOTE 6 If a calibration report states only that the receiver sine-wave voltage accuracy is within the CISPR 16-1-1 tolerance (± 2 dB), then the estimate of the correction δV_{sw} should be taken as zero with a rectangular probability distribution having a half-width of 2 dB. If the calibration report states a value less than the CISPR 16-1-1 tolerance (e.g. ± 1 dB), then this value is to be used in the uncertainty calculation, not the stated uncertainty value of the calibration process. If the calibration report provides detailed deviations from reference values, then the reported deviations and the uncertainties of the calibration laboratory may be used to determine the uncertainties of the measuring receiver.

F4) In general, it is impractical to correct for imperfect receiver pulse response characteristics.

A verification report stating that the receiver pulse amplitude response complies with the CISPR 16-1-1 tolerance of ± 1,5 dB for peak, quasi-peak, average or r.m.s.-average detection is assumed to be available. The correction δV_{pa} is estimated to be zero with a rectangular probability distribution having a half-width of 1,5 dB.

The CISPR 16-1-1 tolerance for pulse repetition rate response varies with repetition rate and detector type. A verification report stating that the receiver pulse repetition rate responses comply with the CISPR 16-1-1 tolerances is assumed to be available. The correction δV_{pr} is estimated to be zero with a rectangular probability distribution having a half-width of 1,5 dB, a value considered to be representative of the various CISPR 16-1-1 tolerances.

NOTE 7 If the pulse amplitude response or the pulse repetition rate response is verified to be within $\pm\,\alpha$ dB of the CISPR specification ($\alpha \le 1{,}5$), the correction for that response may be estimated to be zero with a rectangular probability distribution having a half-width of α dB.

NOTE 8 If a disturbance produces a continuous wave signal at the detector, pulse response corrections do not need to be considered.

F5) The noise floor of a CISPR receiver has to be compared with the TEM waveguide output voltage level S_{lim} corresponding to the OATS-based field-strength limit E_{lim} at 10 m distance below 1 GHz and corresponding to the FAR (FSOATS) based field-strength limit E_{lim} at 3 m distance above 1 GHz in order to determine the signal-to-noise ratio.

Combining equations (A.1) and (A.5) we get:

$$E_{\max} = g_{\max}\sqrt{\frac{D_{\max}\eta_0^2 k_0^2}{12\pi^2 e_{0_y}^2 Z_c}}\cdot S = g_{\max}\frac{\eta_0 k_0}{2\pi e_{0_y}}\sqrt{\frac{D_{\max}}{3Z_c}}\cdot S\,, \qquad \text{(F.2)}$$

with $k_0 = \dfrac{2\pi}{\lambda}$, $\eta_0 = 370\,\Omega$, $Z_C = 50\,\Omega$.

From a manufacturer's manual we find $e_{0_y} = \dfrac{E_y}{\sqrt{P_i}} = \dfrac{10\,\text{V/m}}{\sqrt{1{,}5\,\text{W}}} = 8{,}16\dfrac{\Omega^{1/2}}{\text{m}}$ for a septum height $h = 0{,}8$ m.

NOTE 9 For larger septum heights, e_{0_y} will be proportionally lower.

a) For the OATS-based field strength (below 1 GHz) we use the approximation $g_{\max} = 2/r$, where r = 10 m and $D_{\max}$ = 1,5 to calculate S_{lim}

From equation (F.2) we get $E_{\max} = E_{lim} = \dfrac{1}{\lambda}\cdot 0{,}924\cdot S_{lim}$

or $S_{lim} = \lambda\cdot 1{,}08\cdot E_{lim}$, respectively in dB: $S_{lim} = \lambda/\text{dB(m)} + 0{,}68 + E_{lim}/\text{dB}(\mu\text{V/m})$

The last equation allows us to calculate S_{lim} in table F.3:

Table F.3 – Values of S_{lim} for 30 to 1000 MHz

Frequency/MHz	E_{lim}/dB(μV/m)	S_{lim}/dB(μV)
30	30	50,7
100	30	40,2
230	30	33,0
230	37	40,0
300	37	37,7
1000	37	27,2

For radiated disturbance measurement using the TEM waveguide below 1 GHz, the deviation δV_{nf} is estimated to be between zero and +0,3 dB. The correction is estimated to be zero as if the deviation would be symmetric around the value to be measured with a rectangular probability distribution having a half-width of 0,3 dB. Any correction for the effect of the noise floor would depend on the signal type (e.g. impulsive or unmodulated sinewave) and the signal to noise ratio and would change the noise level indication. The value of 0,3 dB is taken from Figure F.1 for a S/N = 28 dB. The S/N has been obtained for a noise figure of 6 dB, using

$$E_{\text{NQP}} = S_{\text{NQP}} + F_{\text{conv TEM}} + a_{\text{c}} \qquad \text{(F.3)}$$
$$E_{\text{NQP}} = -67 + 10\lg F_{\text{N}} + 10\lg B_{\text{N}} + w_{\text{NQP}} + F_{\text{conv TEM}} + a_{\text{c}}$$

where

E_{NQP}	is the equivalent field strength of the quasi-peak noise floor, in dB(μV/m);
S_{NQP}	is the receiver quasi-peak noise floor, in dB(μV);
$F_{\text{conv TEM}}$	is the TEM conversion factor at the receive frequency, in dB(1/m);
a_{c}	is the attenuation of the antenna connecting cable, in dB;
F_{N}	is the noise factor of the measuring receiver, i.e. a number;
10lg F_{N}	is the noise figure of the measuring receiver, in dB;
B_{N}	is the noise bandwidth of the measuring receiver, in Hz;
w_{NQP}	is the quasi-peak weighting factor of noise, in dB;
-67	is $10\lg(kT_0 \times 1\text{Hz}/P_{1\,\mu\text{V}})$, the absolute noise level in dB(μV) in 1 Hz bandwidth, with k = Boltzmann's Constant, T_0 = 293,15 K, and $P_{1\mu\text{V}}$ is the power generated by 1 μV across 50 Ω.

The worst case S/N is obtained near 1 000 MHz. With 10lg F_{N} = 6, 10lg B_{N} = 50,8 (for 120 kHz), the weighting factor w_{NQP} being 7 dB, the TEM conversion factor of $F_{\text{conv TEM}}$ = 9,8 dB(m^{-1}) for 1 000 MHz and the cable attenuation a_{c} = 2 dB, the quasi-peak noise indication in terms of field strength is E_{NQP} = 9 dB(μV/m). This is compared to a disturbance level at the emission limit of 37 dB(μV/m) at 10 m distance to give a signal-to-noise ratio S/N of 28 dB. In the frequency range below 1000 MHz, the S/N is higher, hence an S/N > 30 dB may be assumed.

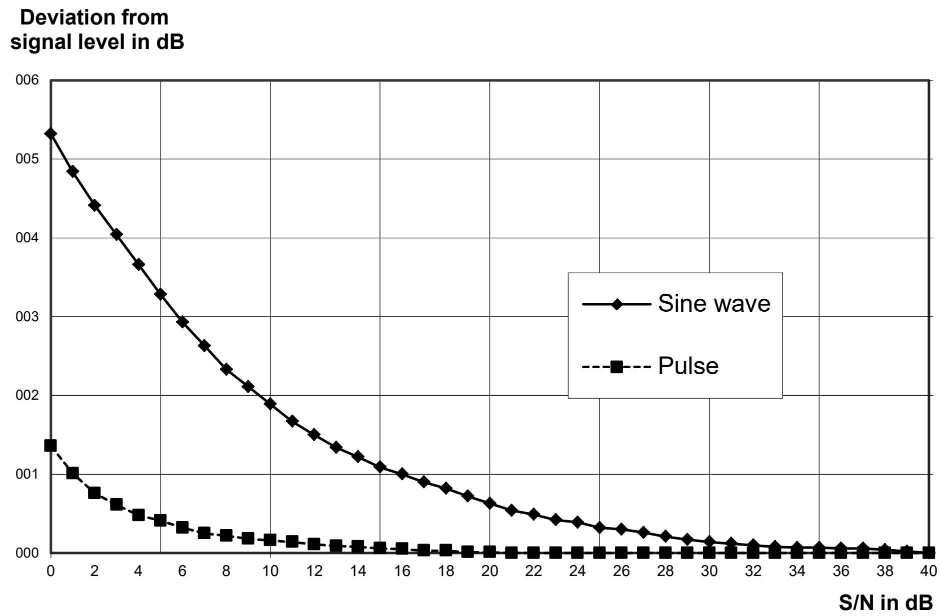


Figure F.1 – Deviation of the QP detector level indication from the signal level at receiver input for two cases, a sine-wave signal and an impulsive signal (PRF 100 Hz)

b) For the FAR (FSOATS) based field strength (above 1 GHz) we use the approximation $g_{\max} = 1/r$, where r = 3 m and $D_{\max}$ = 1,5 to calculate S_{lim}

From equation (F.2) we get $E_{\max} = E_{\text{lim}} = \frac{1}{\lambda} \cdot 1{,}54 \cdot S_{\text{lim}}$, where λ is expressed in m

or $S_{\text{lim}} = \lambda \cdot 0{,}65 \cdot E_{\text{lim}}$ respectively in dB: $S_{\text{lim}} = \lambda / \text{dB(m)} - 3{,}75 + E_{\text{lim}} / \text{dB}(\mu\text{V/m})$

The last equation allows us to calculate S_{lim} in table F.4:

Table F.4 Values of S_{lim} for 1 to 6 GHz

Frequency/GHz	$E_{lim\ pk}$/dB(µV/m)	$S_{lim\ pk}$/dB(µV)
1	70	55,8
3	70	46,2
3	74	50,2
6	74	44,2

For radiated disturbance measurements above 1 GHz limits apply for average and peak detectors. Similar considerations for the noise floor as below 1 GHz apply. The stronger influence of noise and higher uncertainty caused by noise is with the peak detector. Figure F.2 provides graphs for the deviation from signal level as a function of S/N:

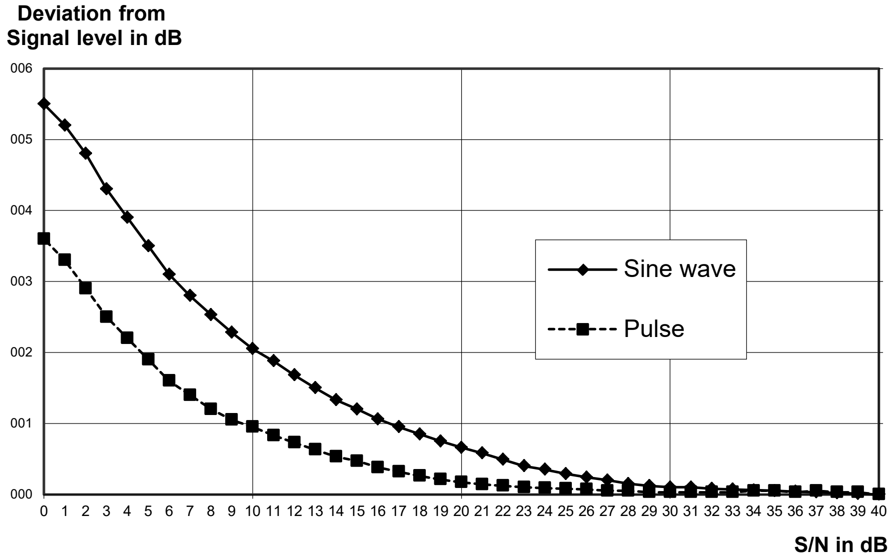


Figure F.2 – Deviation of the peak detector level indication from the signal level at receiver input for two cases, a sine-wave signal and an impulsive signal (PRF 100 Hz)

The worst case S/N is obtained near 6 GHz. With 10 lg F_N = 6, 10 lg B_N = 58,2 (corresponding to 0,66 MHz), the weighting factor w_{NPk} being 11 dB, the TEM conversion factor of $F_{conv\ TEM}$ = 29,8 dB(m^{-1}) for 6 GHz and the cable attenuation a_c = 2 dB, the peak noise indication in terms of field strength is E_{NQP} = 40 dB(µV/m). This is compared to a disturbance level at the emission limit of 74 dB(µV/m) at 3 m distance to give a signal-to-noise ratio S/N of 34 dB. In the frequency range below 6 GHz, the S/N is higher, hence an S/N > 34 dB may be assumed. From Figure F.2 we can read a maximum deviation for sine waves of 0,2 dB.

F6) Mismatch uncertainty

a. General

In general, the receiver port of a TEM waveguide will be connected to port 1 of a two-port network whose port 2 is terminated by a receiver of reflection coefficient Γ_r. The two-port network, which might be a cable, attenuator, attenuator and cable in tandem, or some other combination of components, can be represented by its *S*-parameters. The mismatch correction is then

$$\delta M = 20\ \lg\left[(1-\Gamma_e S_{11})(1-\Gamma_r S_{22}) - S_{21}^2 \Gamma_e \Gamma_r\right] \qquad \text{(F.3)}$$

where Γ_e is the reflection coefficient looking into the receiver port of the TEM waveguide with the EUT inserted when it is set up for disturbance measurement. All parameters are referenced to 50 Ω.

When only the magnitudes, or extremes of magnitudes, of the parameters are known, it is not possible to calculate δM, but its extreme values $\delta M^{\pm}$ are not greater than

$$\delta M^{\pm} = 20\lg\left[1 \pm \left(|\Gamma_e||S_{11}| + |\Gamma_r||S_{22}| + |\Gamma_e||\Gamma_r||S_{11}||S_{22}| + |\Gamma_e||\Gamma_r||S_{21}|^2\right)\right] \quad \text{(F.4)}$$

The probability distribution of δM is approximately U-shaped, with a width not greater than ($\delta M^{+} - \delta M^{-}$) and standard deviation not greater than the half-width divided by $\sqrt{2}$.

b. Radiated disturbance measurement using a TEM waveguide

For radiated disturbance measurements below 1 GHz, a VSWR specification of the TEM waveguide of $s_{wr} \leq 1{,}6:1$ is assumed, implying $|\Gamma_e| \leq 0{,}23$. For radiated disturbance measurements above 1 GHz, a VSWR specification of $s_{wr} \leq 1{,}45:1$ is assumed, implying $|\Gamma_e| \leq 0{,}18$. It is also assumed that the connection to the receiver is made using a well-matched cable ($|S_{11}| << 1$, $|S_{22}| << 1$) of negligible attenuation ($|S_{21}| \approx 1$) and that the receiver RF attenuation is 0 dB, for which the CISPR 16-1-1 tolerance of $s_{wr} \leq 2{,}0:1$ implies $|\Gamma_r| \leq 0{,}33$.

The estimate of the correction δM is zero with a U-shaped probability distribution having width equal to the difference ($\delta M^{+} - \delta M^{-}$).

NOTE 10 The expressions for δM and $\delta M^{\pm}$ show that mismatch error can be reduced by increasing the attenuation of the well-matched two-port network preceding the receiver. The penalty is a reduction in measurement sensitivity.

NOTE 11 Additional considerations related to Equation (F.3): a) Due to non-existing or only weak correlation of the addends (summands, or terms in the sum), the linear addition may be replaced by the root sum square rule. b) Due to the usually small magnitude of the addends, a further approximation (where $\delta M^{\pm}$ is the half width of a U-shaped distribution) is applicable, yielding finally:

$$\delta M^{\pm} \approx 8{,}7\sqrt{(|\Gamma_e||S_{11}|)^2 + (|\Gamma_r||S_{22}|)^2 + (|\Gamma_e||\Gamma_r||S_{21}|^2)^2}\ \text{dB}$$

F7) Conversion factor for radiated disturbance measurements using a TEM waveguide. The conversion factor can be seen as a frequency-dependent antenna factor that converts the disturbance voltage measured by the measuring receiver at the output of the TEM waveguide to an equivalent OATS-based (or FAR based) field strength. The conversion factor will usually be different for horizontal and vertical polarization of the calculated field strength. It depends on OATS/SAC measurement distance, septum height and some further parameters. A rough approximation was calculated in comment F5). It is assumed that the conversion is performed using algorithms e.g. as described in A.3 of this standard or other more sophisticated algorithms following an exact theory and using a computer that does not produce an uncertainty. Any uncertainty caused e.g. by the unpredictable EUT directivity is covered by other influence quantities.

F8) Field non-uniformity. For the useable test volume, the requirements in 5.2.2 apply. In 5.2.2.2.1 and 5.2.2.2.2 the mean value and standard deviation of the primary field component or the forward power are calculated for N test points. Normal distribution of the measurands is assumed. The standard deviation of either the primary field component for the constant forward power method or the forward power for the constant field strength method has to be below 2,61 dB according to equation (1) to (5b), respectively (6) to (10b). From that verification requirement it can be concluded that the field non-uniformity uncertainty contribution is 2,61 dB or better. The actual value of the standard deviation of the primary electric field strength or the forward power may be used as an estimate of the standard uncertainty of this input quantity for the determination of the expanded uncertainty U_{lab} of a test lab and its TEM waveguide.

However, especially for large uniform areas, many TEM waveguides will result in a lower uncertainty. If it is vital to determine a more accurate estimate for the uncertainty of field non-uniformity this can be done with a more complex evaluation of the calibration data of the validation of the usable test volume as explained in the following passage.

The measurements $E_{prim,i}$ in volt per meter for the primary electric field strength in the N calibration points are normalized to the input power and the field factor according to equation (A.4). With equations (F.6) – (F.9) the standard deviation s_N for the intrinsic uncertainties of the testing volume and the waveguide is calculated, where Γ(...) is the gamma function.

$$s_{\mathrm{N}} = \sqrt{\frac{N-1}{2}} \cdot \frac{\Gamma\left(\frac{N-1}{2}\right)}{\Gamma\left(\frac{N}{2}\right)} \cdot \sigma_{\mathrm{EN}} \tag{F.6}$$

$$\sigma_{\mathrm{EN}} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(E_{\mathrm{pn,i}} - \overline{E}_{\mathrm{pn}}\right)^2} \tag{F.7}$$

$$\overline{E}_{\mathrm{pn}} = \frac{1}{N}\sum_{i=1}^{N} E_{\mathrm{pn,i}} \tag{F.8}$$

$$E_{\mathrm{pn,i}} = 20\log_{10}\left(\frac{E_{\mathrm{p,i}}}{P_{\mathrm{i}} \cdot e_{\mathrm{0y,i}}}\right) \tag{F.9}$$

The evaluation of equation (F.10) for a large number I of randomly chosen calibration points (x_{i},y_{i}) in the uniform area results in the standard deviation s_{e0y} of the analytical field homogeneity in the specific testing volume.

$$s_{\mathrm{e0y}} = \sqrt{\frac{1}{I-1}\sum_{i=1}^{I}\left(20\log_{10}\left(e_{\mathrm{oy}}\left(x_{\mathrm{i}}, y_{\mathrm{i}}\right)\right) - \frac{1}{I}\sum_{i=1}^{I} 20\log_{10}\left(e_{\mathrm{oy}}\left(x_{\mathrm{i}}, y_{\mathrm{i}}\right)\right)\right)^2} \tag{F.10}$$

The uncertainty of δS_{uni} in table F.1 is then calculated by equation (F.11). For each frequency interval the maximum value of $u(\delta S_{\mathrm{uni}})$ should be taken into account.

$$u\left(\delta S_{\mathrm{uni}}\right) = \sqrt{s_{\mathrm{N}}^2 + s_{\mathrm{e0y}}^2} \tag{F.11}$$

Detailed information as well as measurement examples for the uncertainty contribution of the field non-uniformity can be found in [27].

F9) The error in separation distance between the EUT and the waveguide port arises from the errors in determining the perimeter of the EUT and the *z*-coordinate of the EUT in the waveguide. The estimate of the correction δS_{d} for the separation error is zero with a rectangular probability distribution having a half-width evaluated from assuming a maximum separation error of ± 0,1 m, and that field strength is inversely proportional to separation over that distance margin. A rectangular pdf is assumed. For a specific TEM waveguide, the uncertainty contribution $u(\delta S_{\mathrm{d}})$ can be calculated from equation (F.12), where r_{TL} is the distance between the EUT position and the feeding section of the TEM waveguide.

$$u\left(\delta S_{\mathrm{d}}\right) = \max\left(\frac{\sqrt{3}}{3} \cdot 20\,\log_{10}\left(\frac{r_{\mathrm{TL}} \pm 0{,}1\,\mathrm{m}}{r_{\mathrm{TL}}}\right)\right) \tag{F.11}$$

NOTE 12 This value can also be understood as an uncertainty contribution of the tapering of a TEM waveguide.

NOTE 13 This value does not apply for TEM waveguides without tapering, e.g. those with constant cross section dimensions in the test volume.

NOTE 14 The value of this uncertainty contribution depends on the distance between the EUT position and the feeding section of the TEM waveguides. Longer separation distances result in a smaller uncertainty.

F10) For electrically small EUTs, the directivity will vary between a minimum of 1,5 (isolated electric or magnetic dipole only) to a maximum of 3 (for combined electric and magnetic dipoles optimally oriented). A directivity of 3 (maximum case) is assumed in the A.3.2.4 correlation algorithm for small EUTs; thus the actual (but unknown) directivity will be up to 1,5 lower yielding an uncertainty. A rectangular distribution is assumed for Table F.1. If the A.5.1.2 12 position antenna factor based method is used for a small EUT, this uncertainty term is not needed. For frequencies above 1 GHz any EUT is assumed to be electrically large, thus the A.5.1.2 12 position antenna factor based method shall be used for the calculation of the equivalent electric field strength and the uncertainty contribution of EUT directivity does no longer apply. Therefore, its value is set to zero in Table F.2.

F11) Effect of EUT turntable/manipulator material. This effect needs to be determined by measurements with and without manipulator in a manner similar to the evaluation of set-up table influence in CISPR 16-1-4. From field-strength measurements above about 500 MHz, values of around ± 2 dB seem to be typical. A rectangular pdf may be assumed. More detailed information and the description of possible measurement setups for the evaluation of that effect in TEM waveguides can be found in [27].

Annex G
(informative)

Measurement uncertainty of immunity testing due to test instrumentation

G.1 General symbols

X_i Input quantity

x_i Estimate of X_i

δX_i Correction for input quantity

$u(x_i)$ Standard uncertainty of *xi*

c_i Sensitivity coefficient

y Result of a measurement, (the estimate of the measurand), corrected for all recognized significant systematic effects

$u_c(y)$ (Combined) Standard uncertainty of y

$U(y)$ Expanded uncertainty of y

k Coverage factor

a^+ Upper abscissa of a probability distribution

a^- Lower abscissa of a probability distribution

G.2 Symbol and definition of the measurand

E Electric field strength, in dB(V/m), at a point of the uniform area described in 5.2.2

G.3 Symbols for input quantities

E_m Field probe indication in a case of calibration process, directly in or converted to dB(V/m)

F_C Field probe calibration factor

δF_{lin} Correction for field probe non-linearity

δF_{iso} Correction for field probe deviation from isotropy

δF_{int} Correction for frequency interpolation of field probe calibration factors

δF_{uni} Correction for field non uniformity over the uniform area

δF_{har} Correction due to the harmonics of the field

δF_{res} Correction due to the limited amplitude resolution of the feedback control loop

δM Correction due to the mismatch between TEM waveguide and amplifier

G.4 Example: Uncertainty budget for immunity test

The measurand E is calculated using:

$$E = E_m + F_C + \delta F_{Lin} + \delta F_{Iso} + \delta F_{Int} + \delta F_{Uni} + \delta F_{Har} + \delta F_{Res} + \delta M \qquad (G.1)$$

Table G.1 – Example uncertainty budget of the immunity test level

Uncertainty source	X_i	Uncertainty of x_i		c_i	$u(x_i)$ in dB
		Value in dB	Probability distribution function		
Field probe indication in a case of calibration process G1)	E_m	0,20	normal k=1	1	0,20
Field probe calibration factor G2)	F_C	0,96	normal k=2	1	0,48

Field probe corrections:					
Non-linearity G3)	δF_{lin}	0,5	rectangular	1	0,29
Isotropy G4)	δF_{iso}	0,5	rectangular	1	0,29
Frequency interpolation G5)	δF_{int}	0,5	rectangular	1	0,29
Field non-uniformity over the uniform area G6)	δF_{uni}	1,5	normal k=1	1	1,5
Presence of harmonics G7)	δF_{har}	0,50	rectangular	1	0,29
Resolution of the feedback control loop G8)	δF_{res}	0,15	rectangular	1	0,09
Mismatch between TEM waveguide and amplifier/directional-coupler G9)	δM	0,17*	U-shape	1	0,12
			$\sum u(x_i)^2$		2,88
			$u_c(y)=\sqrt{\sum u(x_i)^2}$		1,70
			Expanded uncertainty $U(y)$, (k=2)		3,39

G.5 Rationale for the estimates of input quantities

G1) The uncertainty of the indication includes: a) instability of the generator and power amplifier (Type A), and non repeatability originated by b) removal and replacement of the field probe including the alignment of the midpoint (Type A). It can be evaluated as the combined standard uncertainty of the contributions a) and b).

G2) The uncertainty of the field probe calibration factor is due to the calibration inaccuracy. This is a Type B contribution specified in the field probe certificate of calibration as an expanded uncertainty with a coverage factor k = 2, corresponding to a coverage probability of 95% (normal distribution).

G3) Field probe linearity is specified by the manufacturer of the field probe. This is a Type B contribution having a rectangular distribution. The expected value of this correction is zero.

G4) Isotropic deviation is specified by the manufacturer of the field probe. This is a Type B contribution having a rectangular distribution. The expected value of this correction is zero.

G5) The field probe calibration factor is known, within the limits of the calibration accuracy, at the calibration frequencies. It is assumed that at any frequency comprised between the calibration frequencies the calibration factor can achieve any value between those stated in the calibration certificate and corresponding to the calibration frequencies. This is a Type B contribution having a rectangular distribution. The worst case deviation (i.e. maximum deviation between adjacent calibration factors) can be considered. The expected value of this correction is zero.

G6) Field non-uniformity. For the useable test volume the requirements in 5.2.2 apply. In 5.2.2.2.1 and 5.2.2.2.2 the mean value and standard deviation of the primary field component or the forward power are calculated for N test points. Normal distribution of the measurands is assumed. The standard deviation of either the primary field component for the constant forward power method or the forward power for the constant field strength method may be used as a basis for an estimate of the standard uncertainty of this input quantity.

However, especially for large uniform areas many TEM waveguides will result in a lower uncertainty. To calculate an estimate for this input quantity the calibration data of the validation of the usable test volume should be used. The measurements $E_{\mathrm{prim,i}}$ in volt per meter for the primary electric field strength in the N calibration points are normalized to the input power and the field factor according to equation (A.4). With equations (G.2) – (G.7) the standard deviation s_{N} for the intrinsic uncertainties of the testing volume and the waveguide is calculated, where Γ(...) is the gamma function.

$$s_{\mathrm{N}} = \sqrt{\frac{N-1}{2}} \cdot \frac{\Gamma\left(\frac{N-1}{2}\right)}{\Gamma\left(\frac{N}{2}\right)} \cdot \sigma_{\mathrm{EN}} \qquad \text{(G.2)}$$

$$\sigma_{\mathrm{EN}} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(E_{\mathrm{pn,i}} - \overline{E}_{\mathrm{pn}}\right)^2} \qquad \text{(G.3)}$$

$$\overline{E}_{\mathrm{pn}} = \frac{1}{N}\sum_{i=1}^{N} E_{\mathrm{pn,i}} \qquad \text{(G.4)}$$

$$E_{\mathrm{pn,i}} = 20\log_{10}\left(\frac{E_{\mathrm{p,i}}}{P_{\mathrm{i}} \cdot e_{\mathrm{0y,i}}}\right) \qquad \text{(G.5)}$$

The evaluation of equation (G.6) for a large number I of randomly chosen calibration points (x_{i},y_{i}) in the uniform area results in the standard deviation s_{e0y} of the analytical field homogeneity in the specific testing volume.

$$s_{\mathrm{e0y}} = \sqrt{\frac{1}{I-1}\sum_{i=1}^{I}\left(20\log_{10}\left(e_{\mathrm{oy}}\left(x_{\mathrm{i}}, y_{\mathrm{i}}\right)\right) - \frac{1}{I}\sum_{i=1}^{I} 20\log_{10}\left(e_{\mathrm{oy}}\left(x_{\mathrm{i}}, y_{\mathrm{i}}\right)\right)\right)^2} \qquad \text{(G.6)}$$

The uncertainty of δS_{uni} in table F.1 is then calculated by equation (G.7). For each frequency interval the maximum value of $u(\delta S_{\mathrm{uni}})$ should be taken into account.

$$u\left(\delta S_{\mathrm{uni}}\right) = \sqrt{s_{\mathrm{N}}^2 + s_{\mathrm{e0y}}^2} \qquad \text{(G.7)}$$

Detailed information as well as measurement examples for the uncertainty contribution of the field non-uniformity can be found in [27].

G7) The field meter senses the root-mean-square value of the field obtained superimposing the field at the fundamental frequency and with its harmonics. It is assumed that a harmonic of the electric field is present having an amplitude at most 6 dB lower than the fundamental. This causes a maximum error in excess of about 1 dB. This is a Type B contribution and a rectangular distribution of the error is assumed. The expected value of this correction is − 0,5 dB.

G8) This uncertainty contribution originates from the discrete step size of the RF signal generator and the software controlling the feedback loop during the process of test level setting. This value may include the uncertainty of the power meter, including its sensors, taken from either the manufacturer's specification (and treated as a rectangular distribution) or a calibration certificate (and treated as a normal distribution). This is a Type B contribution having rectangular distribution.

G9) This is the uncertainty caused by a mismatch between the input port of a TEM waveguide and the output port of the power amplifier. If a directional coupler is used for measuring the forward power from the amplifier and the reverse power from the TEM waveguide using the power meter, the uncertainty may be caused by the mismatch between the input port of a TEM waveguide and the output port of the directional coupler. This uncertainty is caused by the lack of phase information of reflection coefficients of amplifier, directional coupler, and TEM waveguide because the power reflections are usually given in VSWR that has no information of phase. See IEC TR 61000-1-6 for further information.

Annex H
(informative)

Correlation of Emission and Immunity Limits Between EMC Test Facilities

E.5 H.1 Introduction

Emission and immunity tests can be made at a variety of EMC test facilities. These include open area test sites (OATS), semi-anechoic chambers (SAC), fully anechoic rooms (FAR), transverse electromagnetic mode (TEM) cells, and reverberation chambers (RC). Ideally each of these facilities would yield the same test result for a given test object, that is, a product that passes a test in one facility would pass tests in the others and a product that fails in one facility would fail in the others. This ideal case could be met if emission and immunity data could be exactly correlated between EMC facilities. However, because most test objects are quite complex and because present EMC facility test methods sample different subsets of the full range of possible emission and immunity test variables [58], exact correlation of test data is typically not possible.

An alternative to correlating complicated emission and immunity test data is to correlate test limits based on simple dipole models of the test object. Dipole models are a good starting point for setting “equivalent” test limits. These limits can then be adopted or modified by product committees as appropriate. Immunity limits are usually expressed in terms of electric field strength (V/m) at the test plane/volume in the absence of a test object. The field strength at the test location in a particular EMC test facility is then verified by field measurements using an isotropic receiving probe. In this way the interaction between the source and the test facility is normalized out. This makes setting equivalent immunity limits between EMC facilities straightforward. Emission limits are less straightforward. The equivalent to the immunity case would be to use a small isotropic source probe that could generate a variable field strength over the frequency range of interest (the reciprocal of a field probe that receives a variable field strength over the frequency range of interest). The field probe could then be used as a transfer standard to generate equivalent limits between EMC facilities. The difficulty is that a small, variable, isotropic source is not readily achievable. Thus, in the emission case analytical models are used to correlate the source and facility interactions. Dipole models are the simplest, and various dipole-based correlation algorithms have already been developed and have appeared in the literature [49,56,39,32]. This annex reviews the basics of these, using common terminology and notation. A dipole in free space (FS) is considered first and serves as a model for an ideal FAR. A dipole in half space (HS) is considered next and serves as a model for an ideal OATS or SAC. A dipole in a transmission line (TL) models a TEM transmission line. Finally, a dipole in an ideal cavity models an RC. The emitter geometries discussed in the next sections are shown in Fig. H.1. The results of these models are then correlated and can be used to derive equivalent test limits.

E.6 H.2 Dipole in free space

An ideal free space environment is the simplest case to analyse. A dipole along with a representation of a more general source is shown in Fig. H.1. Only the case of an electric dipole is considered. The results can be extended in a straightforward manner to a magnetic dipole, or combined electric and magnetic dipoles, as is discussed later. For a short electric dipole (length $d\ell$, peak current I_0) located at the origin and aligned with the z-axis, the far-field radiation is given by

$$E_\theta = \frac{\mathrm{j}\omega\mu I_0 d\ell}{4\pi r}\sin\theta e^{-\mathrm{j}kr} \text{ (V/m) and}$$

$$H_\varphi = \frac{\mathrm{j}kI_0 d\ell}{4\pi r}\sin\theta e^{-\mathrm{j}kr} \quad \text{(A/m)}, \qquad \text{(H.1)}$$

where ω is the angular frequency, μ is the permeability of the medium in which the dipole is located (e.g., air), $k = 2\pi/\lambda$, where λ is the wavelength, (θ,φ,r) represents the usual spherical coordinate system, and a $e^{\mathrm{j}\omega t}$ time convention is suppressed. The total power P_0 radiated by the electric dipole is found by integrating the Poynting vector over a sphere enclosing the dipole, resulting in

$$P_0 = \frac{2}{3}\eta_0 \pi I_0^{\,2}\left(\frac{d\ell}{\lambda}\right)^2 \text{ (W)}, \qquad \text{(H.2)}$$

where η_0 is the free space wave impedance of air (= 120π Ω for air). EMC measurements made in a FAR typically measure the electric field. For an emission measurement, the maximum electric field magnitude $E_{\max}$ would be sought over some scan geometry. For the above electric dipole geometry, the maximum in equation (H.1) occurs when $\theta = \pi/2$, where

$$E_{\max}^2 = \frac{\omega^2 \mu^2 (I_0 d\ell)^2}{(4\pi r)^2} \ . \qquad \text{(H.3)}$$

Using equation (H.2), the above expression may be rewritten as

$$E_{\max}^2 = \frac{3}{2} \frac{\eta_0}{4\pi r^2} P_0 \ . \qquad \text{(H.4)}$$

This expression is the electric dipole case of the more general expression given in [49],

$$E_{\max}^2 = D_{\max} \frac{\eta_0}{4\pi r^2} P_0 \ , \qquad \text{(H.5)}$$

for the maximum electric field from an emitter with maximum directivity $D_{\max}$ (= 3/2 for individual electric or magnetic dipoles, or = 3 for combined electric and magnetic dipoles) and total radiated power P_0. $E_{\max}$ is actually measured as a voltage $V_{\max}$ at the output of an antenna with an antenna factor (AF) F_a, where $E_{\max} = F_a V_{\max}$. Collecting results gives

$$V_{\max}^2 = F_a^{-2} D_{\max} \frac{\eta_0}{4\pi r^2} P_0 \ . \qquad \text{(H.6)}$$

This expression can be further rewritten by defining a free-space attenuation term $a_{FS} = 1/\left(4\pi \cdot r^2\right)$ giving

$$V_{\max,FS}^2 = \eta_0 \cdot \left(F_a^{-2} \cdot D_{\max,FS} \cdot P \cdot a_{FS}\right) \cdot P_0 \ . \qquad \text{(H.7)}$$

Subscripts (FS) have been added to differentiate between later cases. In particular, F_a is not an inherent property of free space; rather, it simply denotes the AF of whatever antenna is used to make a free space measurement.

E.7 H.3 Dipole in half space

A half space is formed by introducing an ideal ground plane (a perfect conductor of infinite extent) into the free-space case. As depicted in Fig. H.1, an electric dipole is here located at a height *h* above the ground plane and oriented either vertically or horizontally. Other orientations may be analysed as the superposition of these two cases. The half-space case may be analysed by introducing an image dipole. We introduce a rectangular coordinate system with the ground plane in the *x*-*y* plane, the dipole at z = $+h_{\text{dipole}}$, and the image dipole at z = $-h_{\text{dipole}}$. The distance from the source dipole to the measurement point is designated r_1, from the image dipole to the measurement point r_2, from the origin to the measurement point *r*, and the radial distance from the *z*-axis to the measurement point is designated *s*. In the far-field, the maximum electric field can be shown to be [56, 32]

$$E_{\max}^2 = D_{\max} \frac{\eta_0}{4\pi r^2} g_{\max}^2 P_0 \ , \qquad \text{(H.8)}$$

where $D_{\max}$ is again 3/2 for a single electric dipole, or can be generalized to 3 for combined electric and magnetic dipoles. The geometry factor $g_{\max}$ is defined by

$$g_{\max} = \begin{cases} \left| \frac{r}{r_1} e^{-jkr_1} - \frac{r}{r_2} e^{-jkr_2} \right|_{\max} & \text{for horiz.} \\ \left| \frac{s^2}{r_1^2} \frac{r}{r_1} e^{-jkr_1} + \frac{s^2}{r_2^2} \frac{r}{r_2} e^{-jkr_2} \right|_{\max} & \text{for vert.,} \end{cases} \tag{H.9}$$

where the subscript max denotes the maximum value found over some scan geometry (e.g., a 1 to 4 m vertical height scan at some horizontal offset). We have introduced a normalizing factor *r* into equation (H.9) (versus the expressions found in [56, 32]) to give equation (H.8) a form similar to that of equation (5). If the radial distance ρ is significantly larger than the height above the ground plane *h*, such that $s/r_1 \approx 1$, $s/r_2 \approx 1$, $r/r_1 \approx 1$, and $r/r_2 \approx 1$, then $g_{\max}$ reduces to

$$g_{\max} = \begin{cases} 2\sin k(r_1 - r_2)_{\max} & \textit{horizontal and} \\ 2\cos k(r_1 - r_2)_{\max} & \textit{vertical.} \end{cases} \tag{H.10}$$

Under these assumptions, $g_{\max}$ = 2 in both cases, assuming the measurement scan is such that, at some point, $k(r_1 - r_2) = \pi/2$ or π respectively (or some suitable multiple). Physically, this simply means that the ground plane doubles the maximum electric field through constructive interference due to the reflected path. Figure 3 in [32] shows that $g_{\max}$ = 2 is a good approximation above 200 MHz for a typical 3 m EMC emission test (3 m horizontal separation, 1 m source height, 1 to 4 m measurement height scan) and is a good approximation above 30 MHz for a typical 10 m EMC emission test (10 m horizontal separation, 1 m source height, 1 to 4 m measurement height scan). Thus, a value of $g_{\max}$ equal to 2 should be sufficient for setting equivalent emission test limits and will be used here for the half-space case. Thus, the maximum measured voltage for an electric dipole above a perfect ground plane can be approximated as

$$V_{\max,\mathrm{HS}}^2 = \eta\left(\mathrm{AF}_{\mathrm{HS}}^2 D_{\max,\mathrm{HS}} PL_{\mathrm{HS}}\right)P_0\ , \tag{H.11}$$

where $PL_{\mathrm{HS}} = 4/(\pi r^2)$ for the half-space case. However, if the ground-plane geometry needs to be accounted for more accurately, we can use $PL_{\mathrm{HS}} = g_{\max}^2/(4\pi r^2)$.

E.8 H.4 Dipole in a TEM transmission line

A TEM transmission line (stripline, TEM cell) seeks to approximate a linearly polarized plane-wave field over some test volume. A dipole placed in a TEM line, as shown in Fig. H.3, will couple to the TEM mode and to higher-order modes, if present, and produce a voltage at the measurement port. This measured voltage combined with suitable rotations of the dipole (similar in purpose to the above receive antenna scans) can be used to determine the dipole moment [58] or the total radiated power from the dipole [58, 39]. For example, from equation A.1 (for combined electric and magnetic dipoles), P_0 for an electric dipole alone is given as

$$P_0 = \frac{2\eta_0}{3\pi} \frac{k^2}{{e_{0y}}^2 Z_c} {S_{\mathrm{V}}}^2\ , \tag{H.12}$$

where Z_c is the characteristic impedance of the TL (typically 50 Ω), e_{0y} is a normalized field factor, ${e_{0y}}^2 \approx Z_0/h^2$, where *h* is the plate separation at the dipole location, and S_{V} represents the sum of the measured output port voltage over a set of dipole rotations. These expressions ignore contributions from higher-order modes. If the dipole is oriented for maximum coupling, as in the previous sections, then the voltage at the measurement port will be maximized: ${S_{\mathrm{V}}}^2 = {V_{\max}}^2$ (no rotations needed), and

$$V_{\max}^2 = \frac{3}{2} \frac{\pi}{\eta_0} \frac{{Z_c}^2}{k^2 h^2} P_0\ , \tag{H.13}$$

where a substitution for e_{0y} has been made. Replacing 3/2 with $D_{\max}$, this may be rewritten as

$$V_{\max}^2 = \left(\frac{Z_c}{\eta_0} \frac{r_{TL}}{h} \lambda \right)^2 D_{\max} \frac{\eta}{4\pi r_{TL}{}^2} P_0 \quad . \tag{H.14}$$

Comparing this result to equation (H.6), we see that equation (H.14) defines an equivalent antenna factor for a TEM cell (the term in parenthesis). In a constant flare TEM line (e.g., GHz TEM cell) r_{TL} is the radial distance from the measurement port to the dipole location. In a uniform cross section TEM line (e.g., a standard two-port TEM cell tapered at each end) r_{TL} is the radial distance from the measurement port along the cell taper to the location of the dipole projected back to the plane beginning the uniform section of the transmission line. The equivalent antenna factor is then given by

$$F_{TL} = \frac{\eta_0}{Z_c} \frac{h}{r_{TL}} \frac{1}{\lambda} \quad . \tag{H.15}$$

Using this definition, we again have

$$V_{\max,TL}^2 = \eta_0 \cdot \left(F_{TL}^{-2} \cdot D_{\max,TL} \cdot a_{TL} \right) P_0 \quad , \tag{H.16}$$

where a_{TL} is defined the same as a_{FS} but using r_{TL} as defined in this section.

E.9 H.5 Dipole in a reverberation chamber

A reverberation chamber is an over-moded cavity that seeks to statistically approximate a uniform set of plane waves over some test volume, as depicted in Fig. H.4. The ideal set of plane waves would include all directions and polarizations. A good reverberation chamber approaches this ideal. One can show that the average power $\langle P_r \rangle$ (averaged over multiple modal distributions) received by a matched, lossless reference antenna due to a source in the cavity is given by [31]

$$\langle P_r \rangle = \frac{\lambda^3 Q}{16\pi^2 V} P_0 \quad , \tag{H.17}$$

where Q is the quality factor of the chamber, V is the volume of the chamber, and as before, P_0 is the total radiated power from the source, which is an electric dipole in this case. The difficulties with equation (H.17) are that Q is often not well characterized and we need to correct for antenna-loss effects. To avoid these difficulties, the more usual method of determining P_0 in a reverberation chamber is to make a comparative measurement with a reference source of known power P_{ref}, while keeping the chamber conditions the same: then

$$P_0 = \frac{P_{ref}}{\langle P_{r,ref} \rangle} \langle P_r \rangle \quad . \tag{H.18}$$

Solving for $\langle P_r \rangle$, and rewriting this in terms of the average received voltage yields

$$\langle V^2 \rangle = Z_c \frac{\langle P_{r,ref} \rangle}{P_{ref}} P_0 \quad , \tag{H.19}$$

where $P_r = V^2/Z_c$ (Z_c is the impedance at the antenna measurement port, typically 50 Ω). In this case there is no max subscript since there is no need to scan the receive antenna or rotate the test object. There is also no directivity term as this is negated by averaging over incidence angles and polarization. For consistency with previous expressions, define the following for the reverberation chamber case: $D_{\max,RC}$ = 1 (no directivity), $V_{\max,RC}^2 \equiv \langle V^2 \rangle$ (the receive antenna scan in previous methods is replaced by averaging over the modal distribution variations), $AF_{RC}^2 = \eta_0 / d_{RC}{}^2 Z_c$ (d_{RC} = 1 m is included to give consistent units), and

$$PL_{\mathrm{RC}} = \frac{1}{d_{\mathrm{RC}}{}^{2}} \frac{\left\langle P_{\mathrm{r,ref}} \right\rangle}{P_{\mathrm{ref}}} \ . \qquad \text{(H.20)}$$

This yields

$$V_{\mathrm{max,RC}}^{2} = \eta_{0} \left(\mathrm{AF}_{\mathrm{RC}}^{-2} D_{\mathrm{max,RC}} PL_{\mathrm{RC}} \right) P_{0} \ . \qquad \text{(H.21)}$$

Note that $V_{\mathrm{max,RC}}$ does not denote the maximum voltage measured over the multiple modal distributions; it denotes the average, as defined in equation (H.20) above.

E.10 H.6 Correlation

The above yields equations (H.7), (H.11), (H.16), (H.21) for the received voltage from an electric dipole located in four different test environments: free space (FS), half space (HS), a TEM line (TL), and a reverberation chamber (RC). Assuming the total radiated power from the dipole is the same in each case, one can form the ratios of these expressions to correlate between EMC test facilities,

$$\frac{V_{\mathrm{max},A}^{2}}{V_{\mathrm{max},B}^{2}} = \frac{F_{A}^{-2}}{F_{B}^{-2}} \frac{D_{\mathrm{max},A}}{D_{\mathrm{max},B}} \frac{a_{A}}{a_{B}} \quad , \qquad \text{(H.22)}$$

where A and B can be any combination of FS, HS, TL and RC.

The above euqation (H.22) is based on consideration of an electric dipole. However, the identical form could be used for a magnetic dipole (D_{max} = 3/2), a combination of an electric and magnetic dipole (D_{max} = 3), or, in a general sense, for equipment under test (EUT), as shown in Fig. H.1, having directivities other than these dipole values. If one is not correlating to a reverberation chamber, then the directivity ratio is unity regardless of the test object. For the correlation to a reverberation chamber where $D_{\mathrm{max,RC}}$ = 1, D_{max} for a test object in the other facility must be either known (typically not the case) or must be estimated, as was done in [57], based on the electrical size of the test object.

$$\left\langle D_{\mathrm{max}} \right\rangle \approx \frac{1}{2} \left[0.577 + \ln\left(4(ka)^{2} + 8ka \right) + \frac{1}{8(ka)^{2} + 16ka} \right] \quad ka > 1 \, , \qquad \text{(H.23)}$$

where <> denotes the expected value, a is the radius of the minimum sphere enclosing the test object, and the product ka defines its electrical size (ka > 1 being electrically large and no longer strictly dipole-like). This expression yields a value of 1.55 as ka approaches 1, which is between the minimum value 1.5 and the maximum value 3 for a dipole-like test object, and represents a reasonable estimate for an electrically small source.

The emission correlation parameters are summarized in Table 1. The terms used in Table 1 may be found in the appropriate sections of the annex.

Table 1. Summary of the Emission Correlation Parameters

EMC Test Facility	**AF**	**D_{max}**	**PL**
FS (FAR)	receiving antenna	3/2 for a dipole or equation (H.23)	$1/(4\pi r^2)$
HS (SAC, OATS)	receiving antenna	3/2 for a dipole or equation (H.23)	$4/(4\pi r^2)$ or $g_{max}{}^2/(4\pi r^2)$ (H.9)
TL (TEM Cell, GTEM Cell, stripline)	$\frac{\eta_0}{Z_c}\frac{h}{r_{TL}}\frac{1}{\lambda}$	3/2 for a dipole or equation (H.23)	$1/(4\pi r_{TL}{}^2)$
RC (reverb. chamber)	$\frac{\eta_0}{Z_c}\frac{1}{d_{RC}}$	1 for all emitters	$\frac{1}{d_{RC}{}^2}\frac{\langle P_{r,ref}\rangle}{P_{ref}}$

E.11 H.7 Example Emission Limits

Emission limits may be correlated by substituting E_{max} for $V_{max}F_{TL}$. As an example, if we use the CISPR 22 OATS limits, then the equivalent TEM transmission line limits are shown in Fig. H.5. This requires that the measured transmission line voltage be converted to an equivalent field strength using the AF given in Table 1.

Note 1 The values in Fig. H.1 are found as follows. In equation H.22, let A = TL, B = HS, and note that $E_{\max} = F \cdot V_{\max}$, then simplifying yields $E_{max,\mathrm{TL}} = E_{\max,\mathrm{HS}} \frac{1}{2}\frac{s}{r_{\mathrm{TL}}}$. As an example, take the Class A CISPR 22 limit of 40 dBuV/m for 30 – 230 MHz at 10 m separation (= s), then in decibels we get $20 \cdot \log_{10}(E_{\max,\mathrm{TL}}) + 20\log_{10}(r_{\mathrm{TL}}/1\mathrm{m}) = 40 + 20\log_{10}(5) = 54$, as shown in Fig. H.5. Similar levels follow for Class B and other frequencies.

Alternately, the emissions measured in the transmission line may be compared to an equivalent HS value via

$$E_{\max,\mathrm{HS}} = E_{max,\mathrm{TL}}\, 2\frac{r_{\mathrm{TL}}}{s}, \qquad \text{(H.23)}$$

where s is again the HS separation (e.g., 3 m, 10 m, 30 m, etc.). This comparison is useful if multiple test object orientations are used (for example, 12) and the maximum from these orientations is found.

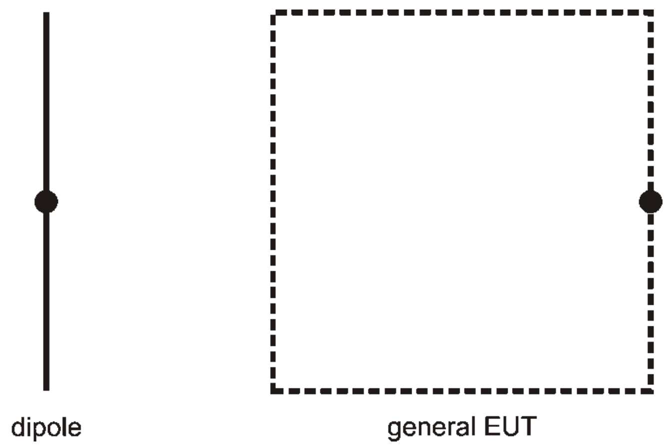


Figure H.1: A representation of a short, centre fed dipole and a more general source representing an equipment under test (EUT).

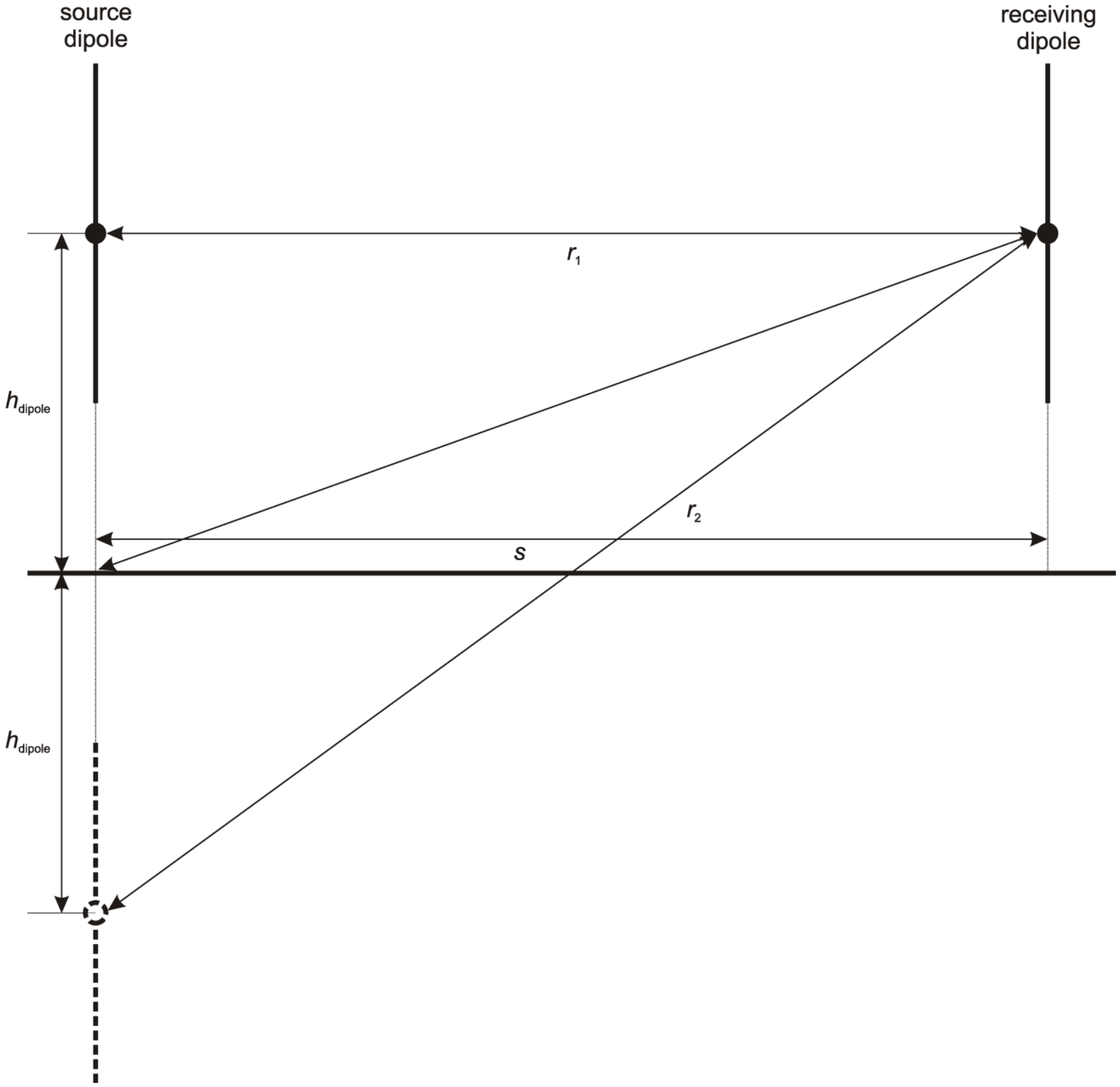
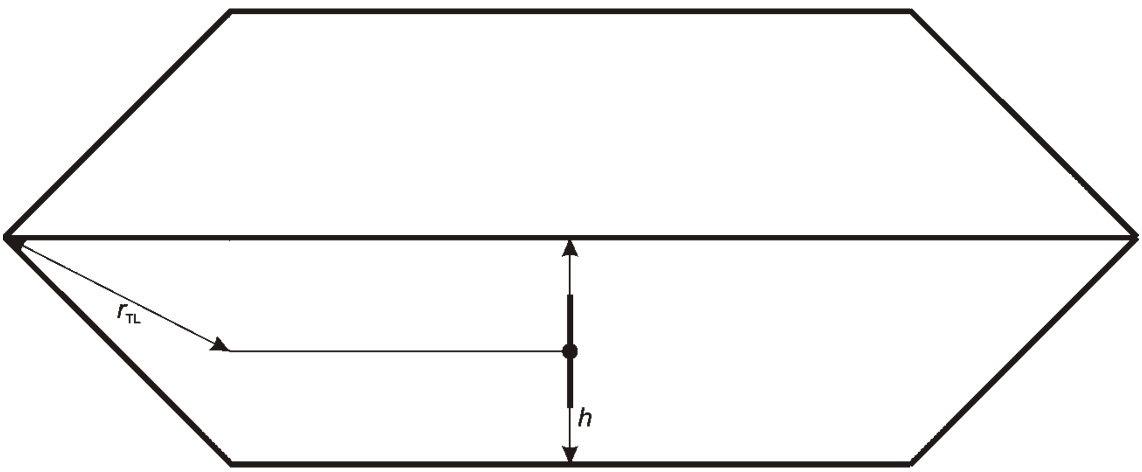
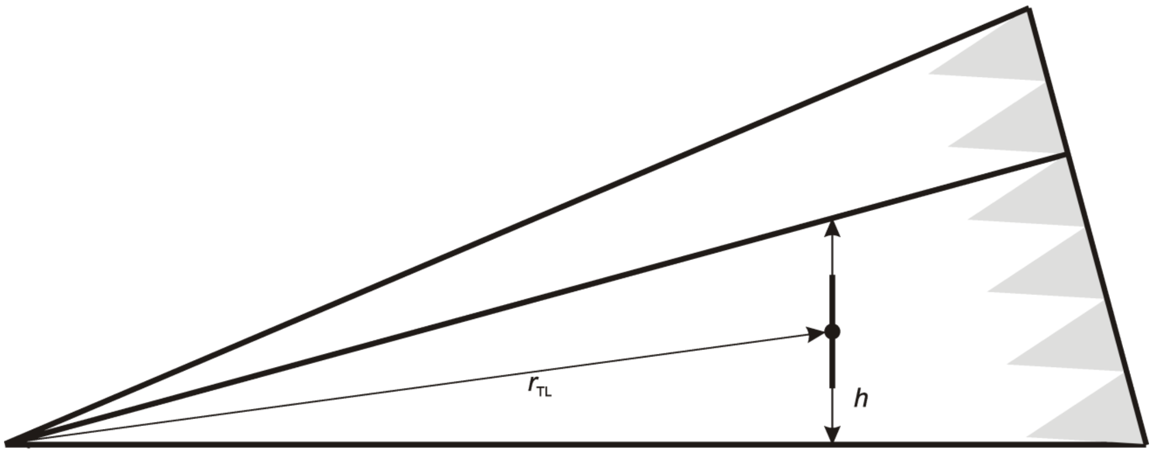


Figure H.2: Vertical source and receiving dipoles located over a perfectly conducting ground plane of infinite extent. The source and receive geometry definition is the same for co-polarized horizontal dipoles, or for source and receive dipoles of arbitrary orientation.



a) A two-port TEM cell.



b) A one-port TEM cell.

Figure H.3: Two types of TEM cells with a vertically polarized dipole source and the source to receive port geometry defined.

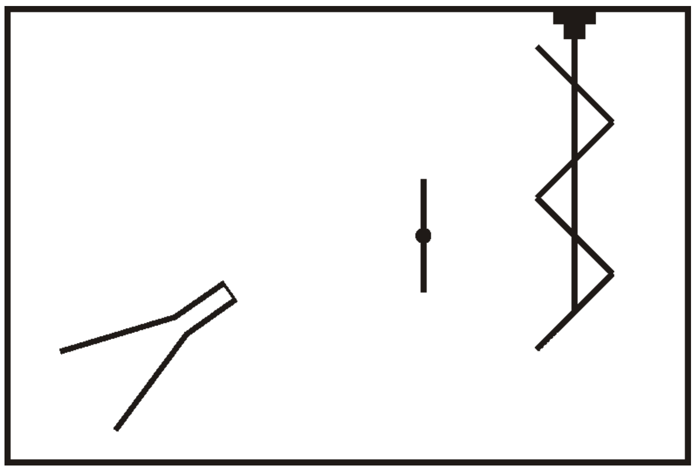


Figure H.4: A reverberation chamber with a source dipole, a stirrer to randomize the fields, and a general receiving antenna. Note the receiving antenna is depicted pointing away from the dipole source to minimise direct path coupling.

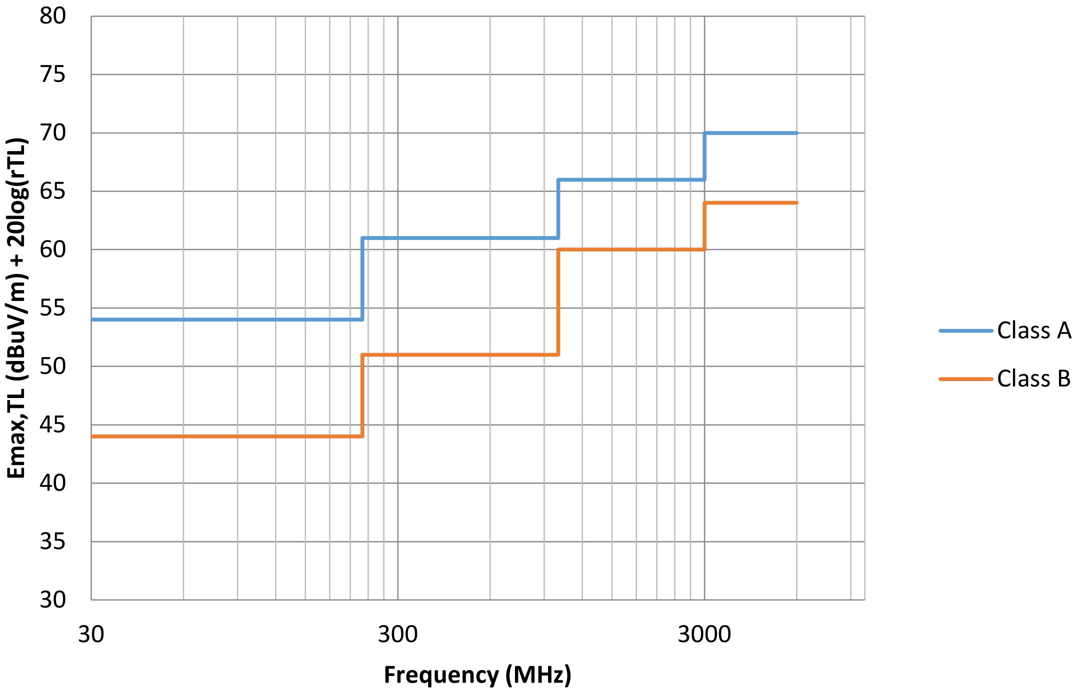


Figure H.5: TEM cell Class A and Class B emission limits correlated from CISPR 22. Note that r_{TL} is the distance (m) from the TEM cell (transmission line facility) measurement port to the emitter (test object) location.

Annex I
(informative)

Transient TEM waveguide characterization

I.1 Overview

This annex describes a characterization method for TEM waveguides based on transient signals. The method allows to evaluate the quality of a shape inherent signal transmission in TEM waveguides. The evaluation is based on the Pearson correlation coefficient (Pcc) and gives the manufacturers a possibility to express the time domain characteristics of a given TEM waveguide by one significant value.

A large variety of different waveforms for distinct technical purposes can be found in the electromagnetic environment. Especially for communication systems new waveforms will develop in the future. Today it takes technical experts to estimate if a measurement with a specific transient signal can be performed in a distinct waveguide. In order to evaluate such future waveforms in TEM waveguides and to offer a manageable waveguide transmission qualification method, the Annex I provides a new test setup and waveguide qualification method.

The waveguide characterization method can be applied to any arbitrary waveform in order to evaluate its compliance with the waveguide. The primary E-field component E_y of the signal is measured at a reference position and at discrete points within the test volume of the TEM waveguide. The correlation of the reference and the test volume signal represents the quality of the shape inherent transmission [10].

I.2 Test equipment

The measurement system - apart from the probe - shall be intrinsically insensitive to electromagnetic radiation by the TEM waveguide. Therefore, the measurement method shall involve the use of a fiber optic transmission link that offers the possibility to measure signals and to transmit them to an oscilloscope without interfering with the EM field in the test volume.

The characterization is performed in time domain. It is recommended that the measurement system has the following characteristics:

- two identical E-Field probes, that have a bandwidth according to the chosen arbitrary transient waveform.
- an oscilloscope that has a bandwidth and a sampling rate in accordance to the Shannon Theorem with respect to the transient signal.
- a transient waveform generator with an internal resistance matched to the waveguides characteristic impedance.

I.3 Test setup

In order to evaluate the waveguides transmission quality the so called reference signal and the signals in the test volume are measured. The usable test volume of a TEM waveguide (see Figures D.7 to D.11) depends on the “uniform area” as defined in *5.2.2.* The *Field uniformity verification* (5.2.2.2) and the *TEM mode verification* (5.2.2.3) are required for the transient TEM waveguide characterization [25].

The test section, marked in Figure I.1a and I.1b, is equivalent to the uniform area as defined in 5.2.2. The number of measuring points for transient TEM waveguide characterization has to be chosen according to 5.2.2. At these measuring points the primary field component E_y shall be recorded. The reference position is located as close as possible to the feeding section within the TEM waveguide and centered to the septum (Figure I.1a). Furthermore it has to be guaranteed that the field probe is small in comparison to the cross section of the waveguide in order to avoid field distortions. In the *y*-direction the reference position is in the middle of the actual septum height at the feeding section. At both positions identical E-field probes have to be used, so that their influence on the measured signal does not have to be taken into account because of the mathematical properties of the Pcc.

I.4 Waveguide characterization by correlation

In order to offer a quick evaluation based on only one qualifying parameter every measured signal in the test section is correlated with the reference signal. To do so both signals have to be windowed [11]. The window has to be chosen in the way that the remaining signal contains the most relevant information and - depending on the waveforms characteristics - reflections. The specifications given in the following passage can be understood as an example for transients with a double exponential envelope (Figure I.2).

Signal windowing:

- t_{start}: time, when 5% of the maximum of E_y is reached
- t_{length}: consists of two time lengths; $t_{length1}$ describes the time between the first exceeding e.g 5% of the peak value (t_{start}) till the last fall below 5% and $t_{length2}$ can be calculated to twice the propagation time from the measuring position to the absorber tips according to (I.1a), where d_{abs} is the distance to the absorber tips and c_0 the speed of light in free space

NOTE 1: t_{start} might be chosen at a rise time to less than 10% percent if the signal to noise ratio of the signals in the reference position and in the test volume is sufficient to allow a precise time mapping.

The beginning of the signal window for the reference signal and the signals within in test volume is defined by the minimum, clearly detectable amplitude – for example 5% of $E_{y,max}$. The signal length depends on the signal itself as well as on the location of the uniform area and its distance to the absorber tips, to ensure that relevant reflections are also covered by the signal window. At the reference position no higher order modes are capable to propagate and no signal distortions will appear. Thus, the reference signal accords to the original signal, which is supplied by the signal generator and contains only those transformations caused by the measurement system. The windowed signals are correlated on basis of (I.1), where the overbar denotes the mean value of a measurand.

$$\rho(E_{y,r}, E_{y,s}) = \frac{\frac{1}{N}\sum_{k=1}^{N}(E_{y,r}(k)-\overline{E}_{y,r})(E_{y,s}(k)-\overline{E}_{y,s})}{\sqrt{\frac{1}{N}\sum_{k=1}^{N}(E_{y,r}(k)-\overline{E}_{y,r})^2}\cdot\sqrt{\frac{1}{N}\sum_{k=1}^{N}(E_{y,s}(k)-\overline{E}_{y,s})^2}} \quad \text{(I.1)}$$

NOTE 2: $E_{y,r}$ is the y component of the signal at the reference position, $E_{y,s}$ is the y component of the signal in the test volume, k is the sample index and N is the total number of samples.

NOTE 3: The magnitude of the measured E field does not have an impact on the Pcc, so no normalization of $E_{y,r}$ and $E_{y,s}$ has to be performed

The correlation coefficient can be visualized by means of a heat map to get a good overview of the transmission quality of the investigated waveguide (Figure I.3). Such a heat map reveals the limits of the test volume and shows influences of the waveguide, for example EM field distortions due to the waveguide door.

I.5. Quantification of the Pcc

To quantify the level of distortion or to verify if a signal is transmitted shape inherent, a threshold has to be defined for the Pcc.

In the IEC 61000-4-20 Annex C the double exponential pulse - the only standardized waveform - is defined by its rise time t_{rise} and its pulse width t_{fwhm}, with the following tolerances:

- t_{rise} between 10% and 90% of the peak value shall be 2,25 ns ± 0,25 ns
- t_{fwhm} shall be 27,5 ns ± 2,5 ns

The Pcc of a double exponential pulse with t_{rise} = 2 ns and t_{fwhm} = 25 ns and a pulse with t_{rise} = 2.5 ns and t_{fwhm} = 30 ns, generated by an arbitrary vector signal generator and measured by an oscilloscope, is calculated to ρ = 0,994 (≙99,4%), a deviation of 0,6% [11].

Taking into account a typical measurement setup and measurement uncertainty, the Pcc should not be less than ρ = 0,9, which has to be understood as a reference value for any arbitrary transient test signal. The final limit value of the Pearson correlation coefficient for a specific transient waveform shall be set by the product committees.

I.6 Performable transient test signals

Basically every transient signal can be used for the waveguide evaluation. It has to be mentioned that an ultra wideband transient signal, like a double exponential pulse presented in C.2.1, is an adequate waveform to qualify the waveguide over a wide frequency band. However, it is not a sufficiently describing waveform. In case of a shape inherent transmission of a double exponential pulse it is not warranted, that every arbitrary signal with a mid-band frequency in the spectrum of the double exponential pulse, can also be transmitted shape inherent. Therefore it is essential to perform an evaluation of the intended waveform during the waveguide evaluation.

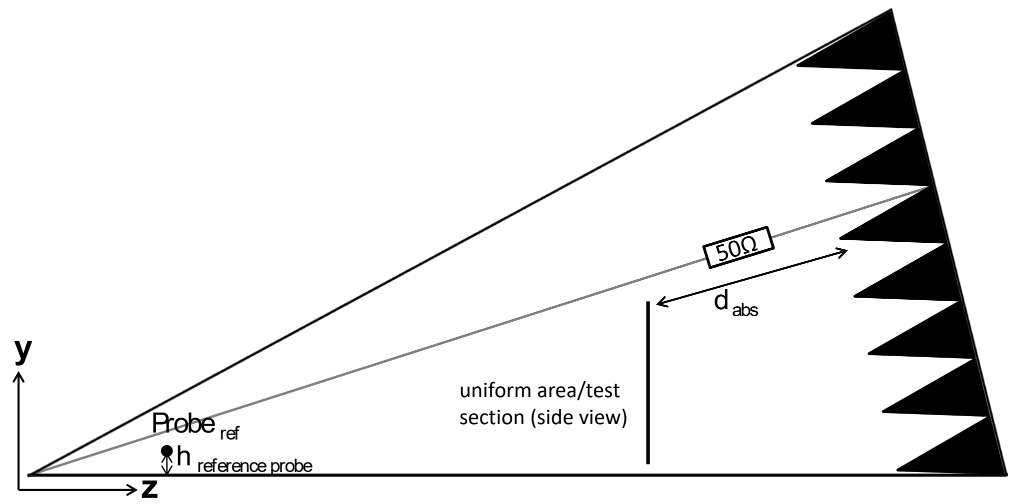


Figure I.1a – Side view

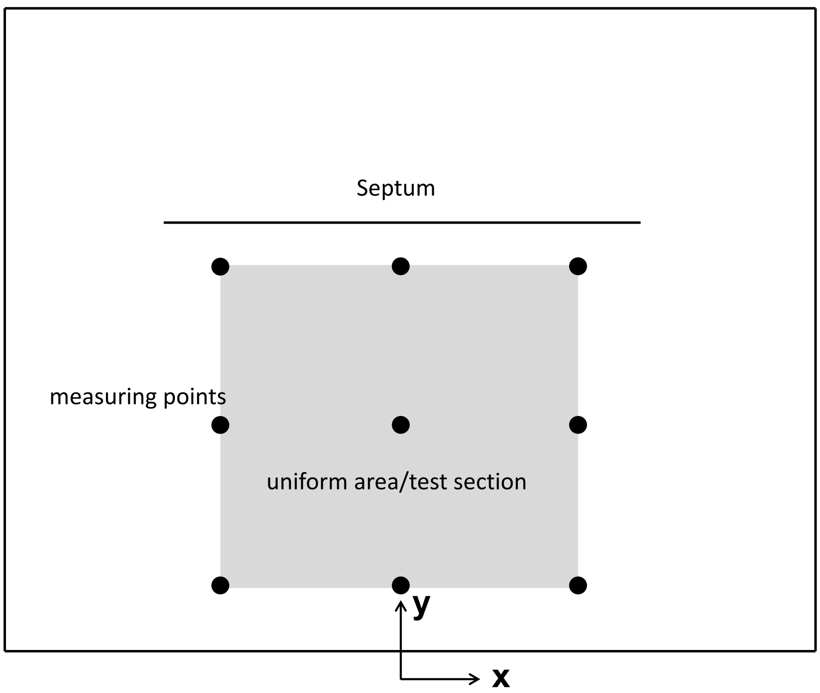


Figure I.1b – Cross section view

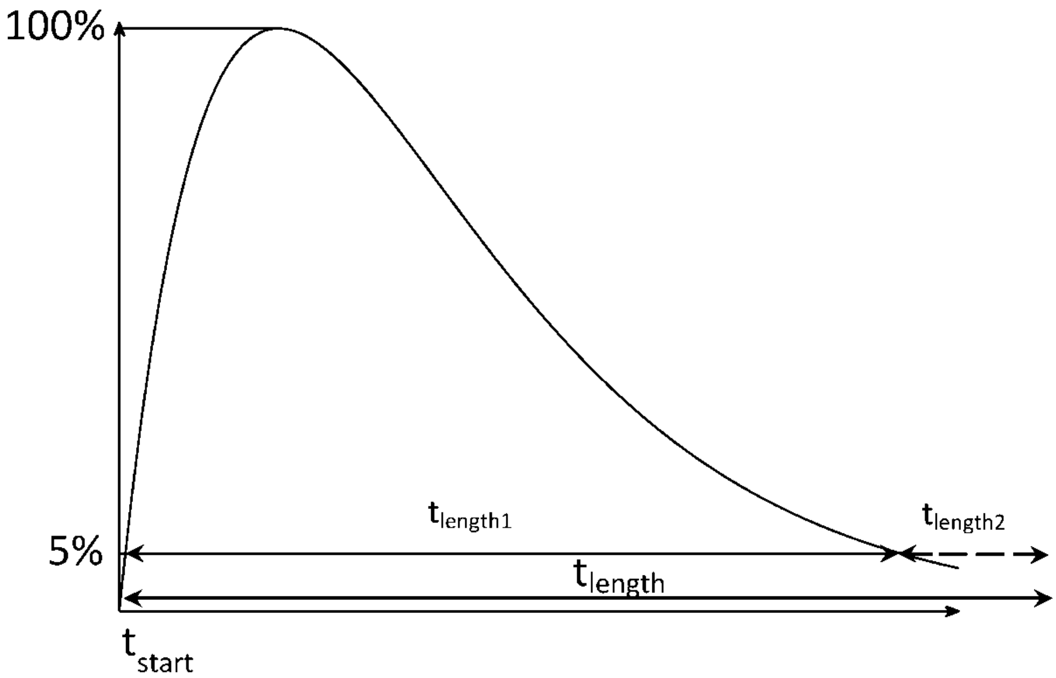


Figure I.2 – Signal windowing

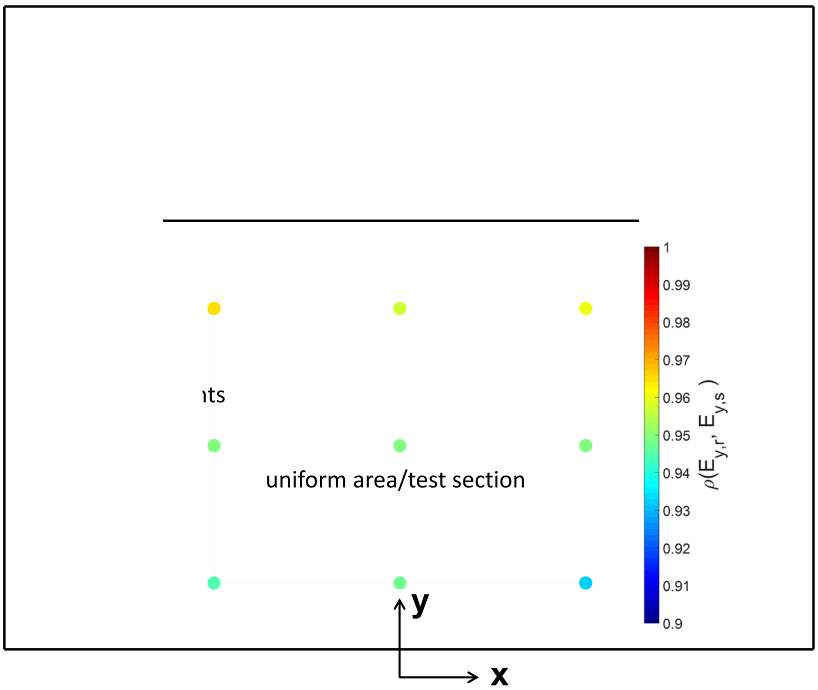


Figure I.3 – Example of a heatmap - Pcc for the measuring point in the uniform area

Bibliography

Standards including TEM waveguides

ANSI C63.4, *Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz*

ANSI C63.19-2014*, Methods of Measurement of Compatibility between Wireless Communication Devices and Hearing Aids*

CISPR 20, *Sound and television broadcast receivers and associated equipment – Immunity characteristics – Limits and methods of measurement*

CISPR 25, *Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of on-board receivers*

EIA/TIA-631, *Telecommunications Telephone Terminal Equipment – Radio Frequency Immunity Requirements for Equipment Having an Acoustic Output*

ETSI TR 102 273-5, *Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Improvement on Radiated Methods of Measurement (using test sites) and evaluation of the corresponding measurement uncertainties – Part 5: Striplines*

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

IEC 60118-13, *Electroacoustics – Hearing aids – Part 13: Electromagnetic compatibility (EMC)*

IEC 60489-1, *Methods of measurement for radio equipment used in the mobile services – Part 1: General definitions and standard conditions of measurement*

IEC 60489-3, *Methods of measurement for radio equipment used in the mobile services – Part 3: Receivers for A3E or F3E emissions*

IEC 61967-2, *Integrated circuits – Measurement of electromagnetic emissions, 150 kHz to 1 GHz – Part 2: Measurement of radiated emission, TEM cell and wideband TEM cell method*

IEC 62132-2, *Integrated circuits – Measurement of electromagnetic immunity – Part 2: Measurement of radiated immunity – TEM-cell and wideband TEM-cell method*

IEEE Std C95.3, *IEEE recommended practice for the measurement of potentially hazardous electromagnetic fields – RF and microwave*

IEEE Std 1309-2005, *IEEE Standard for Calibration of electromagnetic Field Sensors and Probes, Excluding Antennas, from 9 kHz to 40 GHz*

IEEE Std 145-1993, *IEEE Standard Definitions of Terms for Antennas*

IEEE Std 211-1997, *IEEE Standard Definitions of Terms for Radio Wave Propagation*

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

ISO 11452-3, *Road vehicles – Component test methods for electrical disturbances from narrowband radiated electromagnetic energy – Part 3: Transverse electromagnetic mode (TEM) cell*

ISO/IEC Guide 98-3:2008, Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)

MIL-STD 461F, *Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment*

UKAS, M3003, Edition 2, 2007, *The Expression of Uncertainty and Confidence in Measurement*, free download on www.ukas.com

Reference documents

[1] M. Alexander, A. Nothofer, R.C. Dixon, “The use of ferrite clamps and clip-on ferrites,” CISPR/A-TC77 (JTF-TEM-Alexander-Nothofer-Dixon) 01-01, June 2001

[2] ANSI C63.4-2008, *American National Standard for Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz*, The Institute of Electrical and Electronics Engineers, Inc., New York, Dec. 2000

[3] T.M. Babij, “Evaluation of errors in the calibration of TEM cells,” *IEEE Miami Technicon ‘87*, Miami, FL, pp. 199-201, 1987

[4] A. Beggio, G. Borio, and R.E. Zich, “On the unwanted effects on the radiated emission and susceptibility measurements due to the introduction of a wooden table,” *International Symposium on Electromagnetic Compatibility*, Tokyo, Japan, pp.252-255, May 1999

[5] S. Bentz, “Use of the TEM cell for compliance testing of emission and immunity, an IEC perspective,” *IEEE International Symposium on Electromagnetic Compatibility*, Santa Clara, CA, pp. 43-47, 1996

[6] H.S. Berger, and A. Tsaliovich, “Unlicensed PCS product EMC compliance measurement rational and alternatives,” *IEEE International Symposium on Electromagnetic Compatibility*, Santa Clara, CA, pp. 396-401, 1996

[7] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML. Guide to the Expression of Uncertainty in Measurement. International Organization for Standardization, Geneva, Switzerland, ISBN 92-67-10188-9, First Edition, 1993

[8] J. van Bladel, *Electromagnetic Fields*, Hemisphere Publishing Corporation, 1985

[9] Ch. Braun, W. Graf, P. Guidi, H.U. Schmidt “Beeinflussung der Stromverteilung auf Testobjekten in TEM-Wellenleitern bei Variation des Füllfaktors,” (translation: “Influence of current distribution on test objects in TEM waveguides for variable object size"), *Kleinheubach Symposium* of URSI German NC and ITG*,* Kleinheubacher Berichte*,* Deutsche Telekom, Darmstadt, Germany, vol. 39, 1996

[10] N. Briest, S. Potthast, H. Garbe, “Transmission Characteristics of a TEM Waveguide for Transient Signals by the use of a Damped Sinusoidal”, Adv. Radio Sci., 13, 2015, 175-179

[11] N. Briest, H. Garbe, D. Hamann and S. Potthast, “Extension of the IEC 61000-4-20 Annex C to the Use of Arbitrary Transient Signals,” Proc. IEEE Int. Symp. EMC., 2016. 829–834

[12] E.L. Bronaugh, “Simplifying EMI immunity (susceptibility) tests in TEM cells,” *IEEE International Symposium on Electromagnetic Compatibility*, Washington, D.C., pp. 488-491, August 1990

[13] E. Bronaugh, and J. Osburn, "Radiated emissions test performance of the GHz TEM cell,” *IEEE International Symposium on Electromagnetic Compatibility*, Cherry Hill, NJ, pp. 1-7, Aug. 1991

[14] CISPR 14 (all parts), *Electromagnetic compatibility – Requirements for household appliances, electric tools and similar apparatus*

[15] CISPR 16-4-2, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 4-2: Uncertainties, statistics and limit modelling – Uncertainty in EMC measurements*

[16] R. E. Collin, *Field Theory of Guided Waves*, 2nd ed., *IEEE Press*, Piscataway, NJ, 1991

[17] M. Crawford, and J. Workman, "Predicting free-space radiated emissions from electronic equipment using TEM cell and open-field site measurements," *IEEE International Symposium on Electromagnetic Compatibility,* Baltimore, MD, pp. 80-85, 1980

[18] H. Garbe, H. Haase, M. Koch, “Specification of alternative test sites with respect to given EMC field standards,” *International Zurich Symposium on Electromagnetic Compatibility*, Zurich, Switzerland, pp. 459-464, Feb. 1997

[19] H. Garn, M. Buchmayr, and W. Mullner, “Precise calibration of electric field sensors for radiated susceptibility testing”, Frequenz 53 (1999) 9-10, Page 190-194.

[20] J. Glimm, K. Münter, R. Pape, T. Schrader, and M. Spitzer, “The New National Standard of EM Field Strength; Realisation and Dissemination”, 12th Int. Symposium on EMC, February 18-20, 1997, Zurich, Switzerland, ISBN 3-9521199-1-1, Page 611-613

[21] J. Glimm, K. Münter, M. Spitzer, Th. Dötzer, Th. Schrader, “Influence of calibration and measurement techniques on the inhomogeneity of electromagnetic fields for immunity tests,” *International Symposium on Electromagnetic Compatibility*, Tokyo, Japan, pp. 600-603, May 1999

[22] C. Groh, J.P. Kaerst, M. Koch, and H. Garbe, “TEM Waveguides for EMC measurements,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 41, no. 4, pp. 440-445, Nov. 1999

[23] C. Groh, J.P. Kaerst, and H. Garbe, “Einfluss der Beladung auf die Feldmoden in TEM Wellenleitern,” (translation: “Influence of load on field modes in TEM waveguides”), *Elektromagnetische Vertraeglichkeit EMV 2000 (8. Intl. Symp. and Exhb. on EMC)*, VDE Verlag, Berlin, Germany, pp. 287-294, Feb. 2000, ISBN 3-8007-2522-3

[24] C. Groh, *TEM Zellen zur Kalibration von elektromagnetischen Feldsensoren,* (translation: *TEM cells for calibration of electromagnetic field probes*), PhD-thesis, University of Hannover, Germany, VDE Verlag, 2002

[25] D. Hamann and H. Garbe, “Enhanced estimates of field distribution’s uncertainty contribution for TEM waveguides,” Proc. IEEE Int. Symp. Electromagn. Compat., 2014, pp. 899–902

[26] D. Hamann, *Charakterisierung komplexer Systeme in GTEM Zelle,* (translation: Characterization of Complex Systems by GTEM Cell Measurements), PhD-thesis, University of Hannover, Germany, sierke Verlag, 2014

[27] D. Hamann, M.-B. Konerding, H. Garbe, “CISPR 16-4-2 Equivalent Measurement Uncertainty Analysis for TEM Waveguides”, IEEE Trans. Electromag. Compat., vol. 57, no. 4, pp. 616-622, Aug. 2015

[28] T.E. Harrington, Z. Chen, and M. D. Foegelle, “GTEM radiated emissions testing and FDTD modeling,” *IEEE International Symposium on Electromagnetic Compatibility*, Seattle, WA, pp. 770-775, 1999

[29] T.E. Harrington, “Total-radiated-power-based OATS-equivalent emissions testing in reverberation chambers and GTEM cells,” *IEEE International Symposium on Electromagnetic Compatibility,* Washington, DC, pp. 23-28, 2000

[30] T.E. Harrington, and E.L. Bronaugh, “EUT directivity and other uncertainty considerations for GHz-range use of TEM waveguides,” *IEEE International Symposium on Electromagnetic Compatibility*, Montreal, QC, Canada, pp. 117-122, 2001

[31] D. Hill, Electromagnetic Fields in Cavities: Deterministic and Statistical Theories, Wiley, 2009.

[32] C. Holloway, P. Wilson, G. Koepke, and M. Candidi, “Total radiated power limits for emission measurements in a reverberation chamber,” in Proc. 2003 IEEE Intl. Symp. on Electromagn. Compat. (Boston, MA), pp. 838-843, Aug. 2003.

[33] IEC 61000-2-9, *Electromagnetic compatibility (EMC) – Part 2: Environment – Section 9: Description of HEMP environment – Radiated disturbance*

[34] IEEE Std 1309-2005: *IEEE Standard for Calibration of Electromagnetic Field Sensors and Probes, Excluding Antennas, from 9 kHz to 40 GHz*, The Institute of Electrical and Electronics Engineers, Inc., New York, 1996

[35] S. Ishigami and M. Hirata, “A New Calibration Method for an E-field Probe using TEM Waveguides”, The 20th International Zurich Symposium on Electromagnetic Compatibility (EMC Zurich 2009), January 2009

[36] S. B. Jeon, J. H. Yun, and S. K. Park, “On the New Design of a 4-Port TEM Waveguide with a Higher Cutoff Frequency and Wider Test Volume,” ETRI Journal, vol. 34, no. 4, pp. 621~624, Aug. 2012

[37] J.P. Kaerst, C. Groh, and H. Garbe, “Field mode properties of loaded waveguides,” *International Zurich Symposium on Electromagnetic Compatibility*, Zurich, Switzerland, pp. 481-486, Feb. 2001

[38] J.P. Kaerst, *Qualifikation beladener TEM Wellenleiter,* (translation: *Validation of loaded TEM waveguides*), PhD-thesis, University of Hannover, Germany, VDE Verlag, 2002

[39] M. Kanda and D. Hill, “A three-loop method for determining the radiation characteristics of an electrically small source,” IEEE Trans. Electromag. Compat., vol. 34, no. 1, pp. 1-2, Feb. 1992.

[40] M. Klingler, J. Rioult, J.-P. Ghys, and S. Ficheux, “Wideband total radiated power measurements of electronic equipment in TEM and GTEM cells,” *International Zurich Symposium on Electromagnetic Compatibility,* Zurich, Switzerland, pp. 665-670, 1999

[41] M. Koch, *Analytische Feldberechnung in TEM Zellen*, (translation: *Analytical Field Calculation in TEM Cells*"), PhD-thesis, University of Hannover, *Shaker-Verlag*, Aachen, Germany, 1999, ISBN 3-8265-6017-5

[42] G. Koepke, and M. Ma, "A new method to quantify the radiation characteristics of an unknown interference source," *International Zurich Symposium on Electromagnetic Compatibility*, Zurich, Switzerland, pp. 35-40, March 1983

[43] J. Labus, “Rechnerische Ermittlung der Impedanz von Antennen. (Mathematical calculation of the impedance of antennas) Hochfrequenz und Elektroakustik, vol. 41, pp. 17-23; January 1933

[44] M. Ma, and G. Koepke, *Uncertainties in Extracting Radiation Parameters for an Unknown Interference Source Based on Power and Phase Measurements*, *National Institute of Standards and Technology* (NIST, formerly NBS), Technical Note 1064, June 1983

[45] A. Nothofer, A.C. Marvin, and J.F. Dawson, “Uncertainties due to cross-polar coupling in GTEM cell emission measurement,” *International Symposium on Electromagnetic Compatibility*, Rome, Italy, pp. 590-595, 1998

[46] A. Nothofer, A.C. Marvin, and J.F. Dawson: "Indirect measurements of field uniformity in TEM cells Including cross-polar field components," *International Zurich Symposium on Electromagnetic Compatibility*, Zurich, Switzerland, pp. 659-664, March, 1999

[47] D.M. Pozar, *Microwave Engineering*, 2nd ed., John Wiley & Sons, NY, 1998

[48] T. Schrader, *Vergleich von Feldgeneratoren für EMV-Prüfungen*, (translation: *Comparison of Field Generators for EMC Tests*), PhD-thesis, University of Braunschweig, Germany, 1997

[49] I. Sreenivasiah, D. Chang, and M. Ma, "Emission characteristics of electrically small radiating sources from tests inside a TEM cell," *IEEE Transactions on Electromagnetic Compatibility*, vol. 23, no. 3, pp. 113-121, Aug. 1981

[50] E. Steinke, P. Wilson, and H. Garbe, "An equivalent "radiated emission" voltage measurement standard for TEM cells," *International Wroclaw Symposium on Electromagnetic Compatibility*, Wroclaw, Poland, pp. 301-304, Sept. 1992

[51] M.J. Thelberg, E.L. Bronaugh, and J.D.M. Osburn, “GTEM to OATS radiated emissions correlation from 1-5 GHz,” *IEEE International Symposium on Electromagnetic Compatibility*, Chicago, IL, pp. 387-392, 1994

[52] J. Tippet, and D. Chang, "Radiation characteristics of electrically small devices in a TEM transmission cell," *IEEE Transactions on Electromagnetic Compatibility*, vol. 18, no. 4, pp. 134-140, Nov. 1976

[53] L. Turnbull, and A. Marvin, “A treatment of the phase properties of GTEM to open-area test-site correlation techniques,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 40, no. 1, pp. 62-69, Feb. 1998

[54] UKAS M3003 The Expression of Uncertainty and Confidence in Measurement, Ed.2, 2007

[55] P. Wilson, D. Hansen, and D. Koenigstein, "Simulating open area test site emission measurements based on data obtained in a novel broadband TEM cell," *IEEE National Symposium on Electromagnetic Compatibility*, Denver, CO, pp. 171-177, May 1989

[56] P. Wilson, "On correlating TEM cell and OATS emission measurements," *IEEE Transactions on Electromagnetic Compatibility*, vol. 37, no. 1, pp. 1-16, Feb. 1995

[57] P. Wilson, D. Hill, and C. Holloway, “On determining maximum emissions from electrically large sources,” IEEE Trans. Electromag. Compat., vol. 44, no. 1, pp. 79-86, Feb. 2002.

[58] P. Wilson, “Emission and immunity testing: test object electrical size and its implication,” in Proc. IEEE 2004 Intl. Symp. on EMC (Santa Clara, CA), pp. 340-352, Aug. 2004.

[59] J. H. Yun, H. J. Lee, and H. J. Hwang, “Straight Coupled Transmission-Line Cell for Generating Standard Electromagnetic Fields,” IEEE Transactions on Electromagnetic Compatibility, vol. 44, pp. 515~521, Nov. 2002