

INTERNATIONAL STANDARD

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BASIC EMC PUBLICATION

PUBLICATION FONDAMENTALE EN CEM

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

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



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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 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 second edition cancels and replaces the first edition published in 2003 and its amendment 1 (2006), 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 first edition of this standard and its amendment are the following:

- consistency of terms (e.g. test, measurement, etc.) has been improved;

- clauses covering test considerations, evaluations and the test report have been added;
- references to large TEM waveguides have been eliminated;
- a new informative annex has been added to deal with calibration of E-field probes.

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

FDIS	Report on voting
77B/637/FDIS	77B/641/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 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 61000-2-11:1999, *Electromagnetic compatibility (EMC) – Part 2-11: Environment – Classification of HEMP environments*

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

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*

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 input/output ports at both ends

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

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

3.1.8

outer conductor or chassis

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

3.1.9

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.

3.1.10

anechoic material

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

3.1.11

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

3.1.12

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

3.1.13

EUT type

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

3.1.14

exit cable

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

NOTE Test volume is specified in 5.2.2.

3.1.15

interconnecting cable

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

3.1.16

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]²).

3.1.17

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.

3.1.18

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.

3.1.19

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

3.1.20

resultant field (amplitude)

root-sum-squared values in V/m of the primary and the two secondary field components

3.1.21

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.

3.1.22

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].

3.1.23

gravity-dependent / -independent

the gravitation force of the earth has a fixed direction. The EUT can be rotated around all three axes. Due to different rotation positions, the EUT is affected by the gravitation force in different directions. The EUT is gravity-independent if it is working properly in all positions,

² Figures in square brackets refer to the bibliography.

which means working properly regardless of the direction of the gravity vector relative to the EUT. The EUT is gravity-dependent if it does not work properly in one or more test positions

3.2 Abbreviations

BALUN	balanced-to-unbalanced transformer
DFT	discrete Fourier transform
EUT	equipment under test
FFT	fast Fourier transform
GTEM	gigahertz transverse electromagnetic
HEMP	high-altitude electromagnetic pulse
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 Annex E and 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 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 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 5.2.3).

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.

Using an immunity-type uniform-area verification procedure (according to 5.2.3) the magnitudes of the secondary (unintended) electric field components shall be at least 6 dB less than the primary component of the electric field, over at least 75 % of the tested points in a defined cross-section of the TEM waveguide (perpendicular to the propagation direction). For this 75 % of test points, a primary electric field component tolerance greater than $^{-0}_{+6}$ dB up to $^{-0}_{+10}$ dB, or 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. The frequency range is 30 MHz up 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 80 MHz to 1 000 MHz, 5 % below 80 MHz and above 1 000 MHz. One constraint on the sweep speed is the response time of the field probe.

NOTE 2 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 TEM mode verification testing.

NOTE 3 For transient tests the start frequency should be 100 kHz.

NOTE 4 The 6 dB criterion from 5.2.1 specifies the dominant TEM mode and not the field uniformity, and is separate from and not to be confused with the field uniformity requirements of 5.2.3. Further information about field uniformity is given in [17].

5.2.2 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 A.6 to A.9) depends on the “uniform area” as defined in 5.2.3. 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 A.6 to A.9) 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 $z_{\min} \leq z \leq z_{\max}$. The length of the test volume is $L = z_{\max} - z_{\min}$. The requirements of a uniform area shall be validated for cross-sections at each z with $z_{\min} \leq z \leq z_{\max}$. It can be assumed that the TEM mode requirements are fulfilled for $z_{\min} \leq z \leq z_{\max}$ 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 A.6 to A.9 with a constant aspect ratio of h to w (inherent shape) for $0 < z < z_{\max}$, 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 $z_{\min} < z < z_{\max}$ and the derivatives dh/dz and dw/dz are a smooth function for $z_{\min} < z < z_{\max}$ (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 [25].

5.2.3 Validation of usable test volume

5.2.3.1 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 [15]). 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 5.2.2).

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 5.2.2.

The uniform area is validated in the empty enclosure, for the frequency range and frequency steps specified in 5.2.1 using a non-modulated signal.

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 smaller than 50 cm. If the 50 cm limit is exceeded, an equally spaced grid has to be used for the test points. This means that 9 points shall be used.

5.2.3.2 Field uniformity and TEM mode measurement procedure

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

- position the isotropic 3-axis probe at one of the points in the grid;
- 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 of the given limit E_{Limit} through the frequency range and frequency steps specified in 5.2.1, and record all the forward power, primary and secondary components field strength readings;
- with the same forward power, measure and record the primary and secondary field strengths at the remaining grid points;
- calculate the standard deviation according to Equation (1). All measurement results are expressed in dB(V/m);
- the primary field component magnitude of the remaining points shall lie within a range of 6 dB. The level of the secondary field components shall not exceed –6 dB of the primary field component at each of these points;
- of the remaining points, take the location with the lowest primary field component E_{ref} as the reference (this ensures the ${}^{-0}_{+6}$ dB requirement is met);
- knowing the forward power and the field strength, the necessary forward power for the required test-field strength can be calculated using Equation (1), and shall be recorded.

$$P_{\text{test}} = \frac{E_{\text{test}}^2}{E_{\text{ref}}^2} P_{\text{fwd}} \quad \text{with } E \text{ in V/m and } P \text{ in W} \quad (1)$$

EXAMPLE If at a given point, 81 W gives 9 V/m, then 9 W is needed for 3 V/m.

Alternatively, an equivalent procedure is to establish a constant primary component electric field strength in the range of the given E_{Limit} and record the forward power delivered to the input port. Next, steps a), d), e), f) and g) shall be applied. This method is known as the “constant field strength” method.

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).

5.2.3.3 Field uniformity criteria

The uniformity of the field is determined as follows.

At test point i the measured field strength is given as E_i . The mean-value and the standard deviation are calculated for N test points.

$$\text{Mean: } \bar{E} = \frac{1}{N} \sum_{(N)} E_i \quad (2)$$

$$\text{Standard deviation: } \sigma_E = \sqrt{\frac{1}{N-1} \sum_{(N)} (E_i - \bar{E})^2} \quad (3)$$

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

$$\bar{E} - K \cdot \sigma_{\bar{E}} \leq E_i \leq \bar{E} + K \cdot \sigma_{\bar{E}} \quad (4)$$

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

Dealing with dB-values often the probability is requested whether the measurement E_i falls into the band according to Equation (5).

$$E_{\text{Limit}} \leq E_i \leq E_{\text{Limit}} + E_{\text{Margin}} \quad (5)$$

Comparing this band with Equation (4) gives Equation (6).

$$E_{\text{Limit}} \leq E_i \leq E_{\text{Limit}} + 2 \cdot K \cdot \sigma_{\bar{E}} \quad (6)$$

$$\sigma_{\bar{E}} \leq \frac{\text{Margin}}{2 \cdot K} \quad (7)$$

For 75 % = $K = 1,15$ and a margin of 6 dB the standard deviation shall be

$$\sigma_{\bar{E}} \leq \frac{6 \text{ dB}}{2 \cdot 1,15} = 2,61 \text{ dB}.$$

The largest dimension of the sensor shall be smaller than 10 % of the distance between the inner and outer conductor. In this case, any field perturbation can be neglected. More details are given in [18].

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

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

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.

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 $\lambda = 300$ 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

- a small EUT with one or more exit cables,

- a small 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.

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 it is considered that there is sufficient evidence to demonstrate that the effects of the phenomenon covered by this standard are influenced by climatic conditions, this should be brought to the attention of the committee responsible for this standard.

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.

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 [36]).

- **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 $\pm 120^\circ$ about its vertical axis (which is its ortho-axis). The EUT need 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 [24].

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 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], [8], [17], [22], [34], [36], [40] and [41].

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 [31] and [41]).

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 [14], [29], [30], [35] and [38]). 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 [36], [40] and [41]). 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 [10], [28] and [39]). Detailed radiation patterns cannot be simulated. The upper bound estimate is valid for comparison to standards limits. In [31] and [32] 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 [31] and [41]) that the total radiated power P_0 due to the EUT is given by

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

where

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

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

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 $\frac{1}{\text{m}}$;

$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 120 \pi \Omega \approx 377 \Omega$ is the free space wave impedance in Ω ;

Z_C is the characteristic impedance of the TEM waveguide in Ω (typically 50Ω);

e_{0y} 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 [21].

A.3.2.3.3 Determining the field factor

A.3.2.3.3.1 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_{0y} are as follows.

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

A.3.2.3.3.2 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

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

A.3.2.3.3.3 Analytical procedure

For a TEM cell with a rectangular cross-section as shown in [41] the normalized TEM mode component can be analytically approximated with the equation

$$e_{0y} = \frac{4}{a} \sqrt{Z_c} \cdot \sum_{m=1,3,5,\dots}^{\infty} \left(\frac{\cosh(My)}{\sinh(Mh)} \cdot \cos(Mx) \cdot \sin\left(M \frac{a}{2}\right) \cdot J_0(Mg) \right) \quad \text{in} \quad \frac{\sqrt{\Omega}}{\text{m}} \quad (\text{A.4})$$

where

$M = m \frac{\pi}{a}$, $m = 1, 3, 5, \dots, \infty$, in 1/m;

a is the cell width (see Figures A.6 to A.9) 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_{0y} . Field factor results for a variety of geometries are given in [28].

A.3.2.4 Correlation to OATS

EUT emissions over a ground plane are simulated by assuming that the total radiated power, as estimated by the TEM waveguide tests, is the same as that emitted by a dipole (replacing the EUT).

The equations for the fields from a dipole are well known and the 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 maximum signal from the two polarizations then gives the maximum possible field strength. Using the geometry factor $g_{\max}$ determined by the height-scan of the receiving antenna, an estimate for the maximum field $E_{\max}$ on an OATS is given by

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

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

where

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

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

$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 120\pi\Omega \approx 377\Omega$ is the free-space impedance in Ω ;

Z_C is the characteristic impedance in Ω ;

e_{0y} is the TEM-mode field factor in $\frac{\sqrt{\Omega}}{\text{m}}$

and

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

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

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

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

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

s receiving antenna to EUT 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 antenna 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 $E_{\max} = \frac{1}{r} \sqrt{\frac{\eta_0}{4\pi}} D_{\max} P_0$, 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 a 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 “worst case”.

Generally, 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 5.2. Some informative guidance for large EUT correlation and set-up methods is also included in this standard (A.5.1.2).

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(μ V/m) as

$$E_{\max}|_{\text{dB}} = 20 \cdot \lg(g_{\max}) + 10 \cdot \lg(P_0) + 139,5, \text{ in dB}(\mu\text{V/m}) \quad (\text{A.8})$$

The factor $20 \cdot \lg(g_{\max})$ 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(μ V/m) leads to

$$E_{\max}|_{\text{dB}} = 20 \cdot \lg(g_{\max}) + 20 \cdot \lg\left(\left|\frac{\eta_0 k_0}{2\pi \cdot e_{0y}}\right|\right) + 10 \cdot \lg\left(\frac{S^2}{Z_C}\right) + 120, \text{ in dB}(\mu\text{V/m}) \quad (\text{A.9})$$

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 $0,1 \lambda$, 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

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

where

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

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

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

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

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

where

$g_{i,f}$ is the TEM waveguide electric field strength correlated with free space (A.3.2.4), in $\frac{V}{m}$;

$i = 1 \dots n$ n is the number of TEM waveguide measurements;

$o_{k,f}$ is the OATS electric field strength, in $\frac{V}{m}$;

$k = 1 \dots m$ m is the number of OATS measurements;

f is the frequency, in Hz;

$g_{i,f}$ are the correlated field strengths from $i = 1 \dots n$ measurements using one or more TEM waveguides of a specific type and size, and

$o_{k,f}$ are the results from $k = 1 \dots m$ 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

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

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

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

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

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

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

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

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

NOTE 4 If the TEM waveguide is unique ($n = 1$), for example, built for scientific use in a single laboratory, then $s_{\text{TEM},f} = 0$ 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 ($8 \times 3 = 24$ voltage readings). $\bar{E}_\alpha$ is the mean value of the electric field, specifically, $\bar{E}_{0^\circ} = (E_{0^\circ} + E_{90^\circ})/2, \dots, \bar{E}_{225^\circ} = (E_{225^\circ} + E_{315^\circ})/2$. A maximum field strength, $E_{\alpha,\text{max}}$, is obtained as the highest field strength for each pair of values separated by 90° . Specifically, $E_{0^\circ,\text{max}} = \max(E_{0^\circ}, E_{90^\circ}), \dots, E_{225^\circ,\text{max}} = \max(E_{225^\circ}, E_{315^\circ})$. A standard deviation factor is calculated using the following equation.

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

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

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

NOTE 5 An alternative to the t -factor (radiation pattern uncertainty factor) may be the six-position method of [27], or the 12-position method ("enhanced three-position") of [37]. The important issue is that EUT total radiated power should be captured. Comparison data are shown in [20] and [21].

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 $2 \times 3 = 6$ 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

The method of A.5.1.1 can be applied to large EUTs. However, the dipole assumption in the correlation algorithm may not be valid for large EUTs.

The following information is given for guidance purposes.

For compliance testing of large EUTs in TEM waveguides, the following procedure has been proposed. Further details are given in [2].

- a) Three independent tests on a particular EUT type should be completed at a specific compliant OATS and the specific TEM waveguide.
- b) The average difference between TEM waveguide and OATS results is calculated at each frequency using Equation (A.11) with $n = m = 3$.
- c) The average and standard deviation versus frequency of the differences calculated in step 2 for a minimum of 10 frequencies should fulfil the criteria that the average difference is greater than 0 dB and less than, or equal to, 3 dB, and the standard deviation of the differences is less than, or equal to, 4 dB.
- d) No addition of the average difference to the TEM waveguide readings should be made when determining compliance with the disturbance limit. If the criteria of step 3 are satisfied, the EUT type is considered to be compliant with the appropriate limit.

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

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

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

$$E|_{\text{dB}} = E_{\max}|_{\text{dB}} - 20 \cdot \lg(c_f) - 120, \text{ in dB}(\mu\text{V/m}) \quad (\text{A.19b})$$

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

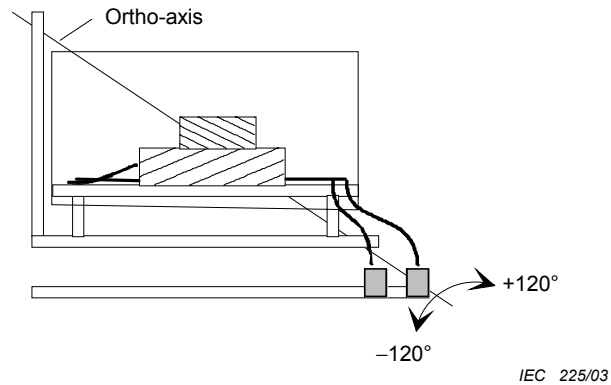


Figure A.1a – Side view

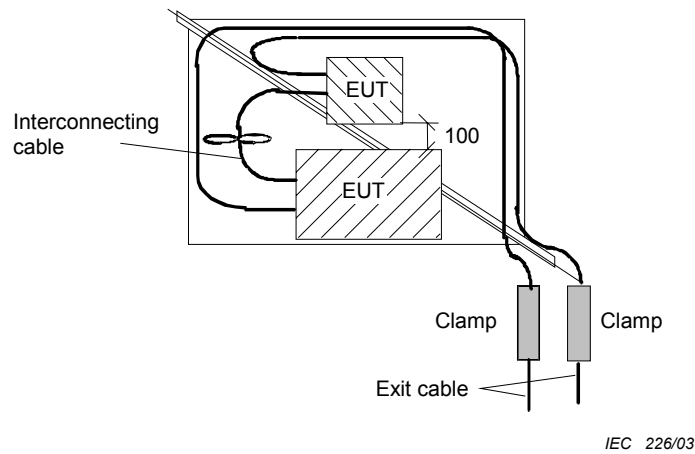


Figure A.1b – Top view

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

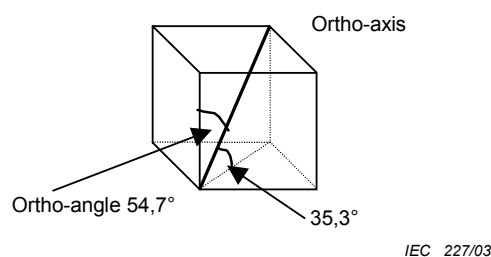


Figure A.2a – The ortho-axis and the ortho-angle

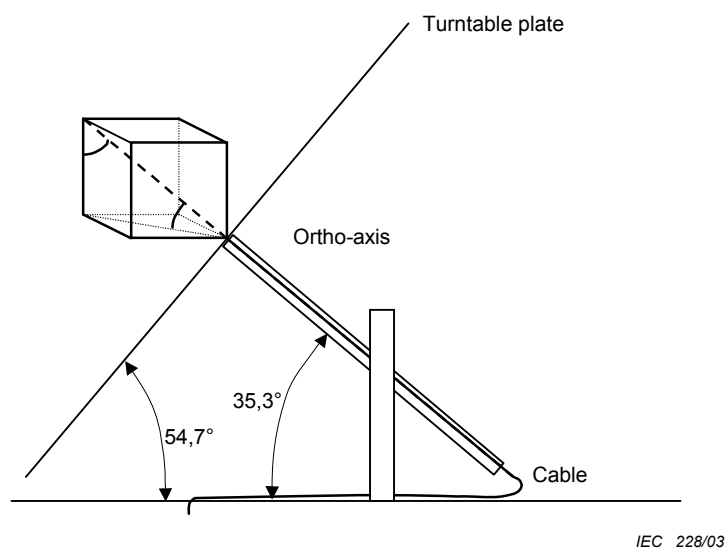


Figure A.2b – Side view (see 3.1.21 and A.5.2)

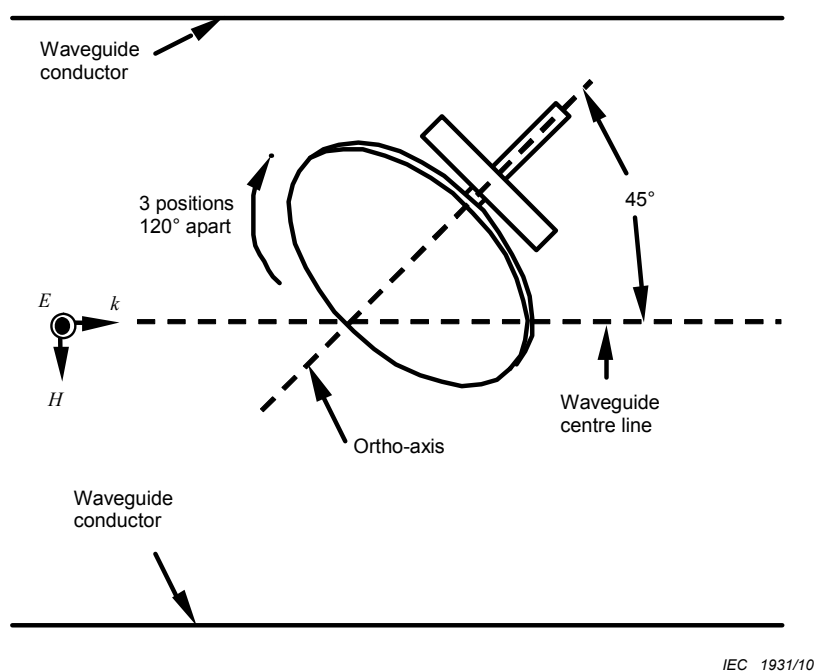
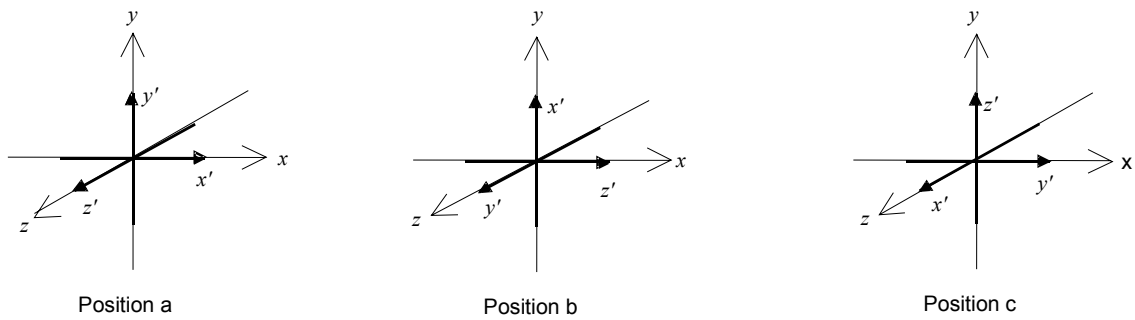


Figure A.2c – Top view (see 3.1.21 and A.5.2)

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.

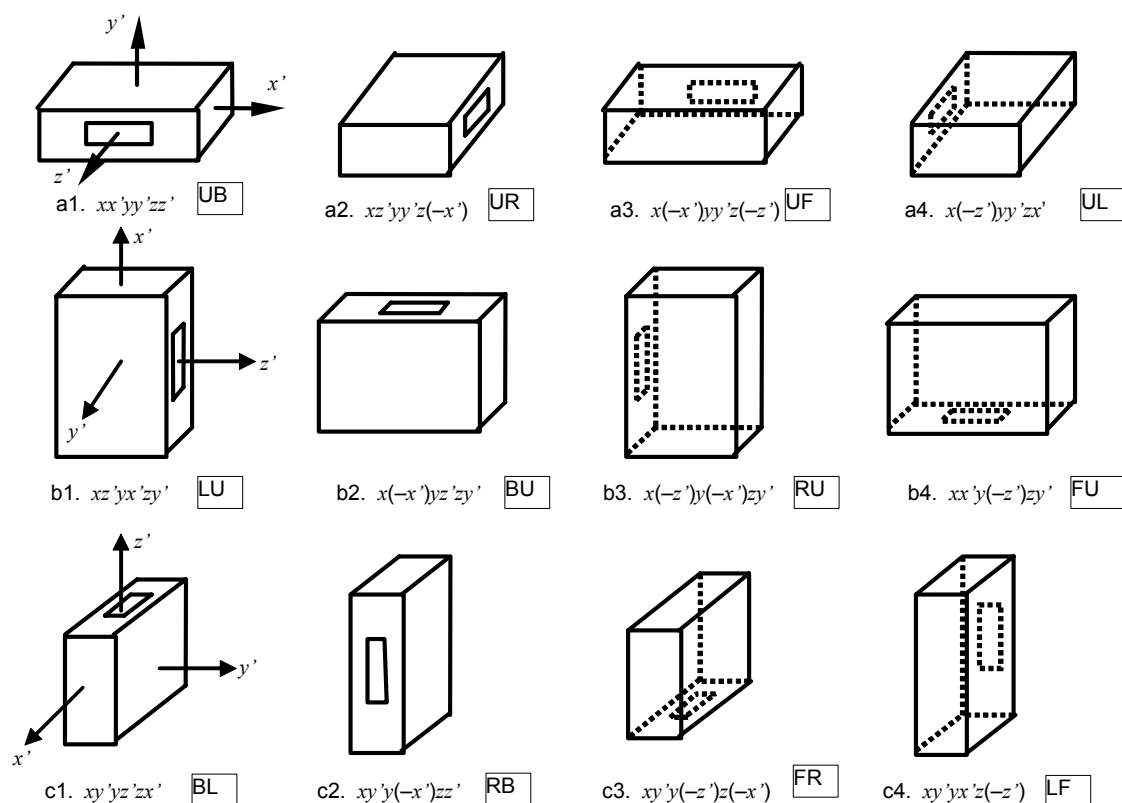
Figure A.2 – Basic ortho-axis positioner or manipulator



IEC 1932/10

NOTE These three orthogonal axis rotation positions correspond to orientations a1, b1, and c1 in Figure A.4. TEM waveguide coordinate axes x , y , z use symbols without prime marks, while the EUT coordinate axes x' , y' , z' use prime mark notation.

Figure A.3 – Three orthogonal axis-rotation positions for emission measurements



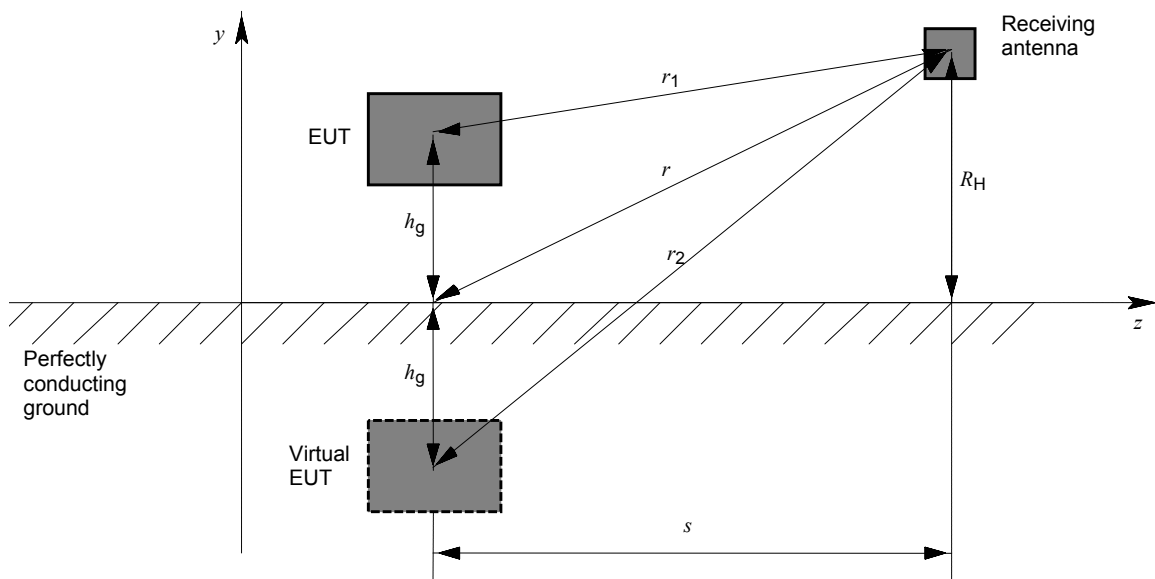
IEC 1933/10

NOTE 1 In this example, 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) centre of the EUT should remain at the same position relative to TEM waveguide conductors.

NOTE 2 The sides of the EUT are defined by orientation a1 with $x' = x, y' = y, z' = z$: Left (L) = Right (R) $\equiv y'z' = yz$ plane, Back (B) = Front (F) $\equiv x'y' = xy$ plane, Top (T) = Underside (U) $\equiv x'z' = xz$ plane. The propagation direction is aligned with the z -axis. Therefore, the wave front in a1 is the back side. Each orientation of the EUT can be described by two letters: the first letter designates the side of the EUT facing the TEM waveguide floor, and the second letter designates the side facing the wave front (towards the propagation direction).

NOTE 3 Each column of this figure/matrix (for example, a3, b3, c3) shows 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 a1, a2, a3, a4, and b1, c2, b3, c4. When all 12 orientations are needed in an immunity test, add orientations c1, b2, c3, b4, where c3 and b4 would typically be rotated around the z -axis by 180° . In this case c3 with $xy'y(-z')z(-x')$ becomes $x(-y')yz'z(-x')$, and b4 with $xx'y(-z')zy'$ becomes $x(-x')yz'zy'$.

Figure A.4 – Twelve-face (surface) and axis orientations for a typical EUT



IEC 1934/10

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

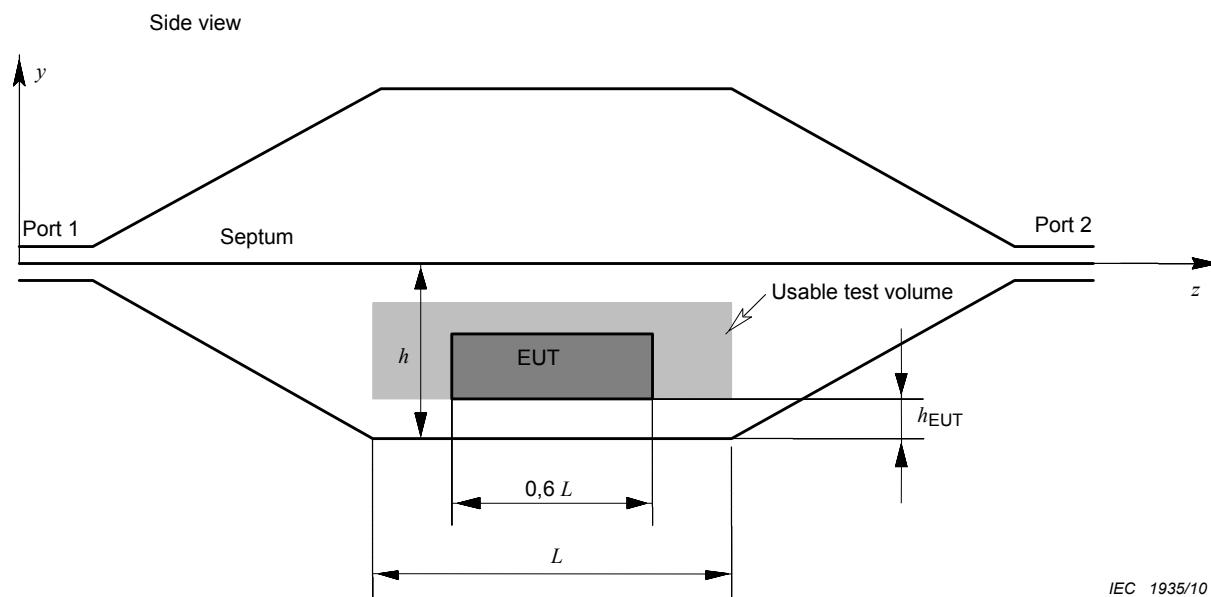


Figure A.6a – Side view

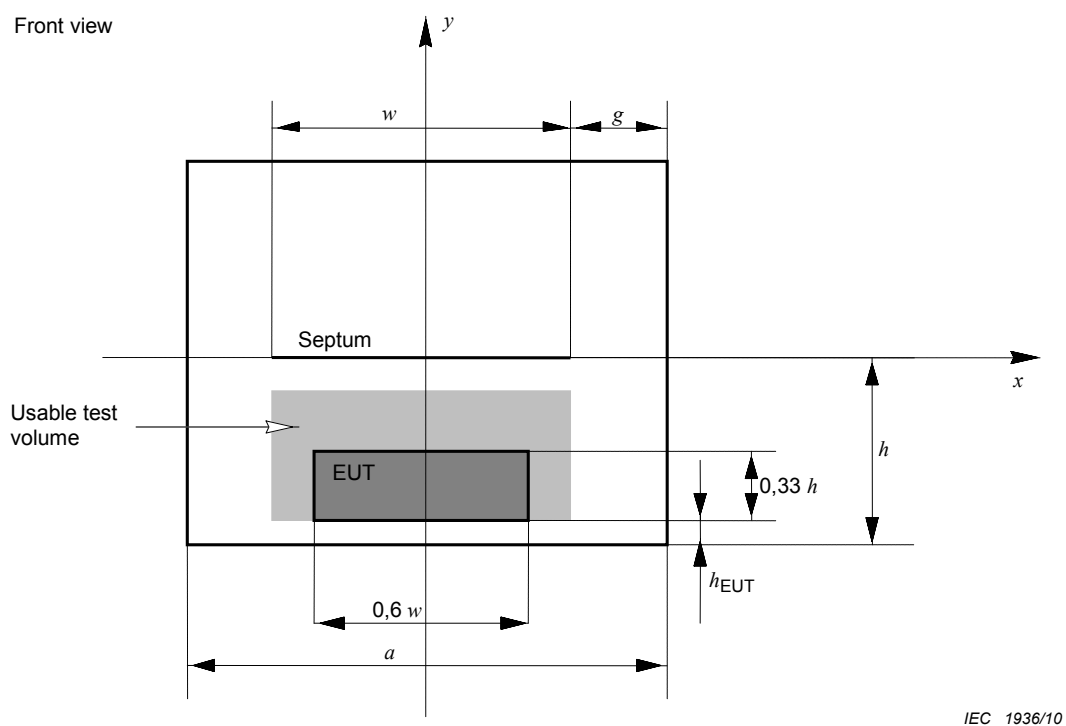
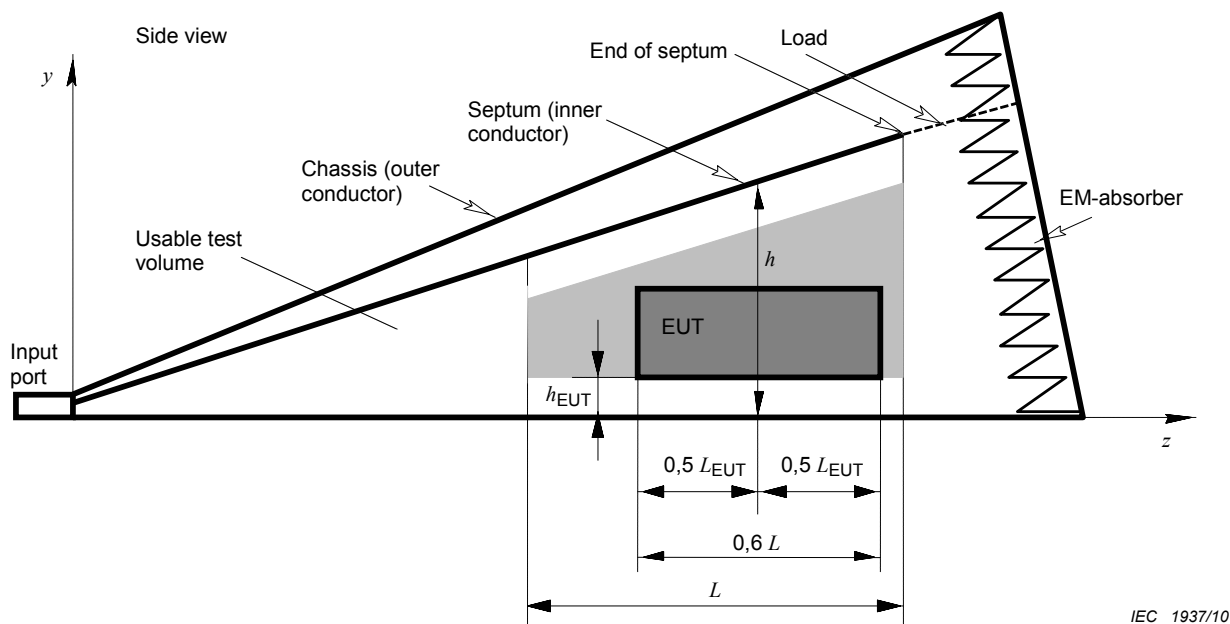


Figure A.6b – Cross-section view

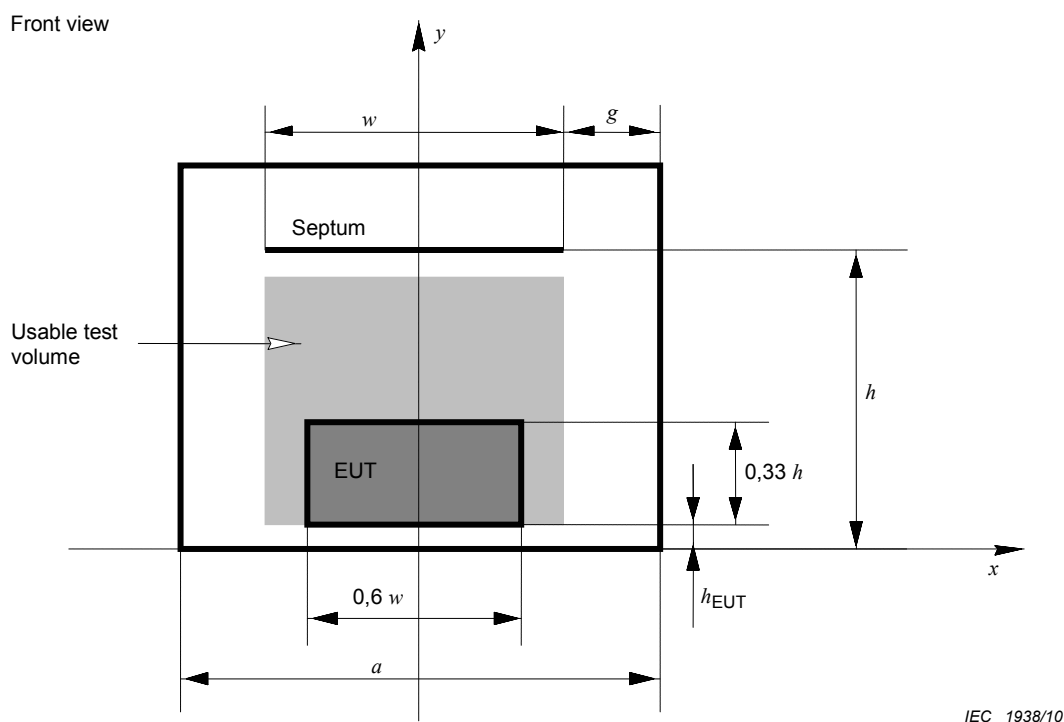
NOTE h_{EUT} is the minimum distance between the EUT and each conductor or absorber of the waveguide

Figure A.6 – Two-port TEM cell (symmetric septum)



IEC 1937/10

Figure A.7a – Side view

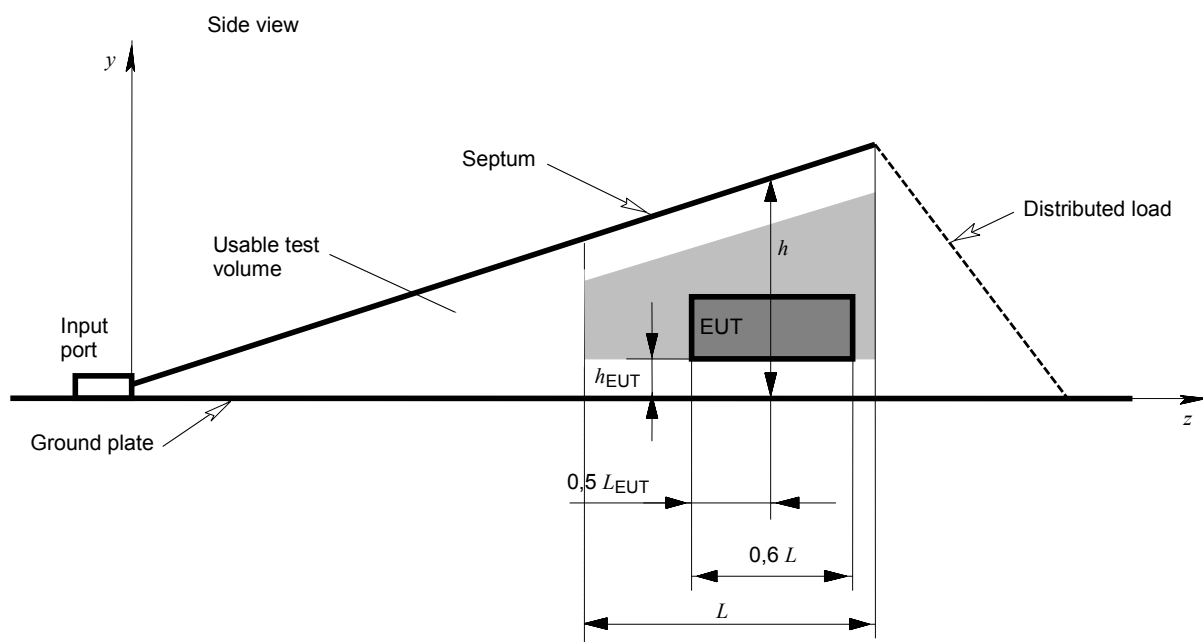


IEC 1938/10

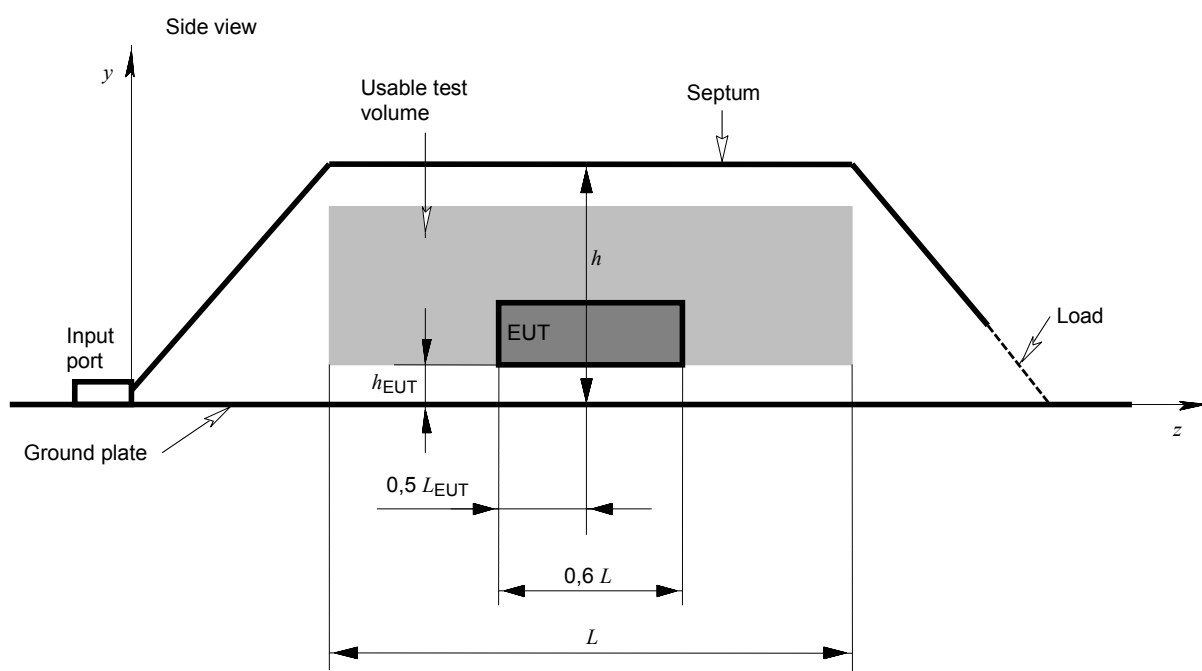
Figure A.7b – Cross-section view

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

Figure A.7 – One-port TEM cell (asymmetric septum)



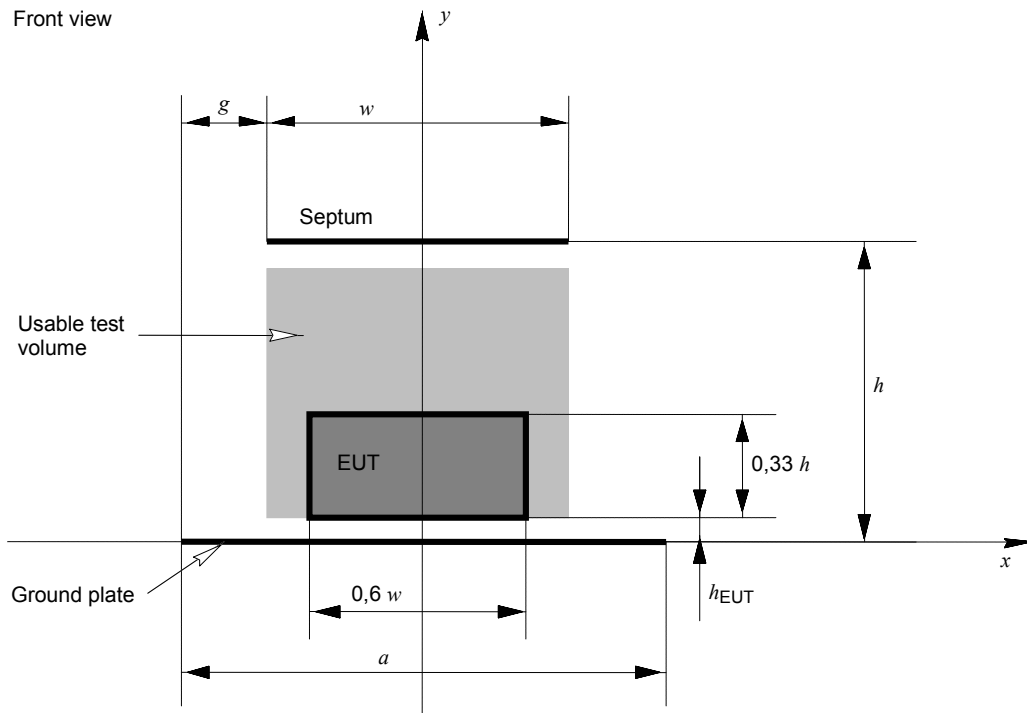
IEC 1939/10

Figure A.8a – Side view (one-port)

IEC 1940/10

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 A.8b – Side view (basically similar to a two-port TEM waveguide, but some versions have a distributed load at the output port)

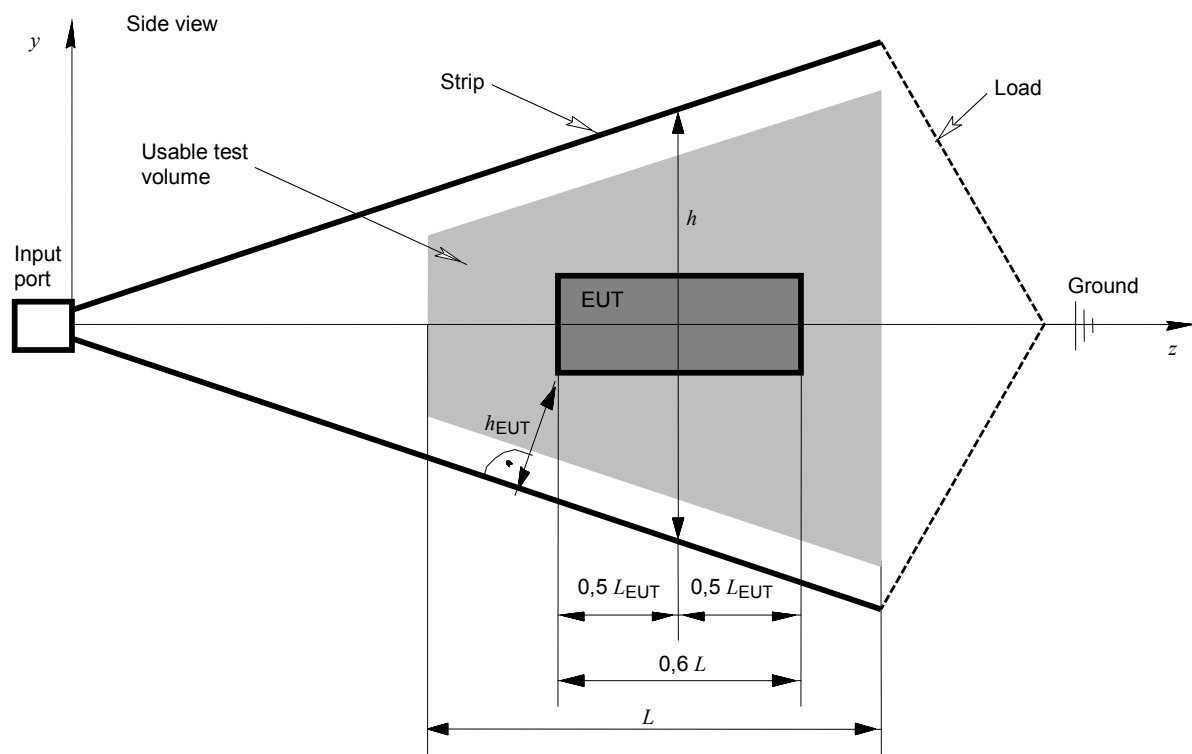


IEC 1941/10

Figure A.8c – Cross-section view

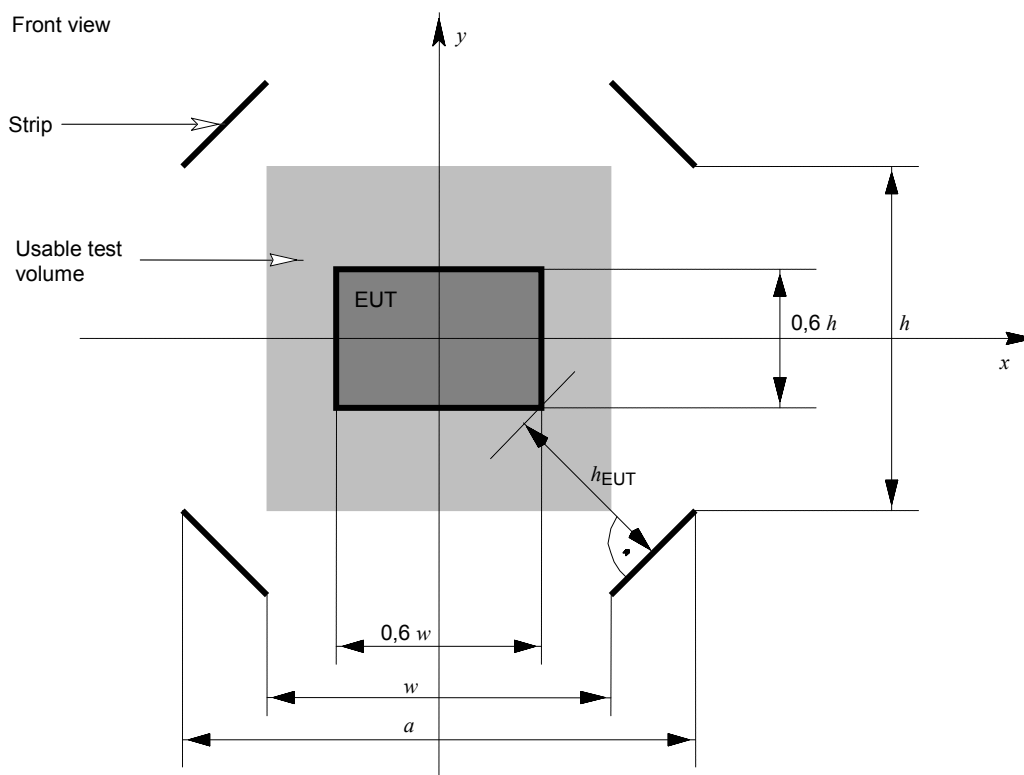
NOTE h_{EUT} is the minimum distance between the EUT and each conductor or absorber of the waveguide

Figure A.8 – Stripline (two plates)



IEC 1942/10

Figure A.9a – Side view



IEC 1943/10

Figure A.9b – 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 A.9 – Stripline (four plates, balanced feeding)

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.2.3 Validation of field uniformity

According to NOTE 2 and NOTE 3 of 5.2.3.1, the validation is carried out for a rectangular plane and at least 5 measurement points (4 at the corners and one at the centre). The uniformity is given if Equation (5) with the standard deviation according to Equation (6) is fulfilled for

- a) 75 % of the measured field strength E_i which are the magnitude of the primary electric field component over the defined area shall fulfil the following equation:

$$E_{\text{Limit}} \leq E_i \leq E_{\text{Limit}} + 2 \cdot K \cdot \sigma_E^-$$

NOTE 1 E_{Limit} is the limit given from the standard.

NOTE 2 According to Table 1 from 5.2.3 K is chosen to 1,15 for 75 %.

NOTE 3 If $2 \cdot K \cdot \sigma_E^-$ must be smaller than 6 dB, the standard deviation is calculated following Equation (6) from 5.2.3 as follows:

$$\begin{matrix} 0 \\ +6 \end{matrix} \Rightarrow \sigma_E^- \leq \frac{6}{2 \cdot 1,15} \leq 2,61 \quad \text{in dB}$$

NOTE 4 If the 75 % interval is set to 10 dB, the acceptable standard deviation is

$$\begin{matrix} 0 \\ +10 \end{matrix} \Rightarrow \sigma_E^- \leq \frac{10}{2 \cdot 1,15} \leq 4,34 \quad \text{in dB}$$

- b) the magnitudes of both secondary (unintended) electric field components are at least 6 dB less than the primary component. A given percentage of these measured relations have to fulfil the equation:

$$\frac{E_{\text{sec}_i}}{E_{\text{pri}_i}} \leq \left(\frac{E_{\text{sec}}}{E_{\text{pri}}} \right)_{\text{dB}} + K \cdot \sigma_{\frac{E_{\text{sec}}}{E_{\text{pri}}}} \leq \begin{cases} -6\text{dB} \\ -8\text{dB} \end{cases}$$

with K chosen according to Table 1 from 5.2.3.

The standard deviation for the set of measurements $\frac{E_{\text{sec}_i}}{E_{\text{pri}_i}}$ must fulfil the following equation:

$$\sigma_{\frac{E_{\text{sec}}}{E_{\text{pri}}}} \leq \frac{1}{K} \left(\begin{matrix} -6\text{dB} \\ -2\text{dB} \end{matrix} - \left(\frac{E_{\text{sec}}}{E_{\text{pri}}} \right)_{\text{dB}} \right)$$

A primary electric field component tolerance (see Equation (7) from 5.2.3) greater than $\begin{matrix} -0 \\ +6 \end{matrix}$ dB up to $\begin{matrix} -0 \\ +10 \end{matrix}$ dB, or a secondary electric field component level up to –2 dB of the primary field component, is allowed for a maximum percentage of test frequencies as defined in 5.2.1, provided that the actual tolerance and frequencies are stated in the test report.

NOTE 5 Following Equation (7) from 5.2.3 the standard deviations are calculated to

$$\begin{matrix} 0 \\ +6 \end{matrix} \Rightarrow \sigma_E^- \leq \frac{6}{2 \cdot 1,15} = 2,61 \quad \text{and} \quad \begin{matrix} 0 \\ +10 \end{matrix} \Rightarrow \sigma_E^- \leq \frac{10}{2 \cdot 1,15} = 4,34 \quad \text{in dB}$$

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

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).

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 5.2.1. 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 5.2.1 are fulfilled. Further information about field homogeneity is given in [17].

B.2.4 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.2.5 Harmonics

Some TEM waveguides may have resonances at frequencies higher than the recommended upper useful frequency.

NOTE ISO 11452-3 requires the installation of a low-pass filter of at least 60 dB at frequencies above 1,5 times the cut-off frequency of the TEM waveguide.

B.3 Test set-up

B.3.1 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 3.1.16) or

manipulator (see 3.1.21) 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.3.2 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.3.3 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.5.2). 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.4 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 A.9) 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.5 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.

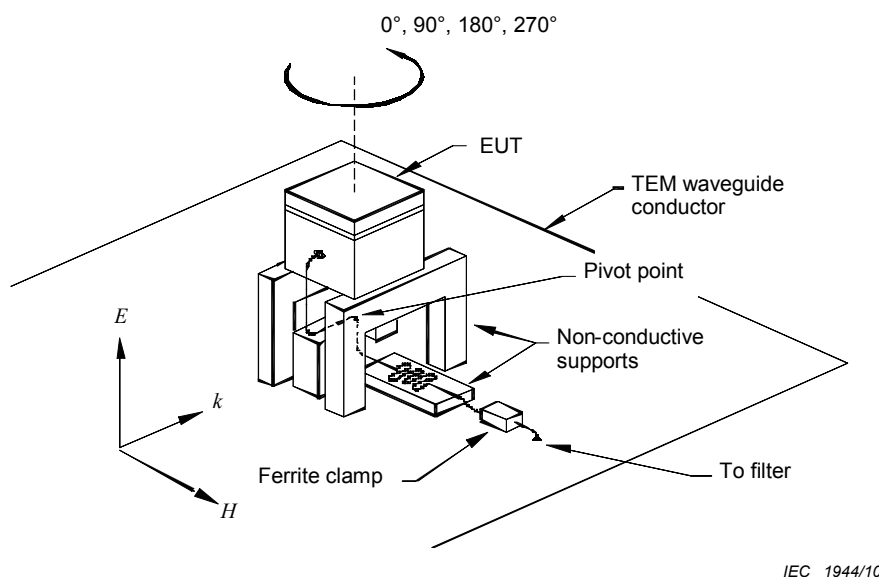


Figure B.1a – Vertical polarization

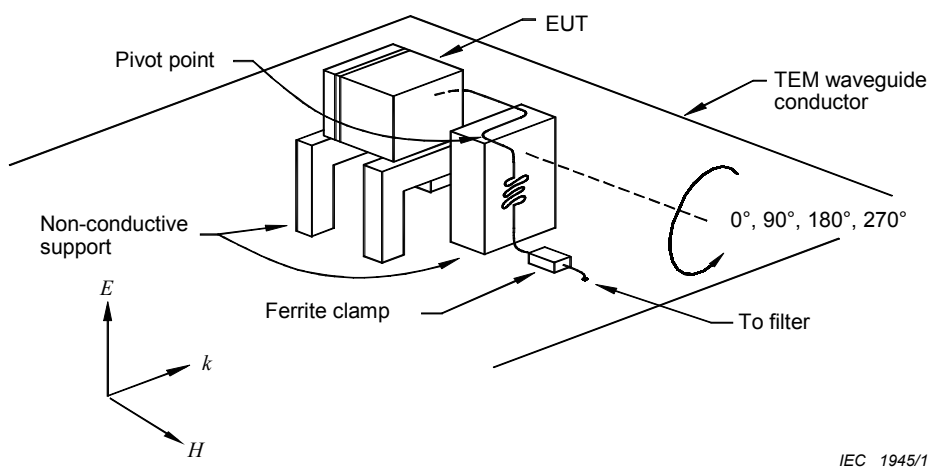


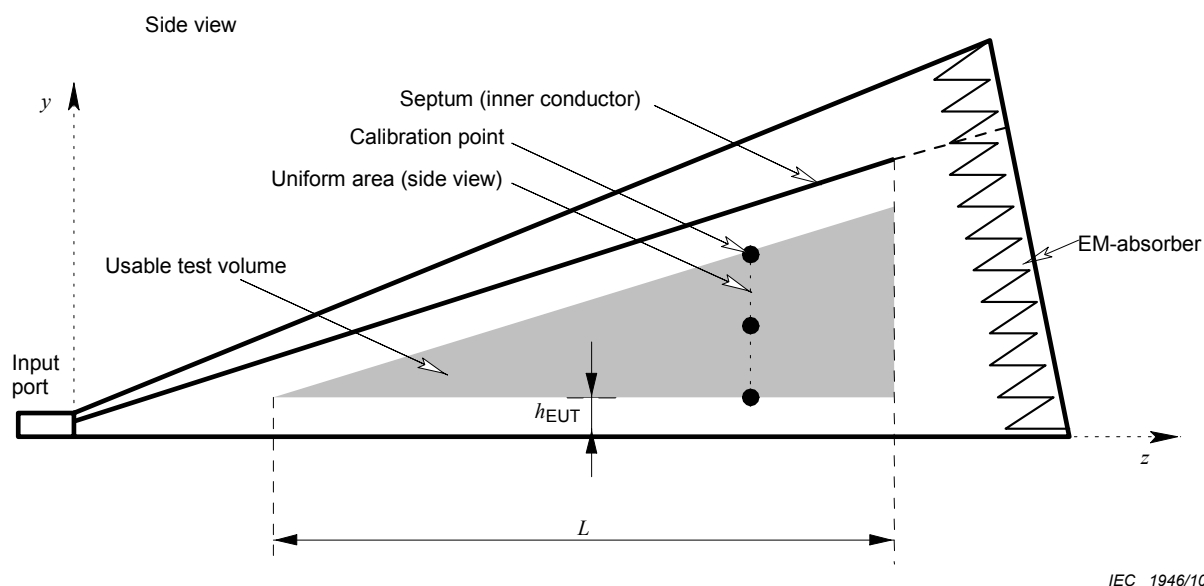
Figure B.1b – Horizontal polarization

Key

- E Primary electric field component
- H Magnetic field
- k Propagation direction (wave vector)

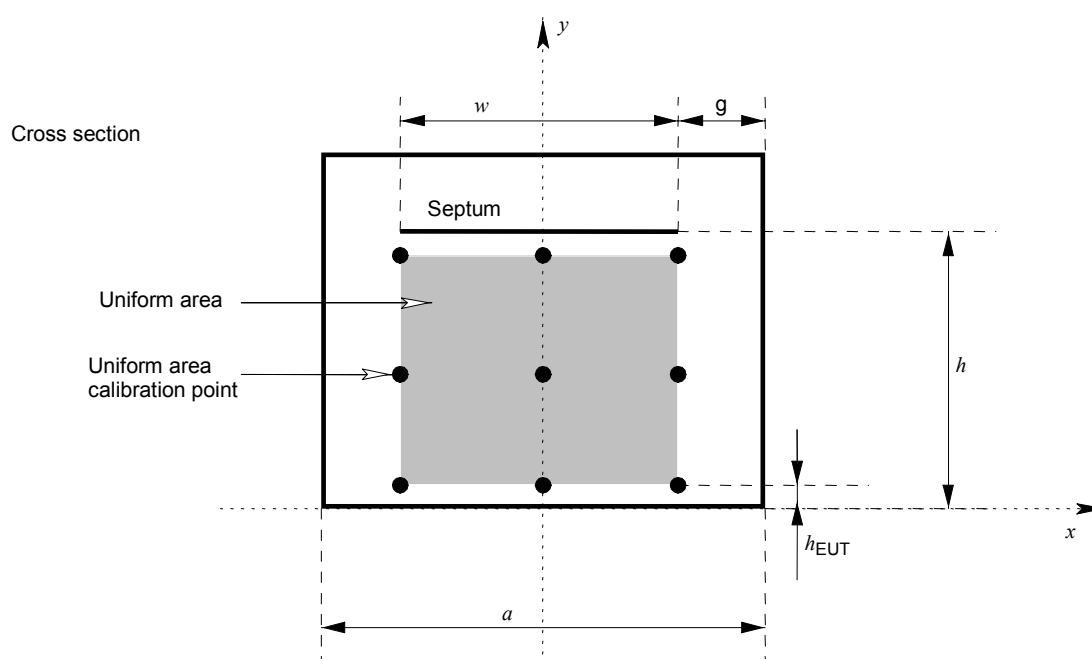
The cable layout on the filter side of the pivot point shall remain stationary. The test set-up supports (3.1.16) may be repositioned as necessary during rotations. The test set-up supports should be 0,1 m thick. Multiple-unit EUTs shall be affixed to a test set-up support or an equivalent platform and rotated in the same manner. Manipulators and rotatable (see [6]) or multiple-polarization TEM waveguides (Figure A.9) 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



IEC 1946/10

Figure B.2a – Side view



IEC 1947/10

Figure B.2b – Cross-section view

NOTE Example for a uniform area with 3×3 calibration points in a GTEM cell according to B.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 5.2.2 and Figures A.6 to A.9).

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