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**Road vehicles — Vehicle test methods  
for electrical disturbances from  
narrowband radiated electromagnetic  
energy —**

**Part 5:  
Reverberation chamber**

*Véhicules routiers — Méthodes d'essai d'un véhicule soumis  
à des perturbations électriques par rayonnement d'énergie  
électromagnétique en bande étroite —*

*Partie 5: Chambre réverbérante*

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## Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see [www.iso.org/directives](http://www.iso.org/directives)).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see [www.iso.org/patents](http://www.iso.org/patents)).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see [www.iso.org/iso/foreword.html](http://www.iso.org/iso/foreword.html).

This document was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 32, *Electrical and electronic components and general system aspects*.

A list of all parts in the ISO 11451 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at [www.iso.org/members.html](http://www.iso.org/members.html).

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# Road vehicles — Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy —

## Part 5: Reverberation chamber

### 1 Scope

This document specifies methods for testing the immunity of passenger cars and commercial vehicles to electromagnetic disturbances, regardless of the vehicle propulsion system (e.g. spark ignition engine, diesel engine, electric motor) using a reverberation chamber.

The electromagnetic disturbances considered are limited to narrowband electromagnetic fields.

While this document refers specifically to passenger cars and commercial vehicles, generalized as “vehicle(s)”, it can readily be applied to other types of vehicles.

ISO 11451-1 specifies general test conditions, definitions, practical use, and basic principles of the test procedure.

Function performance status classification guidelines for immunity to electromagnetic radiation from an off-vehicle radiation source are given in [Annex A](#).

### 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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.

ISO 11451-1:2015, *Road vehicles — Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy — Part 1: General principles and terminology*

IEC 61000-4-21, *Electromagnetic compatibility (EMC) – Part 4-21: Testing and measurement techniques – Reverberation chamber test methods*

### 3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11451-1 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

**3.1**  
**mean absorption cross section**  
**ACS**

$$A_{acs} = \langle \sigma_a \rangle_{\Omega} = \frac{1}{8\pi} \iint_{4\pi} (\sigma_{a,TE} + \sigma_{a,TM}) d\Omega$$

where

- $\sigma_a$  is the absorption cross section for incident waves from a spatial direction averaged over TE and TM waves;
- $\sigma_{a,TE}$  is the absorption cross section for incident TE waves from a spatial direction;
- $\sigma_{a,TM}$  is the absorption cross section for incident TM waves from a spatial direction;
- $\Omega$  is the solid angle which is  $4\pi$  for the full sphere (i.e. waves from all angles).

Note 1 to entry: It is the measure for the ability of a vehicle to absorb energy in a *reverberation chamber* (3.16). It gives the cross section area of an equivalent ideal absorber without any reflections or scattering, which absorbs the same energy as the vehicle in the reverberation chamber. In contrast to the *chamber loading factor (CLF)* (3.5), the ACS is a property of the vehicle only and is the same for all reverberation chambers. Therefore, it allows determination of the necessary extra power to compensate the loading effects by the vehicle without a loading factor measurement or a new chamber characterization with vehicle.

Note 2 to entry: See [Annexes H](#) and [L](#).

Note 3 to entry: See Reference [19].

**3.2**  
**antenna characterization factor**  
**ACF**

ratio of the average received power to forward power obtained in the antenna characterization of the empty chamber characterization

Note 1 to entry: See [8.5.2](#).

**3.3**  
**cavity mode method**

method adopting chamber modes to generate the required field strength with less power for the frequency between *TLS method* (3.22) and the *lowest usable frequency (LUF)* (3.11), typically (30-80) MHz, where the chamber has a lower mode density

Note 1 to entry: See [Annex F](#).

**3.4**  
**chamber characterization factor**  
**CCF**

normalized average received power with the vehicle present

Note 1 to entry: See [8.5.2](#).

**3.5**  
**chamber loading factor**  
**CLF**

ratio of the *antenna characterization factor* (3.2) to the *chamber characterization factor* (3.4)

Note 1 to entry: See [8.5.2](#).

Note 2 to entry: It is a measure for the additional loading of the chamber due to the test setup including, for example, the vehicle and the *support equipment* (3.21).

**3.6****chamber time constant**

mean time decay of the received power delay profile in a *reverberation chamber* (3.16)

Note 1 to entry: See [Annexes H](#) and [L](#).

**3.7****charging mode**

mode of operation intended for charging the rechargeable energy storage system (storage system that provides electric energy for electric propulsion which can be recharged)

**3.7.1****charging mode 1**

*charging mode* (3.7) where the vehicle is connected to a standard socket-outlet of an AC supply network, utilizing a cable and plug, both of which are not fitted with any supplementary pilot or auxiliary contacts

Note 1 to entry: In some countries, mode 1 charging can be prohibited or requires special precautions.

Note 2 to entry: Charging mode 1 is defined in IEC 61851-1:2017,6.2.1.

**3.7.2****charging mode 2**

*charging mode* (3.7) where the vehicle is connected to AC mains using a charging cable, which has an *EV supply equipment (EVSE)* (3.10) box in-line (e.g. in-cable control box / in-cable control and protection device), providing control pilot signalling between the vehicle and the EVSE box and personal protection against electric shock

Note 1 to entry: In some countries, special restrictions are applied for mode 2 charging.

Note 2 to entry: There is no communication with the vehicle.

Note 3 to entry: Charging mode 2 is defined in IEC 61851-1:2017,6.2.2.

**3.7.3****charging mode 3**

*charging mode* (3.7) where the vehicle is connected to a fixed installation [*EV supply equipment (EVSE)* (3.10), e.g. AC charging station, AC wallbox] providing AC power to the vehicle, with communication between the vehicle and the EVSE (through signal/control lines and/or through wired network lines)

Note 1 to entry: Charging mode 3 is defined in IEC 61851-1:2017,6.2.3.

**3.7.4****charging mode 4**

*charging mode* (3.7) where the vehicle is connected to a fixed installation [*EV supply equipment (EVSE)* (3.10), e.g. DC charging station], providing DC power to the vehicle (with an off-board charger), with communication between the vehicle and the EVSE (through signal/control lines and/or through wired network lines)

Note 1 to entry: Charging mode 4 is defined in IEC 61851-1:2017,6.2.4.

**3.8****coherence time of the reverberation chamber**

time interval between two independent *stirring configurations* (3.19) in *stirred mode* (3.18)

Note 1 to entry: The field in the *reverberation chamber* (3.16) conserves its statistical properties [e.g. the positions of the field maxima and minima in the *working volume* (3.27)] during the coherence time.

### 3.9

#### **CDF**

cumulative distribution function

probability that the electromagnetic field strength is less or equal to a specific value

Note 1 to entry: A value of this function can be used as levelling target (e.g. 100 V/m at CDF 0,2 means 20 % of the measured electric field strength values are less or equal to 100 V/m and 80 % are higher than 100 V/m).

### 3.10

#### **EVSE**

EV supply equipment

equipment or a combination of equipment, providing dedicated functions to supply electric energy from a fixed electrical installation or supply network to an EV for the purpose of charging

### 3.11

#### **lowest usable frequency**

#### **LUF**

lowest frequency for which the field uniformity requirements are met for the *reverb method* (3.17) and at least 12 independent *stirring configurations* (3.19) can be achieved

Note 1 to entry: The LUF is determined in accordance with C.6.

### 3.12

#### **maximum chamber loading factor**

#### **MLF**

figure of merit corresponding to the worst case loading configuration for which the field uniformity has been demonstrated

Note 1 to entry: See 8.5.2.

### 3.13

#### **periodization**

method to define an analysis time window for the calculation of autocorrelation coefficients based on the complete period of a periodic stirring process sequence

### 3.14

#### **power delay profile**

#### **PDP**

temporal behaviour of the power decay in a *reverberation chamber* (3.16) after switch-off of the power source

### 3.15

#### **quasi-tuned mode**

operating mode of a *reverberation chamber* (3.16) where the response time of the DUT to the external field is shorter than the *coherence time of the reverberation chamber* (3.8)

Note 1 to entry: See D.3.1.

### 3.16

#### **reverberation chamber**

high Q shielded room (cavity) whose boundary conditions are changed via one or several rotating tuners or moving walls (including *vibrating intrinsic reverberation chambers (VIRCs)* (3.28) with or without conductive contact to the floor) or repositioning of the transmitting antenna(s)

Note 1 to entry: This results in a statistically uniform electromagnetic field.

### 3.17

#### **reverb method**

usage of a *reverberation chamber* (3.16) above the *lowest usable frequency (LUF)* (3.11)

**3.18****stirred mode**

operating mode of a *reverberation chamber* (3.16) where a *tuner* (3.25) or a *vibrating intrinsic reverberation chamber (VIRC)* (3.28) shaker is moved continuously while the test is running

**3.19****stirring configuration**

unique set of conditions that defines the RF environment

Note 1 to entry: It can stand for a single *tuner* (3.25) in a fixed position as in classical *reverberation chambers* (3.16). In addition, it can stand for a position of a *vibrating intrinsic reverberation chamber (VIRC)* (3.28) at a point in time, for a momentary frequency in case of frequency stirring, or a transmitting antenna configuration.

**3.20****stirring scheme**

operating mode of a *reverberation chamber* (3.16) that is a *stirred mode* (3.18) or a *tuned mode* (3.24) or a combination thereof

**3.21****support equipment**

equipment associated with performing an EMC test on a vehicle including (but not all inclusive) load simulator, charging cables, AMN(s), HV-AN(s), AAN(s), DUT monitoring equipment including fibre optic interface modules and TV camera

**3.22****TLS method**

method using a TLS (similar as in ISO 11451-2) inside a *reverberation chamber* (3.16) and which extends the usage beyond TEM-waveguide testing up to the *lowest usable frequency (LUF)* (3.11) of the reverberation chamber

Note 1 to entry: See [Annex E](#).

**3.23****total antenna efficiency**

ratio of radiated power to forward power at antenna port, it is less than 1 or 100 % due to mismatching and losses of the antenna (e.g. ohmic loss of metallic material and dielectric loss of insulation)

Note 1 to entry: See [Annex J](#).

**3.24****tuned mode**

operating mode of a *reverberation chamber* (3.16) where the *tuner* (3.25) is moved stepwise to fixed positions and the test is repeated successively at each of those fixed tuner positions

**3.25****tuner**

large metallic reflector capable of changing the electromagnetic boundary conditions in a *reverberation chamber* (3.16) as it rotates or moves

Note 1 to entry: As the tuner moves, the nulls and maximums in the field change location, ensuring the vehicle is exposed to a statistically uniform field.

**3.26****windowing**

method to define an analysis time window for the calculation of autocorrelation coefficients based on a part of a stirring process sequence

**3.27****working volume**

volume within the *reverberation chamber* (3.16) that contains the vehicle, the *support equipment* (3.21), and the receiving antenna, if used

### 3.28

#### VIRC

vibrating intrinsic reverberation chamber

tent-like structure formed by conductive fabrics where movements of the walls are excited, e.g. by moving arms which push and pull corners or edges of the tent

## 4 Test conditions

The applicable frequency range for the reverb method is LUF to 18 000 MHz. Testing over the full frequency range could require different field-generating devices, but this does not imply that testing of overlapping frequency ranges is required.

NOTE The applicable frequency range is 0,01 MHz to LUF for the TLS method (see [Annex E](#)), 30 MHz to LUF for the cavity mode method (see [Annex F](#)), and LUF to 18 000 MHz for the other reverb methods (see [Annexes G, H and I](#)).

The user shall specify the test severity level or levels over the frequency range. Suggested test severity levels are given in [Annex A](#).

Standard test conditions are given in ISO 11451-1 for the following:

- test temperature;
- supply voltage;
- modulation;
- dwell time;
- frequency step sizes;
- definition of test severity levels;
- test signal quality.

## 5 Test location

### 5.1 Reverberation chamber description

The test shall be performed in a reverberation chamber.

The aim of using a reverberation chamber is to create statistically homogeneous and isotropic electromagnetic fields within the working volume.

These conditions are not valid close to the ground floor in the working volume (see [5.2](#)).

A reverberation chamber for vehicle testing consists of a shielded enclosure, one or several field generating devices, and some mechanical apparatus to change the boundary conditions for the electromagnetic fields. This mechanical apparatus may, for example, contain one or several rotating tuners or moving walls, or may even be realized by using conductive fabrics as shielded enclosure (e.g. a VIRC).

The chamber may contain a vehicle dynamometer, a turntable or both.

It may also contain a TLS (see [Annex E](#)) or other type of field generators (e.g. tunable monopoles, see [Annex F](#)) as field generating device for testing from 0,01 MHz to the LUF.

The chamber may also contain one or several receiving antennas and one or more field probes.

The size, shape and construction of the reverberation chamber can vary considerably. The minimum size of the shielded enclosure is determined by the size of the test region needed, the size of the

field generation device or devices, the size and shape and location of the tuner or tuners, the needed clearances between all these and the largest vehicle to be tested, and the intended LUF of the chamber. An example of a rectangular reverberation chamber with one mechanical tuner and one field generating antenna is shown in [Figure 1](#).

After initial construction, the reverberation chamber shall be characterized in accordance with the test methods intended to be used. For the reverb method, the chamber shall fulfil the field uniformity requirements of [Table C.2](#). The LUF of the reverberation chamber is determined during this initial characterization. Following any major modifications, a new chamber characterization shall be carried out again. Changes to the tuners shall be considered a major modification.

## 5.2 Working volume

The working volume is the volume that contains the vehicle, any support equipment and the receiving antenna, if used. The form of the working volume shall be a cuboid.

The minimum distance between the working volume and the walls and ceiling of the shielded enclosure or any tuner or any transmitting antenna shall be at least  $\lambda/4$  at the lowest used frequency of the reverb method.

The working volume for testing vehicles starts directly on the ground plane in order to contain the full vehicle. Although this differs from the IEC 61000-4-21 working volume definition, for the purpose of chamber calibration, the reverb reference points described in IEC 61000-4-21 shall be used.

NOTE For the TLS method (see [Annex E](#)), and the cavity mode method (see [Annex F](#)), the  $\lambda/4$  minimum distance requirement does not apply.

More than one vehicle can be tested in one immunity test (e.g. testing of communication between vehicles). If the distance between the vehicles is closer than  $\lambda/4$  at the lowest tested frequency there could be significant interaction between the vehicles. This can be desirable for investigating proximity effects. If the distance between the vehicles is larger than  $\lambda/4$  at the lowest tested frequency there will be scattering between the vehicles similar to the scattering from walls, etc. Therefore, this test can be interpreted as the simultaneous independent test of multiple vehicles. In either case, the field homogeneity requirements shall still be fulfilled with multiple vehicles present and the loading shall be compensated appropriately as defined in the applicable test method.

## 6 Test instrumentation

### 6.1 General

Testing consists of generating radiated electromagnetic fields using antenna sets with radio frequency (RF) sources capable of producing the desired field strength over the range of test frequencies.

The following test instrumentation is used:

- field generating device(s): e.g. antenna(s);
- field probe(s);
- RF signal generator with internal or external modulation capability;
- high power amplifier(s);
- power meter (or equivalent measuring instrument) to measure forward power and reflected power;
- optional: receiving antenna(s) and spectrum analyser;
- optional: vector network analyser.

## 6.2 Field generating device

A transmitting antenna is used as the field generating device for the reverb method.

NOTE The TLS method (see [Annex E](#)) uses a TLS as a field generation device, and the cavity mode method (see [Annex F](#)) uses tunable monopoles.

Multiple antennas, amplifiers and directional couplers may be necessary to cover the complete frequency range.

The transmitting antenna(s) shall be linearly polarized antenna(s) capable of satisfying the frequency requirements. The antenna efficiency should be at least 75 % (log periodic and horn antennas typically fulfil this requirement). An example with a horn antenna is shown in [Figure 1](#).

## 6.3 Field probes

Field probes shall be capable of measuring electric field strength in three orthogonal axes. The communication lines from the probes shall be fibre optic links. The sampling rate, bandwidth and dynamic range of the probe shall be capable to measure accurately the field. This is especially important for fast stirred mode techniques.

At high frequencies, the radiation characteristics of the field probes will deviate from the ideal one, due to size relative to wavelength, symmetry and other properties. Above which frequency, this happens or if it is relevant in the frequency range of the probe, depends on the probe properties. For application in the reverberation chamber, the directivity and isotropy of the field probe itself does not matter, since for measuring the mean and maximum values, only the total radiation efficiency of the probe axis is important not the gain. [Annex K](#) describes a method, how to measure and compensate diffuse-field correction factors for field probes. If the properties of a field probe in the diffuse-field are not known, it is recommended to determine the diffuse-field correction factor according to [Annex K](#), and in case deviations are identified, to correct them.

## 6.4 Stimulation and monitoring of the device under test (DUT)

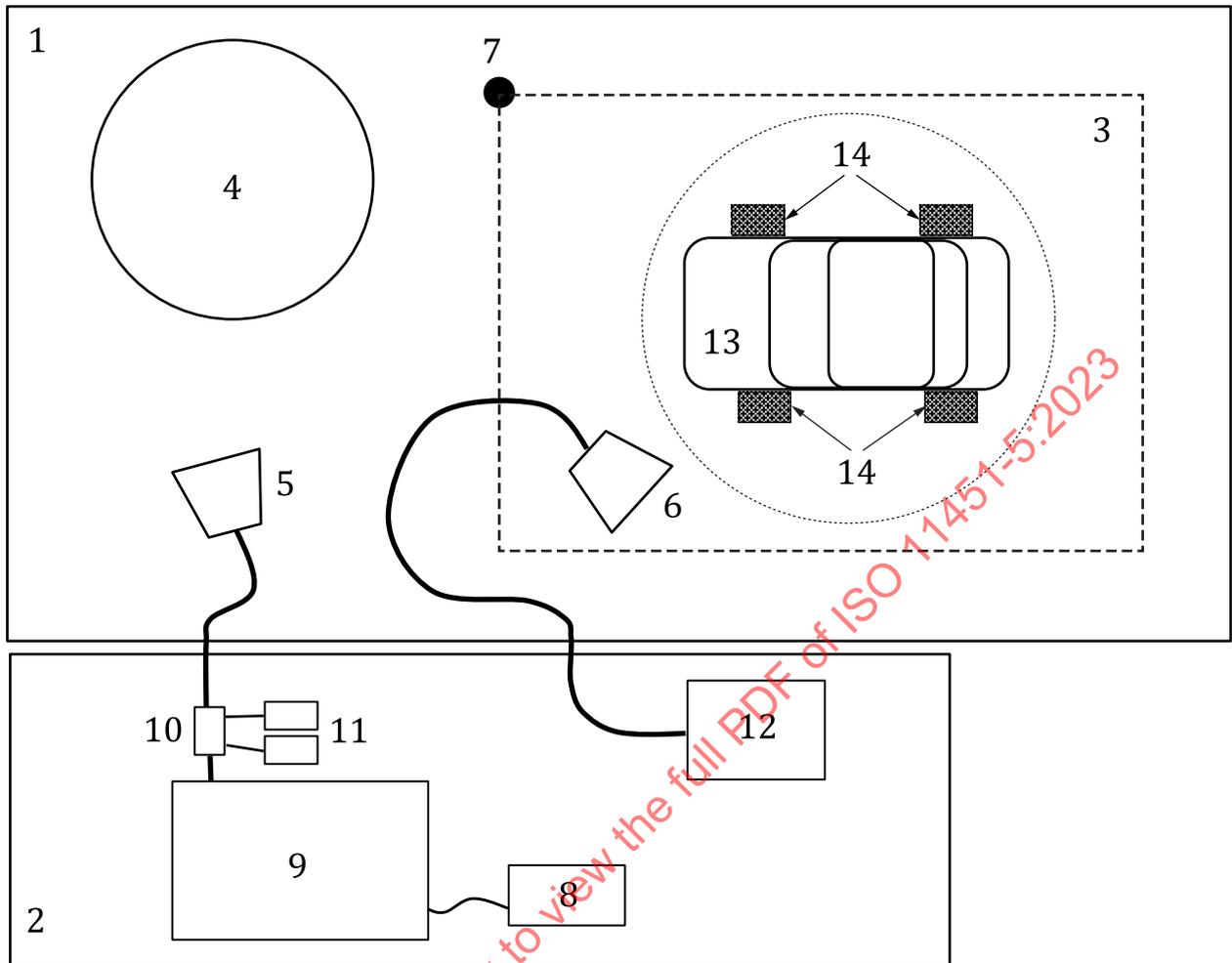
The vehicle shall be operated as required in the test plan by using actuators which have a minimum effect on the electromagnetic characteristics, e.g. plastic blocks on the push-buttons, pneumatic actuators with plastic tubes.

Connections to equipment monitoring electromagnetic interference reactions of the vehicle may be accomplished by using fibre-optics, or high resistance leads. Other type of leads may be used but require extreme care to minimize interactions. The orientation, length and location of such leads shall be carefully documented to ensure repeatability of test results.

Any electrical connection of monitoring equipment to the vehicle may cause malfunctions of the vehicle. Extreme care shall be taken to avoid such an effect.

## 6.5 Optional: receiving antenna(s) and spectrum analyser

For chamber characterization and test, receiving antenna(s) and a spectrum analyser may be used to measure the received power. This measurement may be used to determine the chamber loading factor due to the vehicle and the support equipment (see [8.5.2](#)).



### Key

1	reverberation chamber / VIRC	8	RF signal generator
2	amplifier / operator room	9	RF amplifier
3	working volume	10	directional coupler
4	tuner, if used	11	power meters
5	transmitting antenna	12	spectrum analyser, if used
6	receiving antenna, if used	13	vehicle
7	field probe(s), if used	14	dynamometer (with or without turn-table)

**Figure 1 — Example of a reverberation chamber**

## 6.6 Optional: vector network analyser

For the VNA method ([Annex I](#)) and measurement of the chamber time constant with the spectral method ([Annex L](#)), and of antenna efficiencies ([Annex I](#)), a vector network analyser shall be used.

## 7 Test set-up

Four test setups are described:

- one for all type of vehicles when they are not in charging mode,
- one for vehicles in charging mode 1 or mode 2 (AC powered, without communication),

- one for vehicles in charging mode 3 or mode 4 (AC or DC powered, with communication),
- one for vehicles in charging mode through wireless power transmission (WPT).

## 7.1 Vehicle placement

The vehicle shall be placed in the working volume. The working volume may contain a vehicle dynamometer or turntable or both (see [Figure 1](#)).

## 7.2 Field generating device location – Antenna constraints

The location of the transmitting antenna(s) shall be the same for both characterization and testing. The transmitting antenna shall not directly illuminate the working volume. The transmitting antenna should be directed into a corner of the chamber if possible (see [Figure 1](#) for location of a transmitting antenna as example). Directing the antenna into the tuner is also acceptable.

NOTE An upward tilt of the antenna is advisable to avoid direct incident wave illumination of the chamber wall resulting in a potentially high VSWR situation.

## 7.3 Vehicle test configurations

The configuration of [7.3.1](#) is applicable to all vehicle types (combustion engine, electric or hybrid propulsion).

The configuration of [7.3.2](#) is applicable only to the electric or hybrid / plugin propelled vehicles when they are in charging mode 1 or mode 2.

The configuration of [7.3.3](#) is applicable only to the electric or hybrid / plugin propelled vehicles when they are in charging mode 3 or mode 4.

The configuration of [7.3.4](#) is applicable only to the electric propelled vehicles when they are in charging mode through wireless power transmission (WPT).

### 7.3.1 Vehicle not connected to the power grid

An example of a test set-up is shown in [Figure 1](#).

### 7.3.2 Vehicle in charging mode 1 or mode 2 (AC powered, without communication)

#### 7.3.2.1 General

This configuration concerns only charging mode 1 and mode 2.

The vehicle, AMN(s) and power charging cable shall be placed in the working volume.

Examples of test set-ups are shown in [Figure 2](#) and [Figure 3](#).

#### 7.3.2.2 Power mains

The power mains socket may be placed anywhere in the test location (including the working volume) with the following conditions:

- the socket(s) shall be placed on the ground plane;
- the length of the cable between the power mains socket and the AMN(s) shall be kept as short as possible;
- the cable between the power mains socket and the AMN shall be placed directly on the ground plane.

Care shall be taken to avoid disturbances to the off-board peripheral equipment.

### 7.3.2.3 Artificial mains network

Power mains shall be applied to the vehicle through 50  $\mu$ H/50  $\Omega$  artificial mains networks (AMN(s)) as defined in ISO 11451-1:2015, Annex B.

The AMN(s) shall be mounted directly on the ground plane. The case of the AMN(s) shall be bonded to the ground plane.

The measuring port of each AMN shall be terminated with a 50  $\Omega$  load.

### 7.3.2.4 Power charging cable

The power charging cable shall be laid out in a straight line between the AMN(s) and the vehicle charging inlet and shall be routed perpendicularly to the vehicle's longitudinal axis (see [Figure 2](#) and [Figure 3](#)). The projected cable length from the side of the AMN(s) to the side of the vehicle shall be (800 (+200 / -0)) mm as shown in [Figure 2](#) and [Figure 3](#).

For a longer cable, the extraneous length shall be "Z-folded" symmetrically. No contact or overlap is allowed between windings. The width of the Z-folded cable shall be between 500 mm and 1 000 mm. If it is impractical to do so because of cable bulk or stiffness, or because the testing is being done at a user's installation, the disposition of the excess cable length shall be precisely noted in the test report.

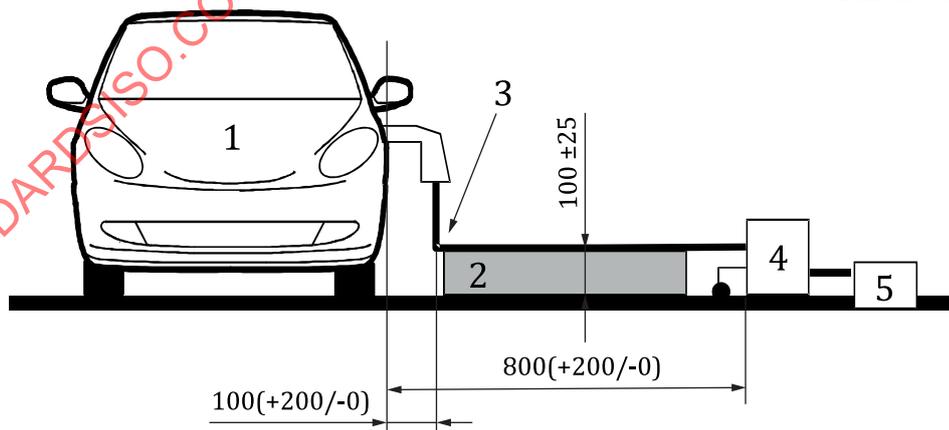
The charging cable at the vehicle side shall hang vertically at a distance of (100 (+200 / -0)) mm from the vehicle body.

The whole cable shall be placed on a non-conductive, low relative permittivity (dielectric-constant) material ( $\epsilon_r \leq 1,4$ ), at (100  $\pm$  25) mm above the ground plane.

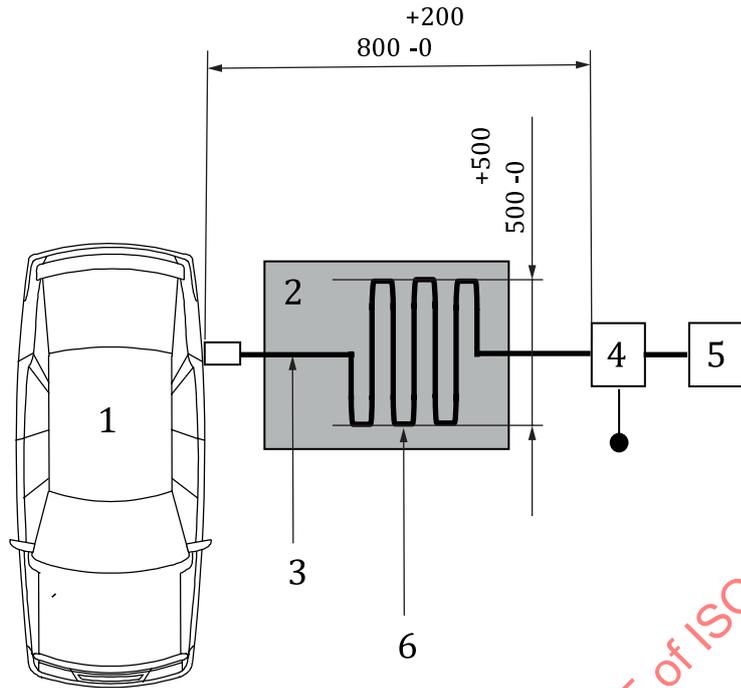
Unless otherwise specified the mode 1 or mode 2 charging cable provided by the manufacturer shall be used and shall have a maximum length of 10 m.

If the vehicle manufacturer delivers more than one mode 1 or mode 2 cable, the measurements may be performed with one representative cable for each mode.

Dimensions in millimetres



a) Front view



b) Top view

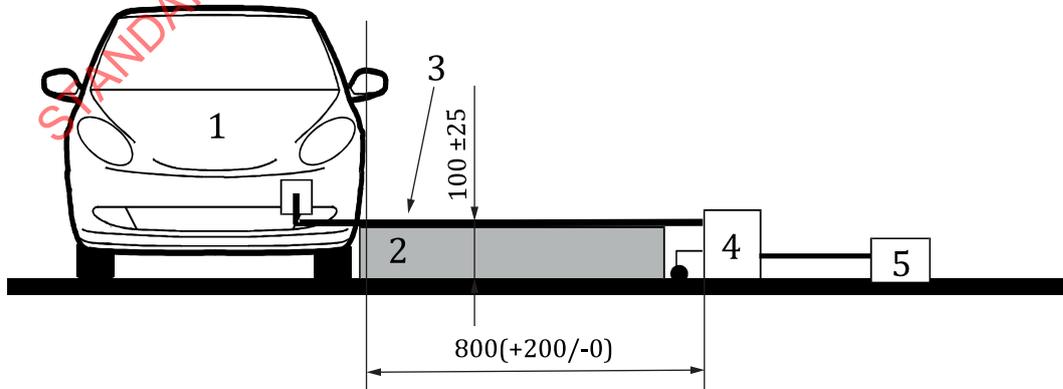
**Key**

- 1 vehicle under test
- 2 insulating support
- 3 charging cable (including EVSE for charging mode 2)
- 4 artificial mains network(s) grounded
- 5 power mains socket (see 7.3.2.2)
- 6 extraneous length Z-folded

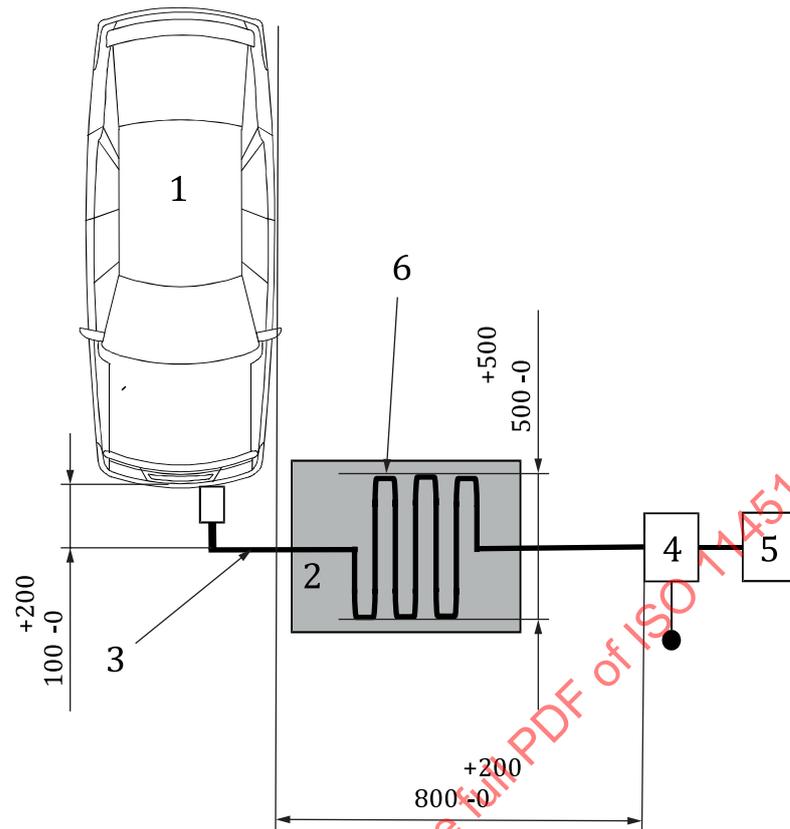
NOTE The cable between the AC mains and the AMN does not need to be aligned in same direction as the cable between the AMN and the EV.

**Figure 2 — Example of test setup for vehicle with socket located on vehicle side (charging mode 1 or mode 2, AC powered, without communication)**

Dimensions in millimetres



a) Front view



b) Top view

**Key**

- 1 vehicle under test
- 2 insulating support
- 3 charging cable (including EVSE for charging mode 2)
- 4 artificial mains network(s) grounded
- 5 power mains socket (see 7.3.2.2)
- 6 extraneous length Z-folded

NOTE The cable between the AC mains and the AMN does not need to be aligned in same direction as the cable between the AMN and the EV.

**Figure 3 — Example of test setup for vehicle with socket located front / rear of vehicle (charging mode 1 or mode 2, AC powered, without communication)**

### 7.3.3 Vehicle in charging mode 3 or mode 4 (AC or DC powered, with communication)

#### 7.3.3.1 General

This configuration concerns charging mode 3 and mode 4.

The vehicle, HV-AN(s)/AMN(s), AAN(s) and power charging harness shall be placed in the working volume.

Examples of test setups are shown in [Figure 4](#) and [Figure 5](#).

### 7.3.3.2 Charging station / power mains

The charging station may be placed either in the test location (including the working volume) or outside the test location.

If the communication between the vehicle and the charging station can be simulated, the charging station may be replaced by a power supply connected to the AC power mains network.

In both cases, power mains/supply and communication or signal lines socket(s) shall be placed in the test location with the following conditions:

- the socket(s) shall be placed on the ground plane;
- the length of the cable between the power mains/supply socket(s) and the AMN(s) or DC-charging-AN(s) should be kept as short as possible and shall be placed directly on the ground plane;
- the length of the cable between the communication socket(s) and the AAN(s) should be kept as short as possible and shall be placed directly on the ground plane.

If the charging station is placed inside the reverberation chamber, then the harnesses between the charging station and the power mains or communication socket shall satisfy the following conditions:

- the harness at charging station side shall hang vertically down to the ground plane;
- the extraneous length shall be placed directly on the ground plane and “Z-folded” if necessary. If it is impractical to do so because of cable bulk or stiffness, or because the testing is being done at a user's installation, the disposition of the excess cable shall be precisely noted in the test report.

Care shall be taken to avoid disturbances to the off-board peripheral equipment.

NOTE In a reverberation chamber, strong electromagnetic fields are everywhere, not only in the working volume. Shielding the off-board power unit or placing it outside can be the simplest countermeasures to avoid disturbances.

### 7.3.3.3 Artificial networks

AC power mains shall be applied to the vehicle through 50  $\mu\text{H}/50 \Omega$  AMN(s) as defined in ISO 11451-1:2015, Annex B.

DC power mains shall be applied to the vehicle through 5  $\mu\text{H}/50 \Omega$  HV-AN(s) as defined in ISO 11451-1:2015, Annex B.

The AMN(s)/HV-AN(s) shall be mounted directly on the ground plane. The case of the AMN(s)/HV-AN(s) shall be bonded to the ground plane.

The measuring port of each AMN/HV-AN shall be terminated with a 50  $\Omega$  load.

### 7.3.3.4 Asymmetric artificial network

Communication lines connected to signal/control ports and lines connected to wired network ports shall be applied to the vehicle through AAN(s).

The various AAN(s) that shall be used are defined in [Annex M](#) and in ISO 11451-1:2015, Annex B:

- ISO 11451-1:2015, B.4.1 for signal/control ports with symmetric lines,
- ISO 11451-1:2015, B.4.3 for signal/control ports with PLC technology on the control pilot line and
- [M.1](#) for signal/control ports with a control pilot line.

The AAN(s) shall be mounted directly on the ground plane. The case of the AAN(s) shall be bonded to the ground plane.

The measuring port of each AAN shall be terminated with a 50 Ω load.

If a charging station is used, AAN(s) are not required for the signal/control ports and/or for the wired network ports. The communication lines between the vehicle and the charging station shall be connected to the associated equipment on the charging station side as in typical installations.

If communication is emulated (i.e. the charging station is replaced by a power supply) and if the presence of the AAN prevents proper communication then no AAN shall be used.

### 7.3.3.5 Power charging harness

The power (charging) harness, including the power and the communication wires/cables, shall be laid out in a straight line between the AMN(s)/HV-AN(s) / AAN(s) and the vehicle charging inlet and shall be routed perpendicularly to the vehicle's longitudinal axis (see Figure 4 and Figure 5). The projected harness length from the side of the AMN(s)/HV-AN(s) / AAN(s) to the side of the vehicle shall be (800 (+200 / -0)) mm.

For a longer harness, the extraneous length shall be “Z-folded” symmetrically. No contact or overlap is allowed between windings. The width of the Z-folded cable shall be between 500 mm and 1 000 mm. If it is impractical to do so because of harness bulk or stiffness, or because the testing is being done at a user installation, the disposition of the excess harness shall be precisely noted in the test report.

The power (charging) harness, including the power and the communication wires/cables, at the vehicle side shall hang vertically at a distance of (100 (+200 / -0)) mm from the vehicle body.

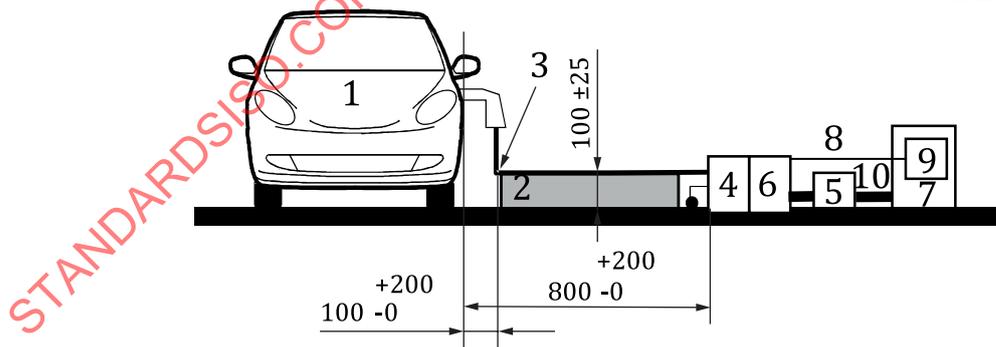
The whole harness shall be placed on a non-conductive, low relative permittivity (dielectric-constant) material ( $\epsilon_r \leq 1,4$ ), at (100 ± 25) mm above the ground plane.

Unless otherwise specified the mode 3 charging cable provided by the manufacturer shall be used and shall have a length greater than 2 m but shorter or equal to 10 m.

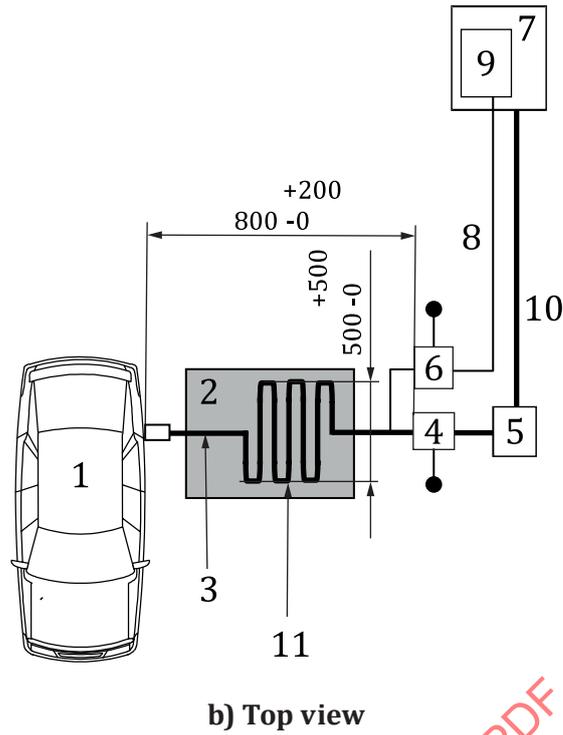
If the vehicle manufacturer delivers more than one mode 3 cable, the measurements may be performed with one representative mode 3 cable.

Unless otherwise specified the mode 4 charging cable of the test facility shall be used.

Dimensions in millimetres



a) Front view

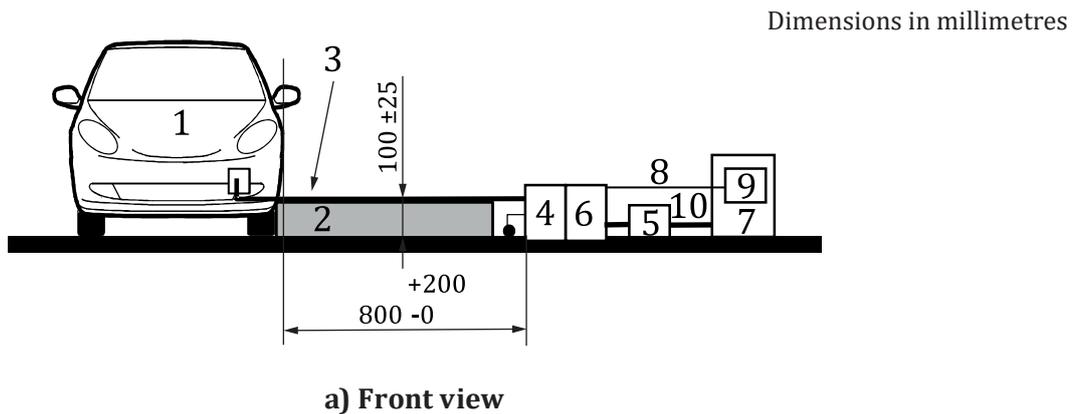


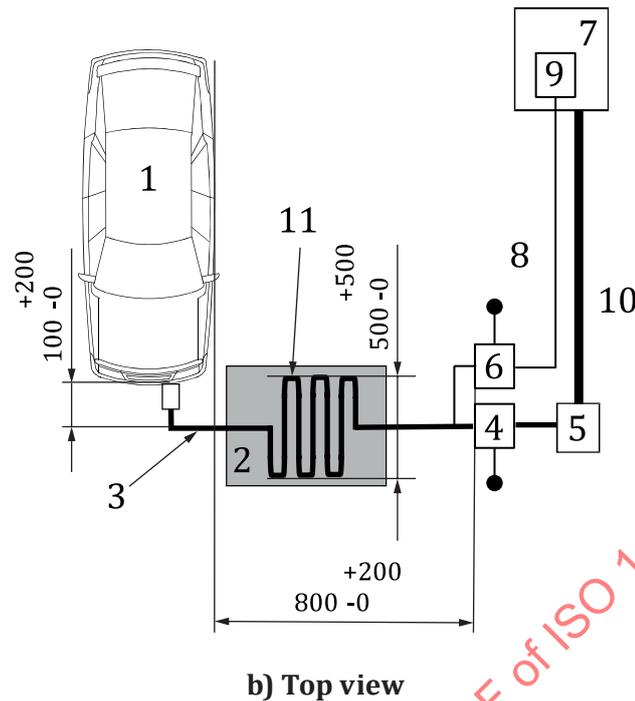
**Key**

- 1 vehicle under test
- 2 insulating support
- 3 charging harness with communication lines
- 4 AMN(s) or DC-charging-AN(s), grounded
- 5 power mains / supply socket (optional, see 7.3.3.2)
- 6 AAN(s), grounded (optional, not represented in the front view)
- 7 charging station (can be emulated)
- 8 communication lines
- 9 communication module
- 10 power cable
- 11 extraneous length Z-folded

NOTE The cable between the AC/DC mains/supply and the AMN/DC-charging-AN does not need to be aligned in same direction as the cable between the AMN/DC-charging-AN and the EV.

**Figure 4 — Example of test setup for vehicle with socket located on vehicle side (charging mode 3 or mode 4, AC or DC powered, with communication)**



**Key**

- 1 vehicle under test
- 2 insulating support
- 3 charging harness with communication lines
- 4 AMN(s) or DC-charging-AN(s), grounded
- 5 power mains / supply socket (optional, see 7.3.3.2)
- 6 AAN(s), grounded (optional, not represented in the front view)
- 7 charging station (can be emulated)
- 8 communication lines
- 9 communication module
- 10 power cable
- 11 extraneous length Z-folded

NOTE The cable between the AC/DC mains/supply and the AMN/DC-charging-AN does not need to be aligned in same direction as the cable between the AMN/DC-charging-AN and the EV.

**Figure 5 — Example of test setup for vehicle with plug located front/rear of vehicle (charging mode 3 or mode 4, AC or DC powered, with communication)**

### 7.3.4 Vehicle in charging mode through wireless power transmission (WPT)

The wireless power transfer (WPT) system mainly consists of a primary device (ground side), a secondary device (vehicle side) and an off-board power unit. In some designs, the primary device and the off-board power unit are both integrated in a single unit.

#### 7.3.4.1 Off-board power unit

The off-board power unit may be placed outside of the reverberation chamber or anywhere on the ground plane of the reverberation chamber.

Care shall be taken to avoid disturbances of the off-board power unit.

NOTE In a reverberation chamber, strong electromagnetic fields are everywhere, not only in the working volume. Shielding the off-board power unit or placing it outside can be the simplest countermeasures to avoid disturbances.

The off-board power unit shall be bonded to ground ( $\leq 2,5 \text{ m}\Omega$ ).

The harness between the off-board power unit and the primary device shall be placed directly on the ground plane.

Use of an artificial mains network (AMN) is recommended on the AC mains feed to the supply device (off-board power device).

If the off-board power unit is placed inside the test site then the harness between the off-board power unit and the primary device shall satisfy the following conditions:

- the harness on the off-board power unit side shall hang vertically down to the ground plane;
- the extraneous length shall be placed directly on the ground plane and “Z folded” if necessary.

#### 7.3.4.2 Primary device

The primary device shall be aligned with the vehicle's secondary device. The distance(s) between the primary device and the secondary device shall be defined in the test plan and documented in the test report.

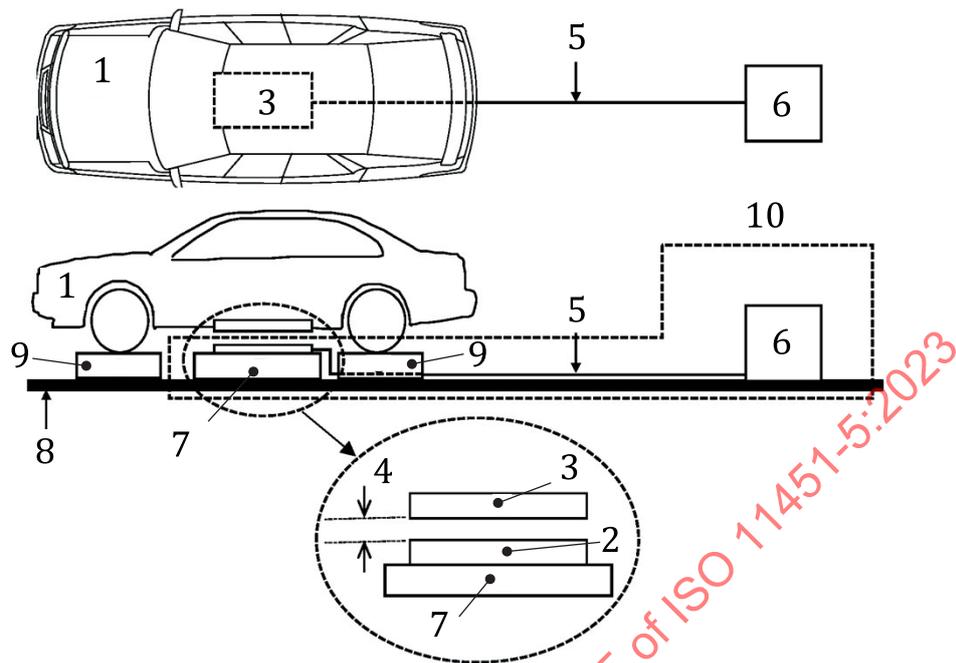
In order to prevent coupling with the ground floor, the primary device shall be raised above the ground plane by non-magnetic and non-metallic material.

The functionality of wireless power transfer shall be ensured by adapting the height of the primary device above the ground plane, so that the air gap between primary and secondary devices emulate the actual coupling that would otherwise be seen by the system. This may lead to the raising of the vehicle under test on metallic spacers such that the necessary air gap separation distance is maintained between the primary and secondary devices.

However, the cable between the primary device and the off-board power unit shall be placed directly on the ground plane.

The arrangement of the vehicle, its secondary device and the primary device that are used for the test, including the air gap size, the misalignment size and direction, as well as the separation from the metallic ground plane shall be documented in the test report.

Example of a test set-up is shown in [Figure 6](#).



### Key

- 1 vehicle under test
- 2 primary device (off-board)
- 3 secondary device (on-board)
- 4 air gap
- 5 cable (between primary device and off-board power unit, placed on ground plane directly)
- 6 off-board power unit (grounded to ground plane)
- 7 non-magnetic and non-metallic support
- 8 ground plane
- 9 metallic spacers (optional)
- 10 associated equipment: key 2, 5, and 6

**Figure 6 — Example of test setup for vehicle in charging mode through wireless power transmission (WPT)**

## 8 Test procedure

### 8.1 General

**CAUTION — Hazardous voltages and fields can exist within the test area. Take care to ensure that the requirements for limiting the exposure of humans to RF energy are met.**

The general arrangement of the disturbance source and vehicle represents a standardized test condition. Any deviations from the standard test configuration shall be agreed upon prior to testing and recorded in the test report.

The vehicle shall be made to operate under typical loading and operating conditions. These operating conditions shall be clearly defined in the test plan.

The orientation(s) of the vehicle for radiated immunity tests shall be defined in the test plan.

In case of tuned mode, the positions of the tuner(s) shall be defined in the test-plan. In case of stirred mode, the speed(s) of the tuner(s) and/or VIRC shaker(s) shall be defined in the test-plan. In case of antenna-stirring, the positions and orientations of the antenna(s) shall be defined in the test plan.

## 8.2 Stirring configurations

Several stirring methods exist and may be used separately or in combination. They can provide a continuous stirring or a discrete stepped or tuned stirring. Consequently, the mathematical operations included in the formulas to calculate the test level, the number of independent stirring configurations, and the field uniformity shall be modified for each stirring method or each combination. The user of this document has to decide which method or combination of methods to use.

The term stirring configuration leaves the individual method open.

Consequently, the calculation of mean values would include summation over discrete values or integration over proper time spans (e.g. the dwell time used for testing) which practically will be approximated by a proper sampling of the field or power over time and proper summation over the sampled values. With the mean value (or the maximum value) over all stirring configurations (totality of methods or combination of methods chosen by the user shall be applied for calibration and testing), a proper calculation over all relevant stirring methods is meant, denoted as  $\langle \cdot \rangle_{sc}$  (or as  $\max(\cdot)$ ).

## 8.3 Test plan

Prior to performing the tests, a test plan shall be generated which shall include:

- test set-up;
- frequency range;
- working volume and reverb reference points (and TLS reference points, if applicable);
- position(s) of receiving antenna(s), if used;
- vehicle mode of operation;
- vehicle acceptance criteria;
- definition of test severity levels;
- vehicle monitoring conditions;
- modulation;
- vehicle orientation;
- positions and/or speed(s) of tuner(s) and/or VIRC shaker(s);
- antenna location(s) of transmitting antenna(s);
- test report content;

and any special instructions and changes from the standard test.

Every DUT shall be verified under the most significant situations, e.g. in stand-by mode and in a mode where all the actuators can be excited.

## 8.4 Test methods

This document defines several test methods described in the main body and in [Annexes E to I](#). [Tables 1](#) and [2](#) summarize the main properties of each test method. [Tables 1](#) and [2](#) are intended to serve as a guide for selecting a test method that best fits the needs.

Unless otherwise specified, methods described in [8.5.2](#) or [8.5.3](#) are the methods to be used. Methods described in [Annexes E](#) to [I](#) are alternative ones.

**Table 1 — Test methods in the main body**

Test method	Subclause	Features
Reverb method with substitution method power control + Loading factor method	<a href="#">8.5.2</a>	<p>Frequency range: <math>f_{LUF}</math> to 18 000 MHz</p> <p>Same method as defined in IEC 61000-4-21.</p> <p>Tuned mode and stirred mode are possible.</p> <p>Requires a spectrum analyser or power meter and a receiving antenna for loading determination.</p> <p>Field uniformity check only for maximum loading. As long as actual loading is smaller, validity of field uniformity is assumed.</p> <p>If only one measurement with receiving antenna is used for determining CLF, this method is less accurate than the two other calibration methods for substitution method. The accuracy may be improved by taking measurements with different receiving antenna positions, but this will take more time.</p> <p>Since power control loop typically is faster than field control loop, settling time of test level is faster than with closed-loop method.</p>
Reverb method with substitution method power control + Field calibration with the vehicle present	<a href="#">8.5.3</a>	<p>Frequency range: <math>f_{LUF}</math> to 18 000 MHz</p> <p>Tuned mode and stirred mode are possible.</p> <p>Needs field probes for the calibration for each new vehicle (class) available.</p> <p>For each vehicle (class) the field uniformity is actually measured and allows therefore a direct comparison with the field homogeneity requirements. Thus a too high loading can be directly determined and the (iterative) experimental determination of the maximum permissible loading is not needed.</p> <p>Unless multi-probe setups are used, this method needs the longest loading determination time.</p> <p>Since power control loop typically is faster than field control loop, settling time of test level is faster than with closed-loop method.</p>

**Table 2 — Alternative test methods in Annexes**

Test method	Annex	Features
TLS method	<a href="#">Annex E</a>	<p>Frequency range: 10 kHz to <math>f_{LUF}</math></p> <p>Only test method below 30 MHz. Alternative method to cavity mode method in frequency range 30 MHz to <math>f_{LUF}</math>.</p> <p>Only stirred mode possible.</p> <p>Extension of TLS testing with TEM mode to higher frequencies with smooth transition from dominantly vertical polarization to statistically isotropic reverb method.</p>

**Table 2 (continued)**

Test method	Annex	Features
Cavity mode method	<a href="#">Annex F</a>	<p>Frequency range: 30 MHz to <math>f_{LUF}</math></p> <p>Alternative method to TLS method in frequency range 30 MHz to <math>f_{LUF}</math>.</p> <p>Mainly intended for tuned mode, but stirred mode possible.</p> <p>Requires tunable monopoles, but other antennas may be used.</p> <p>Extension of the reverb method towards the undermoded frequency range where there might be nearly no modal overlapping, and not for all stirring configurations, energy can be coupled efficiently into the chamber.</p> <p>Allows immunity testing in chambers which are significantly smaller than those required for ISO 11451-2 testing with antennas at 30 MHz and much less power.</p>
Reverb method with closed-loop power control	<a href="#">Annex G</a>	<p>Frequency range: <math>f_{LUF}</math> to 18 000 MHz</p> <p>Only stirred mode possible. Fast stirring (e.g. VIRC) necessary so that statistics can be reasonably measured in a short time.</p> <p>No calibration needed.</p> <p>No need for determining loading effects prior to testing.</p> <p>Always provides the field uniformity with the actual vehicle under test.</p> <p>Needs fast field probes and a multi-probe setup.</p> <p>Only method that directly controls the fields actually measured and not the power with assumption that relation to fields remains the same as during calibration.</p>
Reverb method with substitution method power control + Chamber time constant method	<a href="#">Annex H</a>	<p>Frequency range: <math>f_{LUF}</math> to 18 000 MHz</p> <p>Tuned mode and stirred mode possible.</p> <p>Needs a vector network analyser or spectrum analyser and a signal generator with pulse modulation (both synchronized) for measuring the chamber time constant.</p> <p>Expected maximum of an electric field component estimated from Rayleigh assumption, not measured.</p> <p>ACS of the vehicle is typically more accurate than other two methods and ACS is a property of the vehicle and independent of the reverberation chamber (re-use in other facilities is possible).</p> <p>Since power control loop typically is faster than field control loop, settling time of test level is faster than with closed-loop method.</p>
VNA method	<a href="#">Annex I</a>	<p>Frequency range: <math>f_{LUF}</math> to 18 000 MHz</p> <p>Tuned mode and stirred mode possible.</p> <p>Needs a vector network analyser for calibration.</p> <p>No need for field probes and considerations of isotropy of field probes necessary.</p> <p>Expected maximum of an electric field component not defined as test level and depends on number of independent stirring configurations. Test level is based on CDF value assuming a Rayleigh distribution.</p> <p>Accuracy of loading determination comparable to chamber time constant method.</p>

NOTE The hybrid method of SAE J551-16 describes a special method for very large vehicles where the fields in the reverberation chamber are not homogeneous any more (the vehicle is too large for the room and the energy cannot be distributed to every place in the chamber). This method directly illuminates the vehicle with the transmitting antenna while rotating the tuner(s). The features are: frequency range from  $f_{DIM}$  to 18 000 MHz; lowest frequency  $f_{DIM}$  to be determined during a calibration procedure, but differs from  $f_{LUF}$ ; only stirred mode is defined.

## 8.5 Reverb method with substitution method power control

The substitution method is based upon the use of forward power as the reference parameter used for field calibration and during test.

This method is performed in two phases:

- field calibration of the reverberation chamber;
- test of the vehicle.

The field calibration of a vehicle class needs to be performed only once and is valid for all vehicles of this class. Classes may be, for example, small, mid-size, and large vehicles, or based on the vehicle type. The applicability of the classification shall be demonstrated by sample calibrations. The needed number of classes depends on the differences in sizes of the vehicles tested and the size and instrumentation of the reverberation chamber.

The RF power required to achieve the required test level for the test of the vehicle is determined from the results of the field calibration phase.

For the field calibration of the reverberation chamber, two methods are defined:

- substitution method with empty chamber calibration (see [8.5.2](#));
- substitution method with calibration including the vehicle (see [8.5.3](#)).

NOTE 1 [Annex H](#) describes an alternative calibration method based on the chamber time constant, which can be used, if required in the test plan.

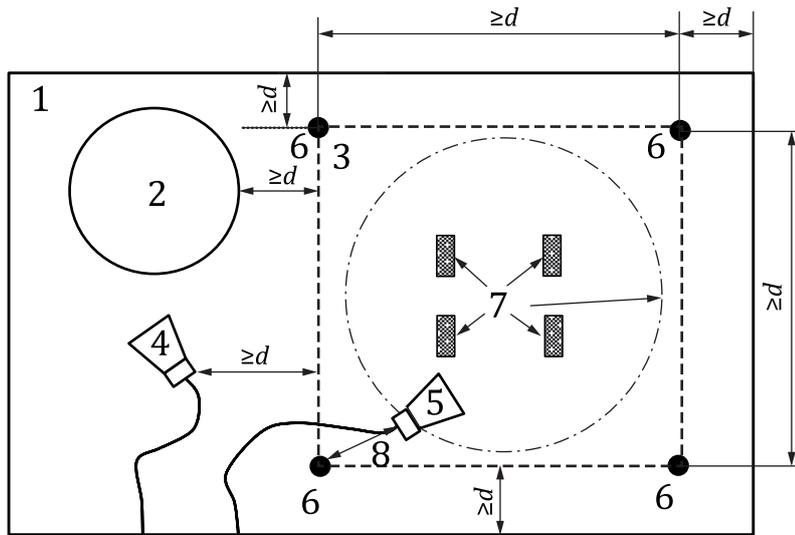
NOTE 2 All three calibration procedures (see [8.5.2](#), [8.5.3](#), and [Annex H](#)) will yield practically the same power requirement and can be combined in a single setup and measured in parallel. This has the advantage that the actual field homogeneity with the vehicle under test, and the mean absorption cross section of the vehicle under test can be measured, and also the comparison with the chamber loading factor from IEC 61000-4-21 can be made.

### 8.5.1 Reverb reference points

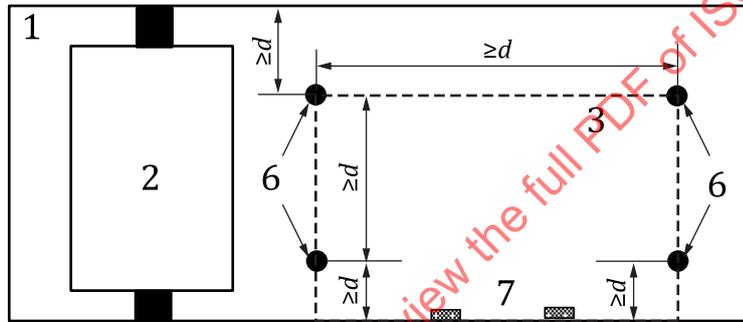
The reverb reference points are the positions of the field probes used for characterizing the chamber for the reverb method.

The reverb reference points are eight points on the four vertical corner edges of the cuboid working volume. The lower four points shall be at least  $\lambda/4$  (at LUF) above the shielding enclosure floor, the upper four points shall be at least as high as the highest vehicle intended to be tested and at least  $\lambda/4$  (at LUF) above the lower four points. The distances between reverb reference points along the sides shall be greater than the dimensions of the vehicle including the peripheral devices that shall be placed inside the working volume (e.g. AMN(s), HV-AN(s), see [Clause 7](#) for details) but not less than  $\lambda/4$  (at LUF).

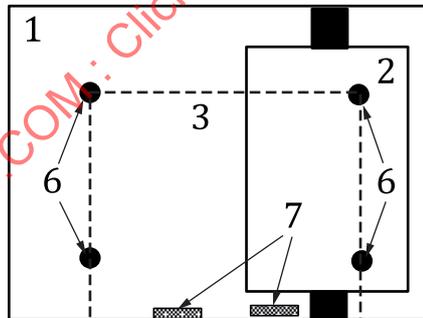
[Figure 7](#) shows an example of choice of a working volume with the corresponding eight reverb reference points.



a) Top view



b) Front view



c) Side view

**Key**

- |     |   |   |  |
|-----|---|---|--|
| 1   | reverberation chamber / VIRC                  | 5 | receiving antenna, if used (only shown in top view)  |
| 2   | tuner   | 6 | reverb reference points (8 points)   |
| 3   | working volume                                | 7 | dynamometer (with or without turn-table)   |
| 4   | transmitting antenna (only shown in top view) | 8 | minimum distance between receiving antenna and any field probe shall be at least $\lambda_{LUF} / 4$ |
| $d$ | minimum distance $d = \lambda_{LUF} / 4$      |   |  |

**Figure 7 — Example of reverb reference point**

## 8.5.2 Substitution method with empty chamber calibration

This subclause describes a field calibration procedure that is based on the field calibration of the empty chamber and uses a power compensation of the vehicle loading. This method uses the mean of the normalized received power to quantify the loading effect. This procedure is the same as defined in IEC 61000-4-21.

The method is performed in four phases:

- field calibration of the empty chamber (see [8.5.2.1](#));
- determination of the maximum loading factor (see [8.5.2.2](#));
- determination of the chamber loading factor (see [8.5.2.3](#));
- vehicle test (see [8.5.2.4](#)).

### 8.5.2.1 Field calibration of the empty chamber

Calibration is performed without a vehicle in the test location.

The specific test level (field) shall be calibrated periodically by recording the forward power required to produce a specific test level (calculated from field probe measurements in the eight reverb reference points) for each test frequency.

This calibration shall be performed with an unmodulated sinusoidal wave.

When requested, the values of forward and reverse power recorded in the calibration file and a precise description of the associated position of the field probe shall be included in the test report.

Place the field generating device(s) at the intended location(s).

A receiving antenna placed within the working volume is used to measure received power. In place of the receiving antenna, a calibrated isotropic field probe may be used. In this case, the received power  $P_{rcv}$  is calculated from the measured electric field strength component  $E_i$  with [Formula \(1\)](#):

$$P_{rcv} = \frac{\lambda^2 E_i^2}{320\pi^2} \quad (1)$$

where

$P_{rcv}$  is the received power for a single stirring configuration in W;

$\lambda$  is the wavelength at the test frequency in m;

$E_i$  is the measured component of the electric field strength in any direction  $x, y$  or  $z$  in V/m.

For all eight reverb reference points, do the following.

- Place a calibrated isotropic field probe at the reverb reference point to be measured and place the receiving antenna somewhere within the working volume, for each of the eight measurements at a different location with a different polarization and different orientation. A direct line-of-sight to any transmitting antenna shall be avoided.
- For each test frequency, record the readings of the three electric field components, the forward power, the reverse power, and the received power for all stirring configurations.

For each test frequency, calculate:

- the reached test level  $E_{RC}$  in V/m according to [Formula \(B.1\)](#),

- the mean forward power  $\langle P_{f,p} \rangle_{sc}$  in W feeding the transmitting antenna,
- and the mean received power  $\langle P_{rcv,p} \rangle_{sc}$  in W measured by the receiving antenna (or field probe and calculated with [Formula \(1\)](#))

for each of the eight measurements (subscript  $p$  denotes the probe position) over all stirring configurations separately.

For the forward power calculate the mean value over all eight measurements using [Formula \(2\)](#):

$$\langle P_f \rangle_{sc} = \frac{1}{8} \sum_{p=1}^8 \langle P_{f,p} \rangle_{sc} \quad (2)$$

For each test frequency, check that the field uniformity requirements given in [Table C.2](#) are met.

Determine the lowest test frequency  $f_c$  that fulfils the field uniformity requirement.

For each test frequency, calculate the chamber gain  $G_{RC,empty}$  of the empty chamber using [Formula \(3\)](#):

$$G_{RC,empty} = \frac{E_{RC}}{\sqrt{\langle P_f \rangle_{sc}}} \quad (3)$$

For each test frequency, calculate the receiving antenna characterization factor of the empty chamber  $A_{ACF,empty}$  using [Formula \(4\)](#):

$$A_{ACF,empty} = \frac{1}{8} \sum_{p=1}^8 \frac{\langle P_{rcv,p} \rangle_{sc}}{\langle P_{f,p} \rangle_{sc}} \quad (4)$$

For lowest test frequency  $f_c$  that fulfils the field uniformity requirement, determine the number of independent stirring configurations  $N_{ind}$  according to [C.2](#). A separate measurement (e.g. with a vector network analyser or with small in-between steps between stirring configurations) might be needed to accomplish this. In case  $N_{ind} \geq 12$ , the lowest usable frequency of the empty chamber is found  $f_{LUF,empty} = f_c$ . Otherwise, check the next larger test frequency, until the requirement  $N_{ind} \geq 12$ , is met and the lowest usable frequency for the empty chamber is found.

### 8.5.2.2 Determination of the maximum loading factor

In order to determine if the chamber is adversely affected by a DUT which “loads” the chamber, perform a one time check of the chamber field uniformity under simulated loading conditions. It is suggested the “loaded” chamber characterization be carried out only once in the life of the chamber or after major modification to the chamber.

In the working volume of the chamber install a sufficient amount of absorber to load the chamber to at least the level expected during normal testing.

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

Repeat the characterization outlined in [8.5.2.1](#) using the eight locations of the E-field probe. Ensure that the E-field probe and receiving antenna maintain a distance of greater than  $\lambda/4$  from any absorber.

Repeat the calculation of the field uniformity using the data from the (at least) eight locations of the E-field probe. If the chamber loading results in a rectangular component of the fields exceeding the allowed standard deviation, or if the standard deviation for all vectors (i.e.  $\sigma$ ) exceeds the allowed standard deviation (see [Table C.2](#)) or the number of independent stirring configurations becomes less than 12, then the chamber has been loaded to the point where the performance of the chamber is

unacceptable. In this case the amount of chamber loading shall be reduced and the loading effects evaluation shall be repeated, or the chamber is only used above  $f_{LUF,maxload}$ .

Determine the maximum chamber loading factor  $F_{MLF}$  by comparing the antenna characterization factor (ACF) from the empty chamber  $A_{ACF,empty}$  to that obtained from the “maximum loaded” chamber  $A_{ACF,maxload}$  using [Formula \(5\)](#):

$$F_{MLF} = \frac{A_{ACF,empty}}{A_{ACF,maxload}} \quad (5)$$

A value of 16 (12 dB) for  $F_{MLF}$  should be considered as a nominal amount of loading.

To avoid overloading the reverberation chamber, the reverberation chamber can be loaded using absorbers which have the same ACS (or slightly higher) as the vehicle under test.

### 8.5.2.3 Determination of the chamber loading factor

This procedure shall be carried out prior to each test, unless the test is performed with an already used vehicle of the same vehicle class. In this case a new determination of the loading effects is not necessary.

Place the receiving antenna at a location within the working volume of the chamber and maintain  $\lambda/4$  separation from the vehicle, support equipment, etc. (at the lowest test frequency).

For each test frequency, record the readings of the forward power and the receiving power for all stirring configurations.

For each test frequency, calculate the mean forward power  $\langle P_f \rangle_{sc}$ , and the mean received power  $\langle P_{rcv} \rangle_{sc}$  over all stirring configurations.

If the value of  $\langle P_{rcv} \rangle_{sc}$  is within (i.e. neither greater nor less than) the values recorded for all eight locations during the field calibration of the empty chamber (see [8.5.2.1](#)), calculation of the CLF is not necessary and the value of  $F_{CLF}$  should be assumed to be 1.

For each test frequency, calculate the chamber characterization factor  $A_{CCF}$  using [Formula \(6\)](#):

$$A_{CCF} = \frac{\langle P_{rcv} \rangle_{sc}}{\langle P_f \rangle_{sc}} \quad (6)$$

**NOTE** It is possible to improve the quality of the estimation of the chamber characterization factor by repeating the procedure for several receiving antenna positions, orientations and polarizations and using the mean value of the individual measurements (like for the determination of the receiving antenna characterization factor). However, this needs more time (e.g. if eight receiving antenna configurations are measured, then making a full chamber calibration with vehicle present will not take longer but would be more accurate).

For each test frequency, calculate the chamber loading factor  $F_{CLF}$  using [Formula \(7\)](#):

$$F_{CLF} = \frac{A_{ACF,empty}}{A_{CCF}} \quad (7)$$

If the dynamic range of the measurement system was insufficient to get accurate average received power measurements  $\langle P_{rcv} \rangle_{sc}$ , the ACF and CCF may be recalculated using maximum received power  $\max(P_{rcv})_{sc}$  and then used to calculate  $F_{CLF}$ . If maximum received power is used, it should be used to recalculate both the  $A_{ACF}$  and  $A_{CCF}$ .

**CAUTION — This applies only to the calculation of the  $F_{CLF}$ . Do not use the  $A_{ACF}$  or  $A_{CCF}$  based on maximum power to determine any other parameters.**

If the chamber loading factor  $F_{CLF}$  is greater than the maximum loading factor  $F_{MLF}$  determined during the chamber characterization for more than 10 % of the frequencies, the chamber may be loaded to a point where field uniformity could be affected. In such case the field uniformity measurements for the loaded chamber shall be repeated with the vehicle in place or with a simulated loading equivalent to the vehicle.

For each test frequency, calculate the chamber gain  $G_{RC,veh}$  of the chamber with vehicle using [Formula \(8\)](#):

$$G_{RC,veh} = \frac{G_{RC,empty}}{\sqrt{F_{CLF}}} \quad (8)$$

#### 8.5.2.4 Vehicle test

The vehicle and associated equipment are installed in the working volume as described in [Clause 7](#) ([Figures 1](#) to [6](#)).

The position of the charging cable between the vehicle and the HV-AN(s)/AMN(s), if any, shall remain unchanged regardless of the vehicle orientation, antenna location(s) and stirring configurations.

The vehicle shall be operated according to the test plan.

The test is conducted by subjecting the vehicle to the test signal based on the calibrated value as predetermined in the test plan. Calculate for each test frequency the necessary forward power  $P_{f,test}$  into the transmitting antenna for the required test level  $E_{RC,test}$  using [Formula \(9\)](#):

$$P_{f,test} = \left( \frac{E_{RC,test}}{G_{RC,veh}} \right)^2 \quad (9)$$

Monitor the forward power into the transmitting antenna(s) and record the average value over all stirring configurations. Variations greater than 3 dB shall be noted in the test report.

NOTE 1 A field probe can be placed in or outside the vehicle during the test.

Tests shall be conducted for all stirring configurations over the test frequency range. Any exceptions to this practice shall be specified in the test plan. The number of independent stirring configurations shall be at least 12 and at least 6 above  $3f_{LUF,veh}$  or  $3f_{LUF,maxload}$ .

For stirred mode testing the minimum dwell time defined in ISO 11451-1 might need to be extended to ensure at least 12 or 6 independent stirring configurations (see [C.4](#)). For example, the coherence time (see [C.3](#)) is 540 ms then the minimum dwell time is 6,48 s and above  $3f_{LUF,veh}$  or  $3f_{LUF,maxload}$  it is 3,24 s.

Interpolation methods may be used between calibration levels to determine the specific forward power to be used for a test. From a practical viewpoint, the increment between calibration levels when the amplifier is operating in a linear range may be larger than when operating in a region where compression occurs.

Scan the frequency range at the test level noting any anomalies.

Continue testing until all frequencies, modulations, stirring configurations and vehicle orientations specified in the test plan are completed.

For pulse modulation, it shall be checked that the pulse duration is long enough to reach a steady-state of the fields in the chamber and the switch-on transients have decayed. This can be easily checked with an oscilloscope or a spectrum analyser in zero-span mode connected to a receiving antenna in the working volume. The pulse duration of the pulse modulation shall be extended so that the steady-state time equals the required pulse duration.

This especially applies to pulse modulation PM2 defined in ISO 11451-1.

NOTE 2 The switch-on and switch-off transients typically last for a few hundred nanoseconds to a few microseconds and can be easily distinguished from the “steady-state” that can change due to a stirred mode.

### 8.5.3 Substitution method with calibration including the vehicle

This subclause describes a method to determine the chamber gain  $G_{RC,veh}$  with the vehicle present.

The method is performed in two phases:

- calibration procedure (see [8.5.3.1](#));
- vehicle test (see [8.5.3.2](#)).

#### 8.5.3.1 Calibration procedure

Calibration is performed with the vehicle in the test location.

The specific test level (field) shall be calibrated periodically, for each vehicle class, by recording the forward power required to produce a specific test level (calculated from field probe measurements in the eight reverb reference points) for each test frequency.

This calibration shall be performed with an unmodulated sinusoidal wave.

If requested, the values of forward and reverse power recorded in the calibration file and a precise description of the associated position of the field probes shall be included in the test report.

Place the field generating device(s) at the intended location(s). Place eight calibrated isotropic field probes at the reverb reference points, or perform several measurements consecutively to obtain the data in the eight reverb reference points.

For each test frequency, record the readings of the 24 electric field components in the eight reverb reference points, the forward power and the reverse power for all stirring configurations.

For each test frequency, calculate:

- the reached test level  $E_{RC}$  in V/m according to [Formula \(B.1\)](#),
- the mean forward power  $\langle P_f \rangle_{sc}$  in W feeding the transmitting antenna,

over all stirring configurations.

For each test frequency, check that the field uniformity requirements according to [Table C.2](#) are met. Determine the lowest test frequency  $f_c$  that fulfils the field uniformity requirement.

For each test frequency, calculate the chamber gain  $G_{RC,veh}$  with vehicle using [Formula \(10\)](#):

$$G_{RC,veh} = \frac{E_{RC}}{\sqrt{\langle P_f \rangle_{sc}}} \quad (10)$$

This chamber gain is valid for all vehicles that belong to the same class as the vehicle present in the reverberation chamber during this calibration.

For lowest test frequency  $f_c$  that fulfils the field uniformity requirement, determine the number of independent stirring configurations  $N_{ind}$  according to [C.2](#). A separate measurement (e.g. with a vector network analyser or with small in-between steps between stirring configurations) might be needed to accomplish this. In case  $N_{ind} \geq 12$ , the lowest usable frequency of the chamber with vehicle is found  $f_{LUF,veh} = f_c$ . Otherwise, check the next larger test frequency, until the requirement  $N_{ind} \geq 12$ , is met and the lowest usable frequency for the chamber with vehicle is found.

Test frequencies below the lowest usable frequency  $f_{LUF,veh}$  cannot be used for testing of any vehicle of the same class as the vehicle present in the reverberation chamber during this calibration.

NOTE In case the user does not intend to use the chamber loading factor, this procedure can also be used to calibrate the empty chamber. The difference is, that a reference antenna is not needed and more than a single probe can be used to accelerate the calibration procedure and save time.

### 8.5.3.2 Vehicle test

The vehicle and associated equipment are installed in the working volume as described in [Clause 7](#) ([Figures 1](#) to [6](#)).

The position of the charging cable between the vehicle and the HV-AN(s)/AMN(s), if any, shall remain unchanged regardless of the vehicle orientation, antenna location(s) and stirring configurations.

The vehicle shall be operated according to the test plan.

The test is conducted by subjecting the vehicle to the test signal based on the calibrated value as predetermined in the test plan. Calculate for each test frequency the necessary forward power  $P_{f,test}$  into the transmitting antenna for the required test level  $E_{RC,test}$  using [Formula \(11\)](#):

$$P_{f,test} = \left( \frac{E_{RC,test}}{G_{RC,veh}} \right)^2 \quad (11)$$

Monitor the forward power into the transmitting antenna(s) and record the average value over all stirring configurations. Variations greater than 3 dB shall be noted in the test report.

NOTE 1 A field probe can be placed in or outside the vehicle during the test.

Tests shall be conducted for all stirring configurations over the test frequency range. Any exceptions to this practice shall be specified in the test plan. The number of stirring configurations shall be at least 12 and at least 6 above  $3f_{LUF,veh}$  or  $3f_{LUF,maxload}$ .

For stirred mode testing the minimum dwell time defined in ISO 11451-1 might need to be extended to ensure at least 12 or 6 independent stirring configurations (see [C.4](#)). E.g. the coherence time (see [C.3](#)) is 540 ms then the minimum dwell time is 6,48 s and above  $3f_{LUF,veh}$  or  $3f_{LUF,maxload}$  it is 3,24 s.

Interpolation methods may be used between calibration levels to determine the specific forward power to be used for a test. From a practical viewpoint, the increment between calibration levels when the amplifier is operating in a linear range may be larger than when operating in a region where compression occurs.

Scan the frequency range at the test level noting any anomalies.

Continue testing until all frequencies, modulations, stirring configurations and vehicle orientations specified in the test plan are completed.

For pulse modulation, it shall be checked that the pulse duration is long enough to reach a steady-state of the fields in the chamber and the switch-on transients have decayed. This can be easily checked with an oscilloscope or a spectrum analyser in zero-span mode connected to a receiving antenna in the working volume. The pulse duration of the pulse modulation shall be extended so that the steady-state time equals the required pulse duration.

This especially applies to pulse modulation PM2 defined in ISO 11451-1.

NOTE 2 The switch-on and switch-off transients typically last for a few hundred nanoseconds to a few microseconds and can be easily distinguished from the "steady-state" that can change due to a stirred mode.

## 8.6 Test report

As required by the test plan, a test report shall be submitted detailing information regarding the test equipment, test site, test set-up, systems tested, frequencies, power levels, system interactions and any other information relevant to the test.

The test report should include the following parameters for each test frequency, in addition to the reporting requirements related to the vehicle:

- curves of maximum and average received power from the receiving antenna used to monitor the field in the chamber over all stirring configurations, if a receiving antenna is used;
- curve of the test level, if applicable;
- curves of the maximum and average readings of a field probe and of the ratio maximum/average, if applicable;
- curve of the average forward power delivered to the transmitting antenna over all stirring configurations;
- variations in forward power during the test greater than 3 dB;
- curves of the chamber loading factor and the maximum loading factor, if applicable;
- stirring configurations used for the test;
- used test method;
- chamber characteristics (coherence time, minimum dwell time, etc.).

Any deviation from the test plan shall be specified in the test report.

## Annex A (informative)

### Function performance status classification

#### A.1 General

This annex gives examples of test severity levels which should be used in line with the principle of functional performance status classification (FPSC) described in ISO 11452-1.

#### A.2 Classification of test severity level

Examples of test severity levels for reverberation chamber are given in [Table A.1](#).

**Table A.1 — Example of test severity levels (reverberation chamber)**

Frequency band [MHz]	Test level I [V/m]	Test level II [V/m]	Test level III [V/m]	Test level IV [V/m]	Test level V [V/m]
0,01 to 10	25	50	75	100	Specific values agreed between the users of this document
10 to 30	25	50	75	100	
30 to 200	20	40	60	80	
200 to 1 000	20	40	60	80	
1 000 to 8 000	25	50	75	100	
8 000 to 18 000	25	50	75	100	

Frequency bands and test levels values given in this table are examples.

#### A.3 Example of FPSC application using test severity levels

An example of severity levels is given in [Table A.2](#).

**Table A.2 — Example of test severity levels (reverberation chamber)**

Test severity level	Function category 1	Function category 2	Function category 3	Function category 4
L4i	Level IV	—	—	—
L3i	Level III	Level IV	—	—
L2i	Level II	Level III	Level IV	—
L1i	Level I	Level II	Level III	Level IV

## Annex B (normative)

### Test level definition

#### B.1 General

In a reverberation chamber the electromagnetic fields change for each stirring configuration and show strong variations with maxima and minima across the chamber volume. The locations of the maxima and minima change when changing the stirring configuration. The field statistics inside a reverberation chamber well above the LUF has well-behaved properties like expected mean values or expected maximum values of the field components which are nearly (within defined statistical variations) the same in all positions inside the working volume irrespective of the orientation of the field component. Consequently, the test level is defined as a statistical property of the electric field.

In practice the mean and maximum values are not exactly the same everywhere within the working volume. The test level  $E_{RC}$  in a reverberation chamber is defined as an estimator for the expectation value of the maximum value of an electric field component inside the working volume.

Three different approaches to estimate  $E_{RC}$  based on the electric field strength components, or on the received power, or on the forward power are used by the different test methods in this document. Which to use, is defined for each test method.

Measurements of antenna efficiencies (see [Annex J](#)), and diffuse field correction factors (see [Annex K](#)) utilize the equivalence of the three approaches.

#### B.2 Test level based on electric field components

The three components of the electric field are measured in all eight reverberation reference points (see [8.5.1](#)) for all stirring configurations and the mean value of the 24 maximum values calculated individually over all stirring configurations is calculated using [Formula \(B.1\)](#):

$$E_{RC} = \frac{1}{24} \sum_{p=1}^8 \left( \max_{sc} (E_{x,p}) + \max_{sc} (E_{y,p}) + \max_{sc} (E_{z,p}) \right) \quad (\text{B.1})$$

The index  $p$  denotes the probe position;  $E_{x,p}$  denotes the  $x$ -component of the electric field strength in V/m in position  $p$ ;  $E_{y,p}$  denotes the  $y$ -component in V/m in position  $p$ ; and  $E_{z,p}$  denotes the  $z$ -component in V/m in position  $p$ .

This definition is used in the reverberation test methods of [8.5.2](#) and [8.5.3](#) and of [Annex G](#).

#### B.3 Test level based on received power

The expectation value of an electric field component may be calculated from the mean value of the received power measured with a linearly polarized receiving antenna with known total antenna efficiency using [Formula \(B.2\)](#):

$$\langle |E_i| \rangle_{sc} = \frac{4\pi}{\lambda} \sqrt{\frac{5\pi \langle P_{rx} \rangle}{\eta_{rx,tot}}} \quad (\text{B.2})$$

where

- $E_i$  is the electric field strength component in direction  $i$  as, e.g. measured with one of the three measurement axis of an isotropic field probe;
- $i$  any of the 3 axis  $x, y$  or  $z$  ;
- $\lambda$  is the wavelength, in m;
- $P_{rx}$  is the received power in W measured by the receiving antenna;
- $\eta_{rx,tot}$  is the total antenna efficiency of the receiving antenna in linear scale (e.g. measured according to [Annex J](#)).

This estimator ([Formula \(B.2\)](#)) is used in the VNA method of [Annex I](#).

The expectation value of the maximum electric field component can be estimated from the mean value by a known ratio of the maximum to mean value  $\alpha$ . This ratio may be determined by experiment as a function of frequency  $\alpha(f)$  or analytically as a function of the number of independent stirring configurations  $\alpha(N_{ind})$  (see [H.2](#)) which varies with frequency, using [Formula \(B.3\)](#):

$$E_{RC} = \alpha(N_{ind}) \langle |E_i| \rangle_{sc} = \alpha(N_{ind}) \frac{4\pi}{\lambda} \sqrt{\frac{5\pi \langle P_{rx} \rangle_{sc}}{\eta_{rx,tot}}} \quad (B.3)$$

The received power measurements may be performed using power meters, spectrum analysers or vector network analysers.

To improve the estimation, calculating the mean value of several measurements with different receiving antenna locations, orientations and polarizations is allowed.

#### B.4 Test level based on the forward power

The expectation value of an electric field component may also be calculated from the mean net input power and the chamber time constant. The mean net input power can be determined from the mean forward power and the total antenna efficiency of the transmitting antenna using [Formula \(B.4\)](#):

$$E_{RC} = \alpha(N_{ind}) \langle |E_i| \rangle_{sc} = \alpha(N_{ind}) \pi \sqrt{\frac{10 c_0 \tau_1 \eta_{tx,tot} \langle P_f \rangle_{sc}}{V}} \quad (B.4)$$

where

- $\alpha$  maximum to mean ratio of the electric field strength in linear scale (see [H.2](#));
- $N_{ind}$  number of independent stirrer positions;
- $E_i$  is the electric field strength component in direction  $i$  as e.g. measured with one of the three measurement axis of an isotropic field probe;
- $i$  any of the 3 axis  $x, y$  or  $z$  ;
- $P_f$  is the forward power in W feeding the transmitting antenna;
- $\eta_{tx,tot}$  is the total antenna efficiency of the transmitting antenna in linear scale (e.g. measured according to [Annex J](#));
- $c_0$  speed of light in air (approximately  $3 \cdot 10^8$  m/s);
- $\tau_1$  chamber time constant in s with loading including the vehicle under test;

$V$  volume of the reverberation chamber in  $\text{m}^3$ .

More details are given in [Annex H](#).

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## Annex C (normative)

### Reverberation chamber characteristics

#### C.1 General

This annex describes procedures to quantify some characteristics of reverberation chambers which are needed to apply the reverb test methods.

#### C.2 Number of independent stirring configurations

The number of independent stirring configurations that the complete ensemble of stirring configurations used for testing can produce shall be determined for the reverb method. The method used is based on the calculation of autocorrelation coefficients of received power, S parameter, or electric field component measurements while applying the stirring scheme.

In the case of the tuned mode method, the number of independent stirring configurations might not be determined as detailed in the present clause. Instead, it is allowed to use the recommended number of tuner positions provided in [Table C.1](#).

**Table C.1 — Recommended number of tuner positions for tuned-mode**

Frequency range	Recommended number of tuner positions	Minimum number of tuner positions
$f_s$ to $3f_s$	50	12
$3f_{LUF}$ to $6f_{LUF}$	18	6
$6f_{LUF}$ to $10f_{LUF}$	12	6
$> 10f_{LUF}$	12	6
$f_s$ : lowest frequency for chamber characterization $f_{LUF}$ : lowest usable frequency of the chamber		

First, the stirring scheme for testing shall be defined. Examples:

- Tuner in tuned mode: value of the angular step (e.g. tuner 1 in 30° steps);
- Tuner in stirred mode: value of the rotation speed in rpm (e.g. tuner 1 with 10 rpm, tuner 2 with 120 rpm and tuner 3 with 75 rpm);
- VIRC: number of shakes per second (e.g. shaker 1 shakes once every 3,9 s, shaker 2 once every 6 s).

If more than one tuner (or shaker) is used, this information shall be available for each.

To calculate the autocorrelation coefficients, a series of measurement values is needed. For stirred mode and VIRC, this series is generated by sampling the received power, S parameter, or electric field with a sufficiently high sampling rate while stirring. For tuned mode, the received power, S parameter, or electric field is measured not only for the tuner positions defined in the stirring scheme for calibration and testing, but also for a number of smaller in-between steps (e.g. with 1° resolution). In case of antenna stirring methods, where distinct transmitting antenna positions and/or antenna polarizations are utilized, this sampling of a smooth transition between stirring configurations is not possible.

NOTE 1 This sequence of course is not unique. There are many ways to define it. In case of stirred mode the exact sequence is not even controlled, just the statistics is repeatable.

To demonstrate a number of independent stirring configurations of  $N_{\text{ind}}$ , at least 10  $N_{\text{ind}}$  measurement samples are needed.

For this (time) sequence, an analysis window for the calculation of the autocorrelation coefficients needs to be defined. This might be the complete sequence (useful for a single tuner or other periodic sequences) which then is periodized for the calculation (called “periodization” below, which is in the case of a single tuner the definition from IEC 61000-4-21:2011, Annex A) or only part of it (called “windowing” below), where the window length corresponds to the intended minimum dwell time of e.g. two seconds.

In case of periodization, measure the received power with the receiving antenna in the working volume for the complete sequence of stirring configurations for the frequency range to be analysed using a vector network analyser, a spectrum analyser or a power meter.

The transmitting antenna(s) shall be used for the excitation of the chamber. Alternatively, one or several electric field components may be measured with field probes instead of the received power for all frequencies and all stirring configuration.

In case of windowing, measure the received power with the receiving antenna in the working volume or one or several electric field components while stirring for a (time) sequence that is at least two times the window width.

NOTE 2 Longer times allow investigation of the stationarity of the stochastic process similar like short-time FFT of signals, i.e. it enables investigations of changes due to different tuner angles or similar influences, but this is not required.

The frequency range shall include the LUF. Usually, the LUF is not known in advance. When  $f_0$  denotes the first resonance of the empty chamber, the LUF occurs between  $3f_0$  and  $10f_0$ . The frequency steps shall be chosen in conformance with ISO 11451-1. It may be reduced to 20/decade in the frequency range above  $10f_0$ .

In case of periodization: calculate the autocorrelation  $r$  for the (time) lags  $l=0, \dots, N-1$  with [Formula \(C.1\)](#):

$$r(l) = \frac{\sum_{i=0}^{N-1} (p(i) - \bar{p})(p((i+l) \bmod(N)) - \bar{p})}{\sum_{i=0}^{N-1} (p(i) - \bar{p})^2} \quad (\text{C.1})$$

where

$N$  size of sample sequence (e.g. 10 001);

$p(i)$  the  $i$ th measured received power value in W (or absolute value of an electric field component or the total electric field strength measured with a field probe in V/m);

$\bar{p}$  mean value over all  $p(i)$ ;

$\text{mod}(\cdot)$  modulo function;

$l$  is the normalized lag and corresponds e.g. to a rotational increment of a tuner in tuned mode or to a time increment in stirred mode.

In case of windowing: calculate the autocorrelation  $r$  for the (time) lags  $l=0, \dots, N-1$  with [Formula \(C.2\)](#):

$$r(l) = \frac{\sum_{i=0}^{N-1} (p(i) - \bar{p})(p(i+l) - \bar{p})}{\sum_{i=0}^{N-1} (p(i) - \bar{p})^2} \quad (\text{C.2})$$

where

- $N$  size of sample sequence (e.g. 10 001);
- $p(i)$  the  $i$  th measured received power value in W (or absolute value of an electric field component or the total electric field strength measured with a field probe in V/m);
- $\bar{p}$  mean value over all  $p(i)$ ;
- $l$  normalized lag and corresponds, e.g. to a rotational increment of a tuner in tuned mode or to a time increment in stirred mode.

In order to be able to calculate the autocorrelation  $r$  for all values of lags  $l$  in [Formula \(C.2\)](#), the sequence of measured received power values (or absolute values of an electric field component measured with a field probe) needs to have at least  $2N$  values.

NOTE 3 By shifting the window by  $M$  samples, the autocorrelation for a time shift can easily be calculated which means it can easily be investigated what happens, if the sequence (i.e. the test start time) is shifted.

The time lags  $l_{ind}$  for which the autocorrelation has dropped below a threshold value using [Formula \(C.3\)](#):

$$r(l_{ind}) < 0,37 \left( 1 - \frac{7,22}{N^{0,64}} \right) \tag{C.3}$$

are said to be independent from the initial sequence.

Since some tuners show partial correlation of the produced sequence after the autocorrelation has dropped below the threshold (e.g. as a consequence of a tuner with some rotational symmetry), the number of independent tuner positions  $N_{ind}$  is defined by [Formula \(C.4\)](#):

$$N_{ind} = \frac{N}{L_{ind}} \tag{C.4}$$

where  $L_{ind}$  denotes the number of time lags  $l_{ind}$  for which the autocorrelation is greater than or equal to the threshold defined in [Formula \(C.3\)](#).

NOTE 4 This deviates from the definition in IEC 61000-4-21. IEC 61000-4-21 only uses the first value that drops below the threshold of [Formula \(C.3\)](#), i.e.  $\min(l_{ind})$ .

This calculated number  $N_{ind}$  changes when changing the antenna or field probe position and/or orientation. Using the mean value of multiple measurements (e.g. from field probes in the eight reverberation reference points) is allowed but not required. Similarly, in case of windowing using the mean value of the result of calculations with shifted window is allowed.

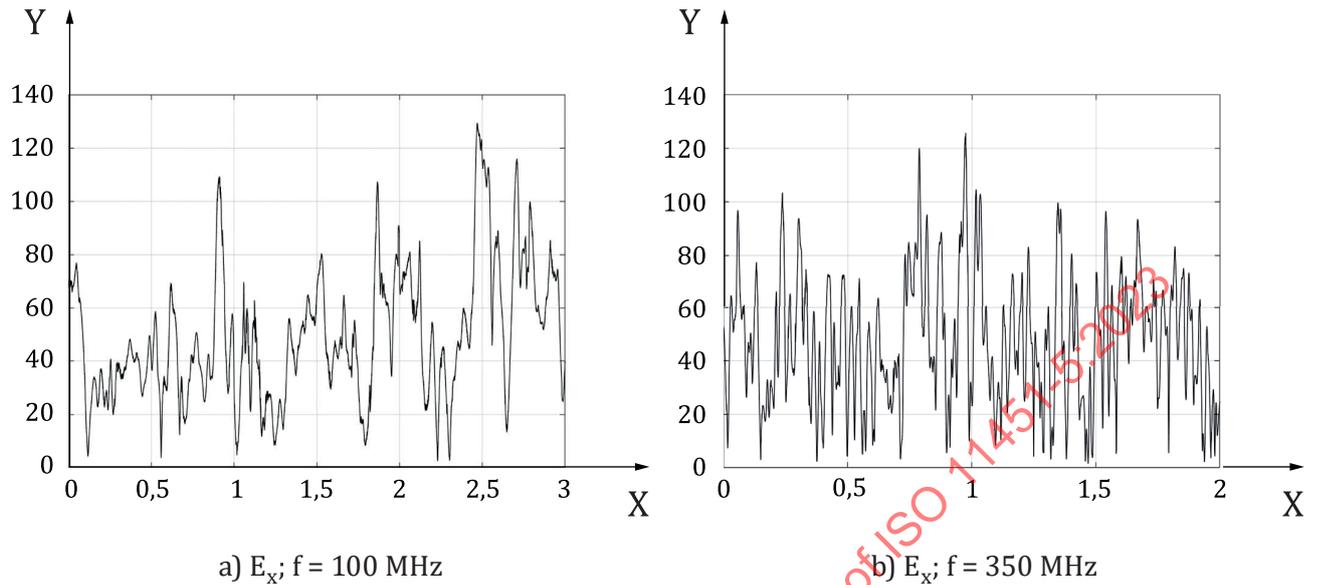
NOTE 5 The number of independent tuner positions can be a fractional value, e.g. 12,7.

Dealing with several transmitting antenna positions or polarizations may be taken into account by determining the numbers of independent stirring configurations individually for each transmitting antenna position or polarization. Assuming that each position and polarization creates uncorrelated sequences, the individually determined  $N_{ind}$  can be simply summed up, e.g. in case of three different transmitting antenna positions, choose three distant locations within the working volume, three different antenna orientations and three different polarization angles. Under these conditions, use [Formula \(C.5\)](#):

$$N_{ind} = N_{ind,pos1} + N_{ind,pos2} + N_{ind,pos3} \tag{C.5}$$

To illustrate the calculation procedure, an example is given from a facility using stirred mode. [Figure C.1](#) shows the electric field component  $E_x$  measured with an isotropic field probe in one of the reverberation

reference points. The sampling rate was 10 kS/s. At 100 MHz, the total measurement time was 3 s; at 350 MHz, it was 2 s.



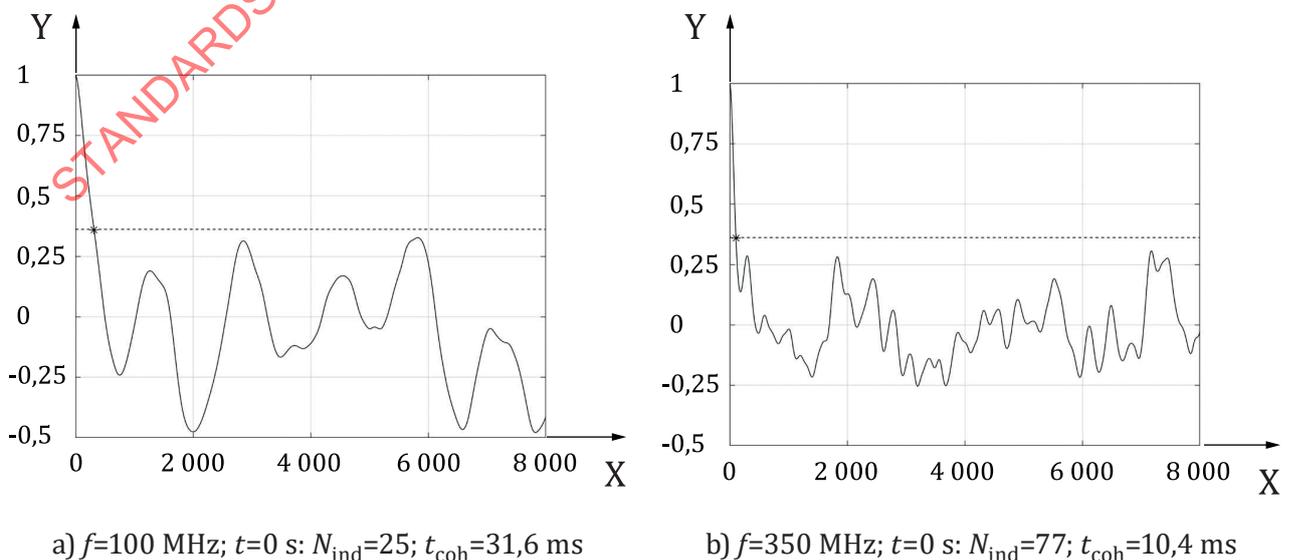
**Key**

X t in s  
 Y E in V/m

**Figure C.1 — Example: measured electric field strength**

Since the signals are not periodic, the windowing method is applied. A window of length 800 ms is chosen, to allow illustrating the effect of choosing different starting times of the window. The window length  $N$  is 8 001 samples (including 0 ms and 800 ms).

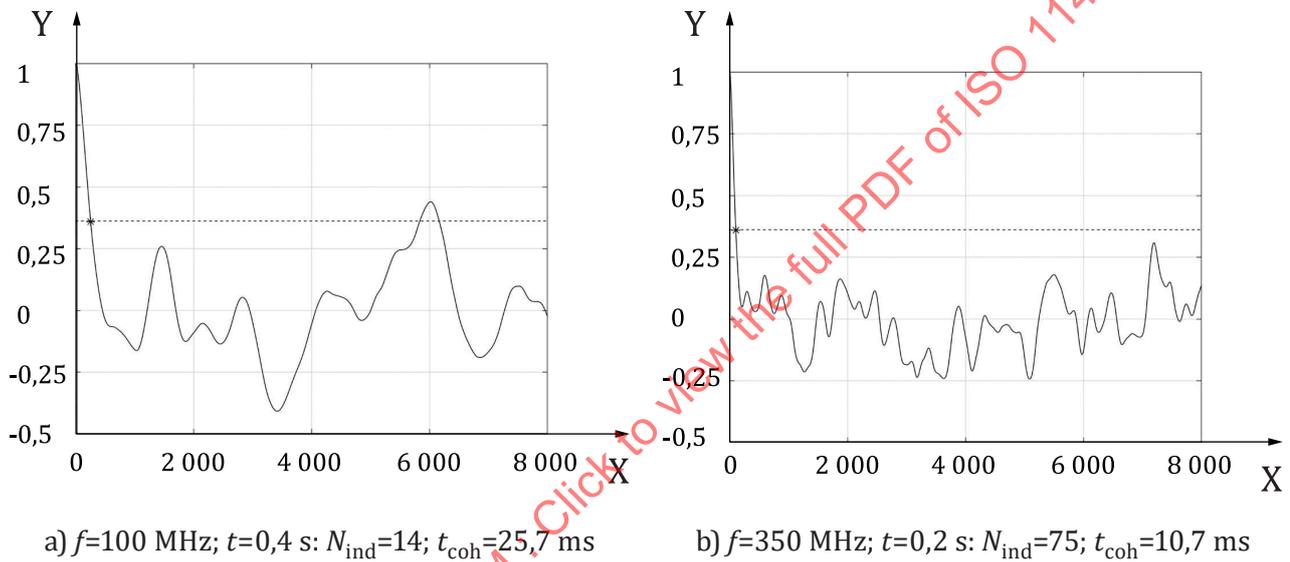
Figure C.2 shows the autocorrelation coefficients calculated according to Formula (C.2). The threshold in case of 8 001 samples is 0,361 5. At 100 MHz, the first lag  $l$  below the threshold is 316; only the lags up to 315 are above or equal to the threshold (including the lag 0, yields  $L_{ind}=316$ ), i.e.  $N_{ind}=8\,001/316 \approx 25,3$ . At 350 MHz, the first lag  $l$  below the threshold is 104; only the lags up to 103 are above or equal to the threshold (including the lag 0, yields  $L_{ind}=104$ ), i.e.  $N_{ind}=8\,001/104 \approx 76,9$ .



<b>Key</b>	<b>Key</b>
X l (star indicates 316 lags)	X l (star indicates 104 lags)
Y r (star indicates 0,359 714)	Y r (star indicates 0,358 949)

**Figure C.2 — Example: autocorrelation coefficients (no offset)**

Figure C.3 shows the autocorrelation coefficients with shifted windows. For 100 MHz, the window was shifted by 0,4 s. In this case, the first lag  $l$  below the threshold is 257; but not only 257 lags are above or equal to the threshold, around 6 000 there are another 329 resulting in  $L_{ind} = 586$ , i.e.  $N_{ind} = 8\,001 / 586 \approx 13,7$ . For 350 MHz, the window was shifted by 0,2 s. In this, the first lag  $l$  below the threshold is 107; only the lags up to 106 are above or equal to the threshold, i.e.  $N_{ind} = 8\,001 / 107 \approx 74,8$ .



<b>Key</b>	<b>Key</b>
X l (star indicates 257 lags)	X l (star indicates 107 lags)
Y r (star indicates 0,359 193)	Y r (star indicates 0,359 915)

**Figure C.3 — Example: autocorrelation coefficients (with offset)**

### C.3 Coherent stirring configurations

For time lags  $l \leq \min(l_{ind})$  the stirring configurations are said to be coherent, i.e. they are not statistically independent.

For tuned mode using a single stirrer, this allows to calculate the minimum angle that the tuner needs to be turned to create a new statistically independent stirring configuration using [Formula \(C.6\)](#):

$$\alpha_{coh} = \Delta\alpha \min(l_{ind}) \tag{C.6}$$

where  $\Delta\alpha$  is the angular increment that was used to measure the sequence of received power (or field strength) values.

Similarly, for stirred mode, this allows to calculate the minimum time span that needs to pass by to create a new statistically independent stirring configuration using [Formula \(C.7\)](#):

$$t_{\text{coh}} = \Delta t \min(l_{\text{ind}}) \quad (\text{C.7})$$

where  $\Delta t$  is the time increment that was used when sampling the sequence of received power (or field strength) values.

This time span  $t_{\text{coh}}$  is called coherence time.

For the example of [C.2](#),  $\Delta t = 100 \mu\text{s}$ . Accordingly, the values for 100 MHz are 31,6 ms (window starts at 0 s) and 25,7 ms (window starts at 0,4 s), and the values for 350 MHz are 10,4 ms (window starts at 0 s) and 10,7 ms.

#### C.4 Minimum dwell time

For tuned mode, the minimum dwell time  $t_{\text{dwell}}$  is defined in ISO 11451-1. It is used for each stirring configuration.

For stirred mode, also the number of independent stirring configurations has to be taken into account. For example, to assure 12 independent stirring configurations, the minimum dwell time shall be at least 12 times the coherence time  $t_{\text{coh}}$  calculated according to [Formula \(C.7\)](#). In case of partial correlation, i.e. the autocorrelation again exceeds the threshold ([C.3](#)), the minimum dwell time shall also be larger than  $\Delta t$  times the minimum window length  $N_{\text{min},12}$  in ([C.2](#)) that results in at least 12 independent stirring configurations. This means that the dwell time shall be the maximum of these two or three values (depending on the partial correlation, without partial correlation  $12t_{\text{coh}} = \Delta t N_{\text{min},12}$  holds) using [Formula \(C.8\)](#):

$$t_{\text{dwell}} = \max(\{t_{\text{dwell,ISO11451-1}}; 12t_{\text{coh}}; \Delta t N_{\text{min},12}\}) \quad (\text{C.8})$$

In the example of [C.2](#)  $N_{\text{ind}}$  (for 0,8 s window or dwell time) is always larger than 12, i.e. in case  $t_{\text{dwell,ISO11451-1}} = 1 \text{ s}$  this always gives  $t_{\text{dwell}} = 1 \text{ s}$ . To illustrate the application of [Formula \(C.8\)](#), assume that the sampling rate would have been 1 kHz instead of 10 kHz. The calculated numbers  $N$ ,  $l_{\text{ind}}$ ,  $L_{\text{ind}}$  and  $N_{\text{ind}}$  still are correct, only the time scales, i.e. the window length would be 8 s instead of 800 ms, and the coherence times would be 316 ms, 257 ms, 104 ms and 107 ms. For 12 independent stirring configurations this equates approximately in 3,8 s, 3,1 s, 1,2 s and 1,3 s. For the first, third and fourth case, there was no partial correlation, i.e. again in case  $t_{\text{dwell,ISO11451-1}} = 1 \text{ s}$  this gives  $t_{\text{dwell}} = 3,8 \text{ s}$ ,  $t_{\text{dwell}} = 1,2 \text{ s}$  and  $t_{\text{dwell}} = 1,3 \text{ s}$ . For the second case, a more detailed analysis changing the window length is required. An engineering rough estimate would simply argue that in 8 s only 13,7 independent stirrer positions are created. The simple application of the calculated 3,1 s would therefore be clearly too small to ensure 12 independent stirring configurations. In this case of partial correlation, the dwell time may have to be adjusted in order to get a sufficient number of independent stirring configurations.

#### C.5 Field uniformity

The field uniformity is specified as a standard deviation from the mean value of the maximum values obtained from each of the probes in the reverb reference points during all stirring configurations. The standard deviation is calculated using data from each probe axis independently and the total data set. The maximum permissible standard deviations are given in [Table C.2](#).

From the data collected during the chamber calibration procedure (e.g. 8.5.2.1 or 8.5.3.1), determine for each frequency and for each probe location  $n \in \{1, \dots, N\}$  (usually  $N=8$ ) using Formulae (C.9, C.10 and C.11):

$$e_{x,n} = \max_{sc}(E_{x,n}) \quad (C.9)$$

$$e_{y,n} = \max_{sc}(E_{y,n}) \quad (C.10)$$

$$e_{z,n} = \max_{sc}(E_{z,n}) \quad (C.11)$$

where  $E_{i,n}$  are the measured electric field components in direction  $i \in \{x, y, z\}$  in probe location  $n$ .

Alternatively, the maximum electric field strengths may also be normalized to the mean forward power  $\langle P_f \rangle_{sc}$  using Formulae (C.12, C.13 and C.14):

$$e_{x,n} = \max_{sc}(E_{x,n}) / \sqrt{\langle P_f \rangle_{sc}} \quad (C.12)$$

$$e_{y,n} = \max_{sc}(E_{y,n}) / \sqrt{\langle P_f \rangle_{sc}} \quad (C.13)$$

$$e_{z,n} = \max_{sc}(E_{z,n}) / \sqrt{\langle P_f \rangle_{sc}} \quad (C.14)$$

This normalization is not required for the calculation of the standard deviation in dB, since the normalization term would cancel. So either Formulae (C.9), (C.10) and (C.11) can be used or Formulae (C.12), (C.13) and (C.14).

For each frequency calculate for each probe axis the average of the maxima of the E-field measurements over all  $N$  probe locations using Formulae (C.15, C.16, C.17 and C.18):

$$\langle e_x \rangle = \frac{1}{N} \sum_{n=1}^N e_{x,n} \quad (C.15)$$

$$\langle e_y \rangle = \frac{1}{N} \sum_{n=1}^N e_{y,n} \quad (C.16)$$

$$\langle e_z \rangle = \frac{1}{N} \sum_{n=1}^N e_{z,n} \quad (C.17)$$

$$\langle e \rangle = \frac{1}{3N} \sum_{n=1}^N (e_{x,n} + e_{y,n} + e_{z,n}) \quad (C.18)$$

NOTE If Formulae (C.9), (C.10) and (C.11) are used, then  $\langle e \rangle = E_{RC}$  holds (see Formula (B.1)). If Formulae (C.12), (C.13) and (C.14) are used, then  $\langle e \rangle = G_{RC}$  holds (see, e.g. Formula (3)).

The standard deviations shall be calculated using the following Formulae (C.19, C.20, C.21 and C.22):

$$\sigma_x = \sqrt{\frac{1}{N-1} \sum_{n=1}^N (e_{x,n} - \langle e_x \rangle)^2} \quad (C.19)$$

$$\sigma_y = \sqrt{\frac{1}{N-1} \sum_{n=1}^N (e_{y,n} - \langle e_y \rangle)^2} \quad (C.20)$$

$$\sigma_z = \sqrt{\frac{1}{N-1} \sum_{n=1}^N (e_{z,n} - \langle e_z \rangle)^2} \quad (\text{C.21})$$

$$\sigma = \sqrt{\frac{1}{3N-1} \sum_{n=1}^N \left( (e_{x,n} - \langle e_x \rangle)^2 + (e_{y,n} - \langle e_y \rangle)^2 + (e_{z,n} - \langle e_z \rangle)^2 \right)} \quad (\text{C.22})$$

The standard deviations shall be expressed in terms of dB relative to the mean using [Formulae \(C.23, C.24, C.25 and C.26\)](#):

$$\sigma_{x,\text{dB}} = 20 \log_{10} \left( \frac{\sigma_x + \langle e_x \rangle}{\langle e_x \rangle} \right) \quad (\text{C.23})$$

$$\sigma_{y,\text{dB}} = 20 \log_{10} \left( \frac{\sigma_y + \langle e_y \rangle}{\langle e_y \rangle} \right) \quad (\text{C.24})$$

$$\sigma_{z,\text{dB}} = 20 \log_{10} \left( \frac{\sigma_z + \langle e_z \rangle}{\langle e_z \rangle} \right) \quad (\text{C.25})$$

$$\sigma_{\text{dB}} = 20 \log_{10} \left( \frac{\sigma + \langle e \rangle}{\langle e \rangle} \right) \quad (\text{C.26})$$

The field uniformity can also be measured using the received power  $p_x$ ,  $p_y$  and  $p_z$  (using a vector network analyser or a spectrum analyser). In this case,  $10 \log_{10}$  shall be used when converting to dB unit.  $p_x$ ,  $p_y$ , and  $p_z$  are the received powers measured by an antenna (in three orthogonal orientations) instead of using a field probe, e.g. as used in the VNA method ([Annex F](#)).

**Table C.2 — Field uniformity requirements**

Frequency range	Tolerance requirements for standard deviation <sup>a</sup>
below 100 MHz	6 dB <sup>b</sup>
100 MHz to 400 MHz	6 dB <sup>b</sup> at 100 MHz decreasing linearly to 3 dB at 400 MHz
above 400 MHz	3 dB

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

<sup>b</sup> The standard deviation requirement of IEC 61000-4-21 (4 dB at frequencies ≤ 100 MHz) may be necessary if required by the test plan. Additional tuner steps may be necessary to achieve this more stringent standard deviation requirement.

## C.6 Lowest usable frequency (LUF)

The lowest usable frequency  $f_{\text{LUF}}$  of the chamber is the minimum frequency for which at least 12 independent stirring configurations can be achieved (i.e.  $N_{\text{ind}} \geq 12$ , see [C.2](#)) and the field uniformity requirements of [Table C.2](#) are met for the standard deviations of the three individual field components and for the total data set (see [C.5](#), [Formulae \(C.23\) to \(C.26\)](#)).

In the case of using [Table C.1](#), the lowest usable frequency  $f_{\text{LUF}}$  of the chamber is the minimum frequency that only meets the field uniformity requirements of [Table C.2](#) for the standard deviations of the three individual field components and for the total data set (see [C.5](#), [Formulae \(C.23\) to \(C.26\)](#)).

The LUF shall be determined after initial construction and major changes.

## Annex D (informative)

### Tuned mode and stirred mode

#### D.1 General

Reverberation chambers provide a means to create a statistical radiated immunity test environment. Two different basic philosophies how to create the statistics have been developed already during the early investigations on applying reverberation ideas in electromagnetics: the tuned mode and the stirred mode methods. This annex summarizes the main pros and cons for each method to provide the users of this document with the knowledge necessary to balance the benefits and risks. For further reading, Reference [9] is recommended.

#### D.2 Tuned mode

In tuned mode, a sequence of fixed stirring configurations (e.g. the angles of rotating tuners, which transmitting antenna to be used, or the angle of a turn-table) is defined prior to calibration or test. The procedure is that the necessary measurements (in case of calibration) or the application of the required field level for the defined dwell time (in case of test) are performed for each frequency and for each stirring configuration of the sequence. Neither the frequency nor the stirring configuration are changed during the measurement or dwell time. Often, the settling time of mechanical tuners is larger than the dwell time, so typically, the change of stirring configuration is implemented as the outer loop and the change of frequency as the inner loop in the test automation software to optimize the total time needed for calibration or test.

For VIRCs, the positions of the fabric walls practically cannot be fixed in their position. So the tuned mode method is practically impossible to implement for a VIRC.

Similarly, frequency stirring typically uses bandlimited white noise or some kind of frequency modulation. In principle, the signal modulation may be discretized into a fixed sequence, but usually stirred mode is used with frequency stirring.

A special case of a tuned mode can be created with applying pulse-modulated signals which are longer than the chamber time constant, but significantly shorter than the (mechanical) changes of the stirred mode method. The idea is similar to stroboscopes or the usage of flashlights in photography to freeze fast moving objects. This method, for example, can be used to efficiently measure the chamber time constant.

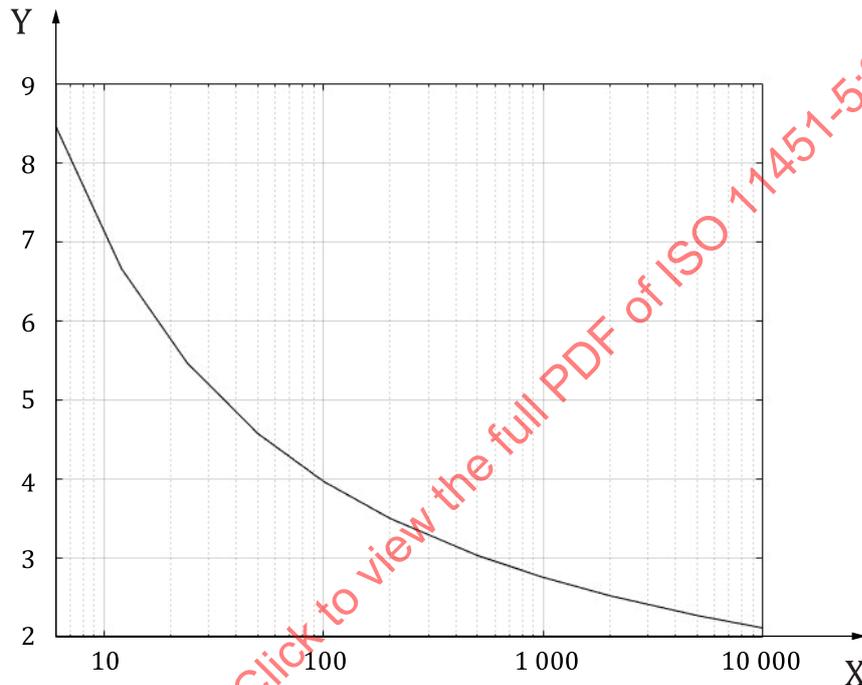
The main advantage of tuned mode is, that during the dwell time, the field patterns inside the reverberation chamber are constant. Of course, for each stirring configuration, this pattern is different, and in different places in and around the vehicle the values of the field components significantly differ. But the time behaviour of the field components is nearly the same as that of the output signal of the amplifier (except for changes which are not slower than the chamber time constant e.g. pulse modulation with pulse width of 3  $\mu$ s or less). An electronic device or system in the vehicle therefore has the full dwell time to react to the electromagnetic field configuration. This means that the same considerations for the choice of the dwell time apply as for the other parts of the ISO 11451 series. Also a CW test can be performed with tuned mode.

The main drawback of the tuned mode is the time required for performing calibration and test. All stirring configurations need to be measured or tested. For example, the total test time for a test with 12 stirring configurations with mode-tune is six times the test time of a test with antenna irradiation according to ISO 11451-2 with frontal irradiation and the two antenna polarizations horizontal and vertical. Depending on the instrumentation available for calibration, a new calibration may require

a significant amount in time. It is not unusual that a full calibration takes several days when using a single field probe.

Another drawback is that the test level uncertainty is directly influenced by the number of independent stirring configurations. For the well-stirred frequency range where the underlying assumption of a Rayleigh distribution for an electric field component holds, the confidence interval for the maximum value at a given input power can be calculated analytically, see Reference [21] and IEC 61000-4-21:2011, K.3.

Figure D.1 shows the ratio  $R_{95\%}$  of the upper bound to the lower bound of the 95 % confidence interval in dependence of the number of independent stirring configurations  $N_{\text{ind}}$ .



#### Key

X  $N$

Y  $R_{95\%}$  in dB

Figure D.1 — Width of 95 % confidence interval

For only 6 stirring configurations, the width is 8,5 dB, for 12 stirring configurations 6,7 dB, for 100 stirring configurations 4 dB, for 500 stirring configurations 3 dB, for 2 000 stirring configurations 2,5 dB. These results show that the more stirring configurations are tested, the smaller becomes the width of the 95 % confidence interval of the maximum field component and thus in the end the measurement uncertainty.

### D.3 Stirred mode

In stirred mode, the frequency is kept constant while the stirring configurations are changing continuously during the measurement or dwell time. For example, mechanical tuners are rotating with a defined speed, a VIRC is excited by a shaker. This means that the automation control loop just steps through the frequencies. The rest is done by, e.g. controllers of the mechanical tuners that set fixed speeds and turning directions during the dwell time.

This creates a constantly changing field pattern and the field values at any position are never constant during the dwell time. They change all the time. In other words, they are amplitude modulated but not with a 1 kHz constant frequency. It is a statistically amplitude variation. To some extent there will be

also a varying frequency shift due to the Doppler effect caused by moving walls or mechanical tuners. This effect is known to influence the measurement results of mobile transmitters, but is believed to be of little influence in EMC immunity testing, due to the limited frequency shifts of just a few 10 s or 100 s of Hertz. In the end, CW testing in stirred mode is impossible. On the other hand, there is only a very limited number of significant unmodulated CW sources installed, and when the vehicle is moving, the amplitude will change due to the distance change and due to the wave interference introduced by scattering objects like buildings, trees, and of course other vehicles. So usually, real-world electromagnetic fields, which may cause malfunctions, are also in some sense amplitude modulated and not CW.

The main advantage of stirred mode is that it allows a significant speed-up of the required total test time. It has been demonstrated that even in less than one (or a few) seconds, more than 12 independent stirring configurations can be produced. This means that instead of, for example, 12 separate frequency sweeps with different stirring configurations for tuned mode, a single sweep suffices, leading to a speed-up of 12 of the test or calibration.

Another advantage is, that the higher the frequency, the more independent stirring configurations are created per second. This means that the higher the frequency, the smaller is the variation of the mean and maximum values when the test is repeated with, e.g. another vehicle or a fixed component. In the end measurement uncertainty is significantly reduced (see [Figure D.1](#) for the width of the 95 % confidence value of a maximum field component) at higher frequencies compared to tuned mode where typically the number of stirring configurations is the same and sometimes even lowered at higher frequencies.

The drawback of stirred mode is that the field values constantly change completely independent of the time needed for a potential reaction of an electrical/electronic component or system. Two cases need to be considered: the quasi-tuned mode which means that the reaction of the vehicle or electronics is quicker than the field changes, and the turbo-stirred mode where the field changes are faster than the slowest reaction time.

### D.3.1 Quasi-tuned mode

In cases where the reactions are fast enough, the stirred mode method may be safely applied and any malfunctions will be found. This is also true for calibration, where the response time is the response time of the field probe or the receiving antenna and spectrum analyser which can be in the range of the chamber time constant.

This quasi-tuned mode is the stirred mode method from IEC 61000-4-21:2011, Annex C which defines an upper limit of the stirring speed considering the needed reaction time of the vehicle and its electronics. In cases where the reaction time is larger than a few  $\mu\text{s}$ , the formula given in IEC 61000-4-21 results in very significant test times. For several ms as reaction time, the time for one revolution of a single tuner exceeds easily 10 min for one revolution, making this method very impractical for slow reacting devices, and impossible for unknown devices when the default dwell time of 1 s would be used as reaction time of the vehicle electronics.

Some devices integrate the field and do not react on the maximum values, e.g. electro-explosive devices. In this case, the speed limit does not apply, but as test level in such case, the expected rms value of the field should be used instead of the expected maximum value.

### D.3.2 Turbo-stirred mode

In case of turbo-stirring, the actual testing is more like testing with AM modulation, but not with 1 kHz modulation frequency. The modulation is with a stochastic signal with a spectrum of several Hz to some 100 s of Hz in the case of mechanical stirring methods. Electronically, several 10 s of kHz can be easily achieved.

NOTE 1 Examples for implementations of turbo-stirring are the reverberation chamber at the University of Naples, Italy<sup>[9]</sup>, and VIRC<sup>[10]</sup>.

Since this signal is not a CW signal and also not AM, 80 %, 1kHz, it might be possible that the vehicle electronics might react differently than in a test with tuned mode due to the different test signal shape. Whether this happens or not depends heavily on the electronics. There might be electronics with reaction times in the ms range or below, which will react in this modulated signal in a similar way as with a CW signal with completely similar effect thresholds only depending on the maximum field value. But there might be also electronics, that react after several seconds of dwell time (e.g. in cases where internal error counters are increased until an observable malfunction is displayed or causes an error message).

Since each reverberation chamber is quite unique, the generated test signals differ from chamber to chamber and are not identical. As a consequence different responses in different chambers cannot be absolutely excluded. Many malfunctions are closely related to the maximum value achieved in the chamber, and then statistics and calibration guarantee that the expectation values of the field will be very similar (typically smaller than 1-3 dB).

NOTE 2 The distinction between quasi-tuned and turbo-stirred is based on both, the properties of the reverberation chamber and the reaction time of the vehicle or its electronics under test. This makes it impossible to label a facility itself as a quasi-tuned or turbo-stirred chamber.

## D.4 Comparison

[Table D.1](#) summarizes the pros and cons. In the end, the user has to balance the risk of missing an issue of an electronic device because the device did not react due to the modulation against the risk of not finding an issue because the test could not be performed due to limitation of resources like availability of a prototype vehicle, the facility, or the personnel to conduct the test in time plus the acceptance of a higher measurement uncertainty. In addition, the user has to decide between the possibility of CW testing with a higher test level uncertainty and an increased testing efficiency with higher test level accuracy.

**Table D.1 — Comparison tuned mode and stirred mode**

Method	Pros	Cons
tuned mode	<ul style="list-style-type: none"> <li>— CW test possible</li> <li>— same considerations of dwell time and vehicle electronics response time applicable as in ISO11451-2 testing</li> </ul>	<ul style="list-style-type: none"> <li>— significantly longer calibration and test time; much lower efficiency</li> <li>— higher test level uncertainty</li> </ul>
stirred mode	<ul style="list-style-type: none"> <li>— calibration and test time are significantly reduced; much higher efficiency</li> <li>— higher test level accuracy</li> </ul>	<ul style="list-style-type: none"> <li>— CW test not possible</li> <li>— uncertainty due to vehicle electronics response time</li> </ul>

## Annex E (informative)

### TLS method

#### E.1 General

This annex describes the TLS method which is an extension of reverberation chamber testing to frequencies below the lowest usable frequency of the reverberation chamber. This TLS method is similar to TLS testing inside an ALSE at low frequencies but includes several changes.

The applicable frequency range of the TLS method is 0,01 MHz to LUF.

This method requires the ability to shift room resonances, i.e. only mechanical stirring works (either rotating or moving tuners or moving or vibrating walls).

This method uses stirred mode only.

For TLS method, in contrast to the reverb method the  $\lambda/4$  minimum distance requirement does not apply.

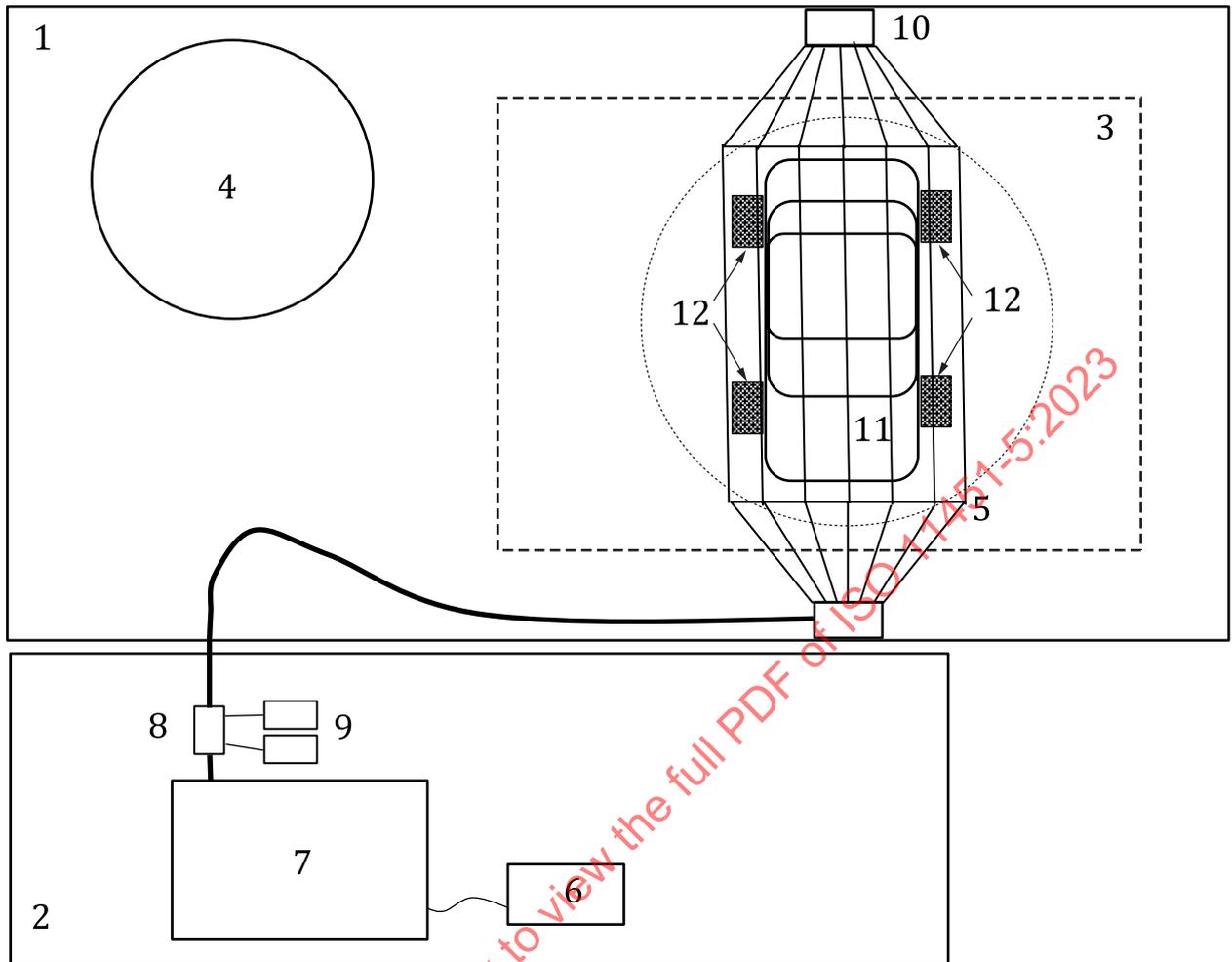
#### E.2 TLS

The TLS shall be designed for vertical polarization at low frequencies. An example of reverberation chamber with a parallel-plate TLS is shown in [Figure E.1](#).

No part of a TLS, with the exception of the ground plane, shall be closer than 0,5 m to any part of the vehicle. The TLS radiating elements shall be separated by at least 1 m vertically from the TLS reference points (see [E.3.2](#)).

The TLS shall extend centrally over at least 75 % of the length of the vehicle.

Particular care needs to be taken when testing heavy vehicles such as buses and large trucks. Under certain conditions related to dimensions and frequency, it is possible that close to 100 % of the applied power can be coupled to the vehicle by a directional coupler mechanism. Room resonances can also have a significant effect on the field uniformity, amplitude and direction under the TLS. Moving tuners may help to shift the resonances out of target band and frequencies, if needed.

**Key**

- |   |                                 |    |  |
|---|---------------------------------|----|--|
| 1 | reverberation chamber / VIRC    | 7  | RF amplifier                             |
| 2 | amplifier / operator room       | 8  | directional coupler                      |
| 3 | working volume                  | 9  | power meters                             |
| 4 | tuner, if used                  | 10 | load                                     |
| 5 | TLS (conductive plate or wires) | 11 | vehicle                                  |
| 6 | RF signal generator             | 12 | dynamometer (with or without turn-table) |

**Figure E.1 — Example of parallel-plate TLS**

### E.3 TLS method with substitution method power control

#### E.3.1 General

The test shall be performed with the substitution method. The substitution method is based upon the use of forward power as the reference parameter used for field calibration (corrected by the TLS loading correction factor) and during test.

This method is performed in three phases:

- field calibration without the vehicle present;
- loading measurement with the vehicle present;

- test of the vehicle.

The RF power required to achieve the required field strength is determined during the field calibration phase and the loading measurement phase.

The TLS loading correction factor determined during the loading measurement phase describes two phenomena:

- the change of strong resonances of the chamber which are caused by the vehicle compared to the field calibration measurement without vehicle present;
- the loading of the chamber caused by the vehicle because it adds loss to the chamber and hence consumes power and decreases the field strengths (like in the reverb method).

The loading measurement of a vehicle class needs to be performed only once, and is valid for all vehicles of this class. Classes may be, for example, small, mid-size, and large vehicles, or based on the vehicle type. The applicability of the classification shall be demonstrated by sample loading measurements. The needed number of classes depends on the differences in sizes of the vehicles tested and the size and instrumentation of the reverberation chamber.

During field calibration, loading measurement and test, all defined stirring configurations shall be used.

### E.3.2 TLS reference points

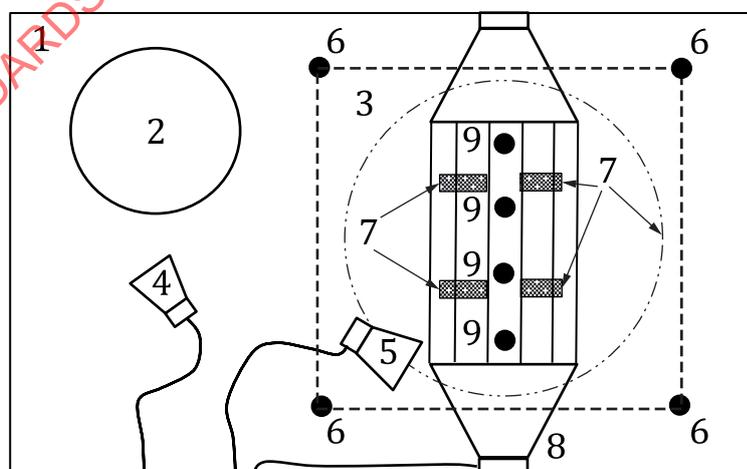
The TLS reference points are the positions of the field probes used for characterizing the chamber for the TLS method.

At least four points shall be used as TLS reference points. The points shall be evenly spaced on the midline along the septum of the TLS over the area where the vehicle will be placed for this test. The spacing between the points shall be chosen such that the longest vehicle will be covered. For example, if the vehicle intended to be tested have lengths of up to 6 m, in case of four TLS reference points the spacing between the TLS reference points should be 2 m (maximum length divided by 3), in case of seven TLS reference points the spacing should be 1 m (maximum length divided by 6).

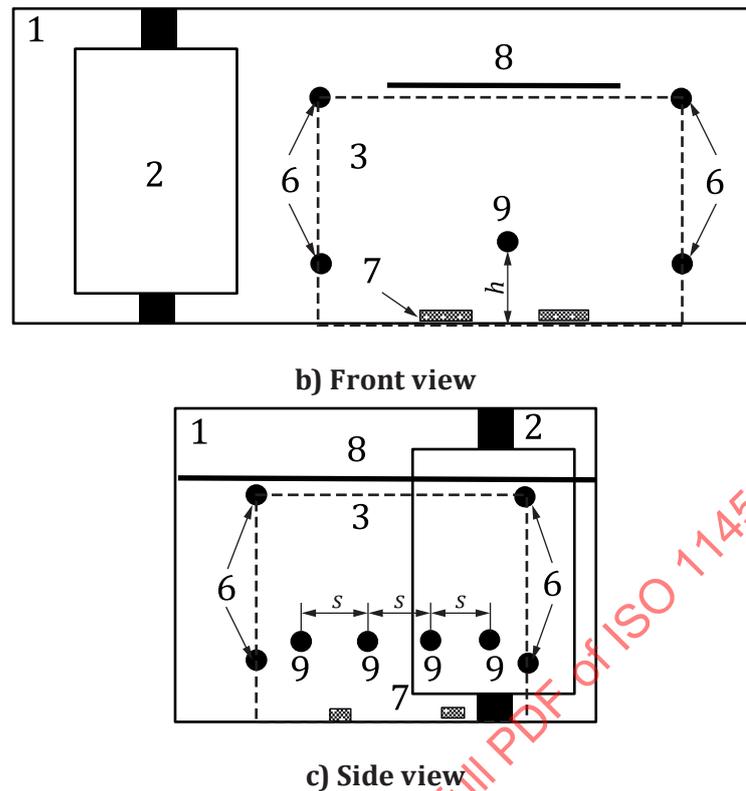
The TLS reference points shall be located at a height of  $(1 \pm 0,05)$  m above the shielded enclosure floor for vehicles with a roof height  $\leq 3$  m, or  $(1,8 \pm 0,05)$  m for vehicles with roof heights  $> 3$  m.

Figure E.2 shows an example of the TLS reference points.

The reverb reference points are additionally used to determine the loading effects of a vehicle for the TLS method.



a) Top view

**Key**

- |   |   |     |   |
|---|---|-----|---|
| 1 | reverberation chamber / VIRC                        | 6   | reverb reference points (8 points)                                |
| 2 | tuner   | 7   | dynamometer (with or without turn-table)                          |
| 3 | working volume                                      | 8   | TLS   |
| 4 | transmitting antenna (only shown in top view)       | 9   | TLS reference points (minimum of 4 shown)                         |
| 5 | receiving antenna, if used (only shown in top view) | $s$ | spacing between TLS reference points (see <a href="#">E.3.2</a> ) |
|   |   | $h$ | height of TLS reference points (see <a href="#">E.3.2</a> )       |

**Figure E.2 — Example of TLS reference points****E.3.3 TLS field calibration**

Calibration is performed without a vehicle in the test location.

The specific test level (field) shall be calibrated periodically by recording the forward power required to produce a specific test level (calculated from field probe measurements in the TLS reference points) for each test frequency.

This calibration shall be performed with an unmodulated sinusoidal wave.

When requested, the values of forward and reverse power recorded in the calibration file and a precise description of the associated reference and monitoring positions of the field probe(s) shall be included in the test report.

The mean of the field probe maximum field component readings is used as the calibration value.

**NOTE** In contrast to the TLS method of ISO 11451-2, the test level definition is based on the field probe component readings and not on the readings of the total values. For low frequencies where the field is almost perfectly vertically polarized, the difference is very small, but for higher frequencies this choice gives a smooth transition to the usual reverb test level definition which is based on the maximum readings of the individual field components.

The reference line is a horizontal line over which the field strength shall be established. The TLS reference points are defined in [E.3.2](#).

Additionally, for the purpose of loading determination, the maximum field strength in the eight reverb reference points (see [8.5.1](#)) shall be measured with a field probe (indicated in formulas by a subscript “mon” for “monitoring”).

The LUF breakpoint is dependent on the design of the user’s facility.

Place the TLS at the intended location. Place a field probe at TLS reference points on the horizontal TLS reference line (see [E.3.2](#)) and in the reverb reference points for monitoring the field for loading measurement. More than one field probe may be used at the same time.

Use for the TLS field calibration all stirring configurations as intended for testing (i.e. at the defined speeds).

For each test frequency, measure

- the mean value of the forward power  $\langle P_f \rangle_{sc}$  over all stirring configurations;
- the maximum values of the electric field strength components in the TLS reference points over all stirring configurations;
- the maximum values of the electric field strength components in the eight reverb reference points over all stirring configurations.

For each test frequency, calculate the TLS transfer factor  $F_{TLS}$  using [Formula \(E.1\)](#):

$$F_{TLS} = \frac{1}{M \sqrt{\langle P_f \rangle_{sc}}} \sum_{m=1}^M \max \left( \left\{ \max_{sc} (E_{TLS,x,m}); \max_{sc} (E_{TLS,y,m}); \max_{sc} (E_{TLS,z,m}) \right\} \right) \quad (E.1)$$

where

- $M$  is the number of TLS reference points used;
- $\langle P_f \rangle_{sc}$  is the mean value of the forward power in W over all stirring configurations;
- $E_{TLS,i,m}$  is the electric field strength in V/m measured in the  $m$ th TLS reference point for probe axis  $i \in \{x, y, z\}$ ;

and the normalized field level  $K_{TLS}$  of the empty chamber using [Formula \(E.2\)](#):

$$K_{TLS,empty} = \frac{1}{24 \sqrt{\langle P_f \rangle_{sc}}} \sum_{n=1}^8 \left( \max_{sc} (E_{RP,x,n}) + \max_{sc} (E_{RP,y,n}) + \max_{sc} (E_{RP,z,n}) \right) \quad (E.2)$$

where

- $\langle P_f \rangle_{sc}$  is the mean value of the forward power in W over all stirring configurations;
- $E_{RP,i,n}$  is the electric field strength in V/m measured in the  $n$ th reverb reference point for probe axis  $i \in \{x, y, z\}$ .

### E.3.4 TLS loading measurement

Loading measurement is performed with the vehicle in the test location.

This loading measurement shall be performed with an unmodulated sinusoidal wave.

Place the TLS at the intended location. Place a field probe in the reverb reference points for monitoring the field. More than one field probe may be used at a time.

Use for the TLS loading measurement the same stirring configurations as used for TLS field calibration intended for testing.

For each test frequency, measure

- the mean value of the forward power  $\langle P_f \rangle_{sc}$  over all stirring configurations;
- the maximum values of the electric field strength components in the eight reverb reference points over all stirring configurations.

For each test frequency, calculate the normalized field level  $K_{TLS}$  of the chamber with vehicle using [Formula \(E.3\)](#):

$$K_{TLS,veh} = \frac{1}{24\sqrt{\langle P_f \rangle_{sc}}} \sum_{n=1}^8 \left( \max_{sc} (E_{RP,x,n}) + \max_{sc} (E_{RP,y,n}) + \max_{sc} (E_{RP,z,n}) \right) \quad (E.3)$$

where

$\langle P_f \rangle_{sc}$  is the mean value of the forward power in W over all stirring configurations;

$E_{RP,i,n}$  is the electric field strength in V/m measured in the  $n$ th reverb reference point for probe axis  $i \in \{x, y, z\}$ ;

and the TLS loading factor using [Formula \(E.4\)](#):

$$M_{CLF} = \frac{K_{TLS,empty}}{K_{TLS,veh}} \quad (E.4)$$

### E.3.5 Vehicle test

The vehicle and associated equipment are installed in the working volume as described in [Figure E.1](#) and in the main body in [Clause 7](#) ([Figures 2](#) to [6](#)).

The position or positions of the vehicle relative to the TLS shall be specified in the test plan (see [8.1](#)).

The position of the charging cable between the vehicle and the HV-AN(s)/AMN(s), if any, shall remain unchanged regardless of the vehicle orientation, antenna location(s) and stirring configurations.

The vehicle shall be operated according to the test plan.

The test is conducted by subjecting the vehicle to the test signal based on the calibrated value and the TLS loading factor for the vehicle (class) as predetermined in the test plan. Calculate for each test frequency the necessary forward power  $P_{f,test}$  into the transmitting antenna for the required test level

$E_{TLS,test}$  using [Formula \(E.5\)](#):

$$P_{f,test} = \left( \frac{E_{TLS,test}}{F_{TLS}} M_{CLF} \right)^2 \quad (E.5)$$

Monitor the forward power into the transmitting antenna(s) and record the average value over all stirring configurations. Variations greater than 3 dB shall be noted in the test report.

Tests shall be conducted for all stirring configurations over the test frequency range. Any exceptions to this practice shall be specified in the test plan.

Interpolation methods may be used between calibration levels to determine the specific forward power to be used for a test. From a practical viewpoint, the increment between calibration levels when the amplifier is operating in a linear range may be larger than when operating in a region where compression occurs.

Scan the frequency range at the test level noting any anomalies.

Continue testing until all frequencies, modulations, stirring configurations and vehicle orientations specified in the test plan are completed.

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## Annex F (informative)

### Cavity mode method

#### F.1 General

This method consists of adopting chamber modes to generate required field strength with less power for the frequency between TLS method and LUF, typically (30-80) MHz, where the chamber has less modes density, however, tuner acts as moving cavity boundary to have modes of continuous frequencies during its movement and rotation.

For cavity mode method, in contrast to the reverb method, the  $\lambda/4$  minimum distance requirement does not apply.

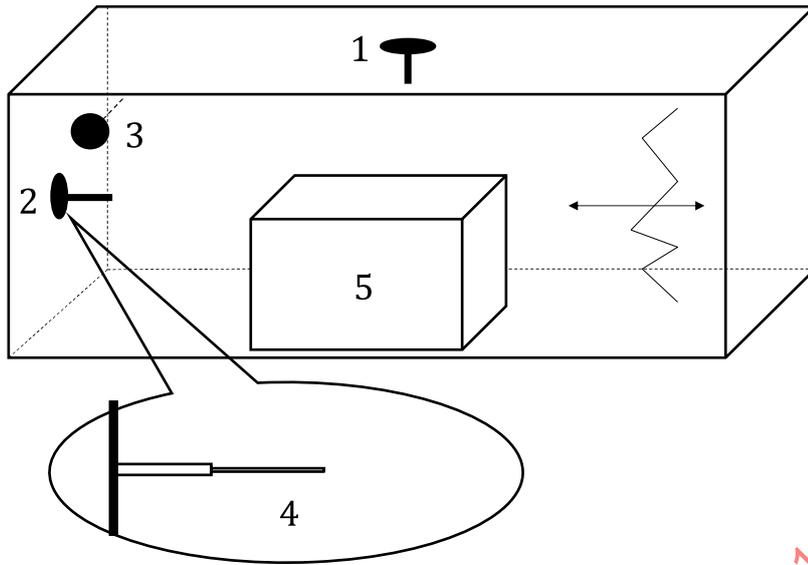
At least one eigen mode exists during the full travel of tuner at a frequency, if the chamber has no big contrast dimension for width and length, at least two modes exist because width and length is switchable at somewhere of tuner travel/rotation, e.g.  $TE_{nm} \approx TE_{nm}$ , called rotated modes like changing illumination for ALSE, considering the wavelength and electrical boundary restriction, the field strength and uniformity inside test volume is comparable better than that of ALSE for this band. Furthermore, FU can be improved if more than one mode exists for a frequency. For a reverberation chamber with  $L>W>10$  meters, normally there exists at least two modes for frequency greater than 30 MHz if stirring efficiency is high enough.

Transmitting antennas below 100 MHz normally have large structure and low efficiency, this is the limitation of field quality for ALSE, however monopole antennas can be used inside reverberation chamber acting as a feeding probe into cavity or waveguide, and extra advantage of neglectable ohmic loss. In open area site, monopole antenna gets resonance at frequency of  $n\lambda/4$ , indicated by low S11, inside the enclosed shielding structure, low S11 happens at not only correlating to  $L/\lambda$ , but also frequencies of chamber modes because of energy storage inside chamber, the phenomena can be observed by a VNA connected to a monopole of any length inside the reverberation chamber.

A problem to be solved that a probe (herein monopole antenna) at fixed location cannot launch the field of all existing modes, so still need multi location or multi monopole antennas to ensure all possible modes are activated. Motorized screw drive monopoles are adopted to provide variable lengths of whip to cover whole bands. The locations and monopole lengths can be obtained by trials for the target as many modes as possible. Three locations for XYZ polarizations are recommended, discrete length of monopoles 1 m/1,5 m/2,5 m are compromised to both cover (30-80) MHz and reduce variance for time saving.

Other antenna types than monopoles may be used (e.g. antennas especially designed to excite shielded rooms, if it can be demonstrated that the antenna (or antennas for multi-location/multi-antenna setups) excites the chamber modes well (i.e. low return loss and high field strength at least for one stirring configuration for each test frequency).

Example of instrumentation is shown in [Figure F.1](#).



**Key**

- |   |                              |   |  |
|---|------------------------------|---|--|
| 1 | tunable monopole, position 1 | 4 | detail of a tunable monopole: motorized tuning |
| 2 | tunable monopole, position 2 | 5 | working volume                                 |
| 3 | tunable monopole, position 3 |   |  |

**Figure F.1 — Example of instrumentation**

**F.2 Chamber characterization**

The verification of frequency coverage shall be carried on by antennas at three locations and network analyser, composite minimum S11 of all antennas and all lengths shall be less -10 dB in whole bands for full travel of tuner, this can be finished by  $N$  scans using [Formula \(F.1\)](#):

$$N = mn \tag{F.1}$$

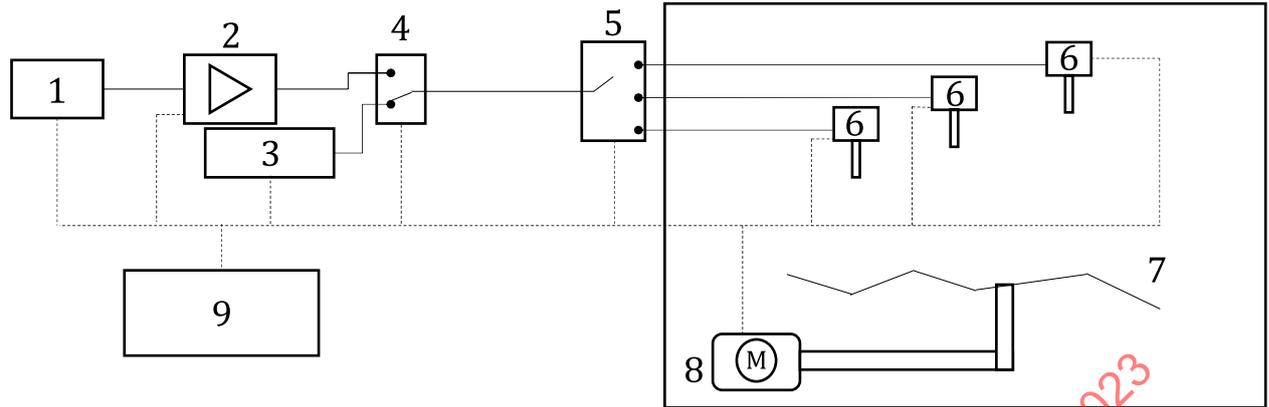
where

$m$  is the number of antenna locations;

$n$  is the number of antenna lengths.

For each scan, set network analyser S11 to minimum hold for full tuner cycle. Switch antenna one by one with antenna(s) which are not used in the scan in open circuit condition.

If composite S11 has S11 > -10 dB at some frequencies (normally < 10 %), additional diffusion structure shall be brought into chamber to increase complexity of reflection. See Figure F.2 for a test setup for chamber characterization.

**Key**

- |   |  |   |   |
|---|--|---|---|
| 1 | signal generator   | 6 | transmitting antennas (tunable monopoles) |
| 2 | power amplifier (if no internal sensor, external power sensors are needed) | 7 | tuner                                     |
| 3 | network analyser   | 8 | motor                                     |
| 4 | power switch   | 9 | control PC                                |
| 5 | power switch   |   |   |

**Figure F.2 — Test setup for chamber characterization**

### F.3 Calibration and test procedure

- Step 1: switch antennas connected with network analyser, log S11 of three antennas for full stirring cycle, repeat the same data record for all combinations of selected antenna lengths (default sets like early slide), stirring resolution =1 % or less, sweep frequency points is set to contain test frequencies.
- Step 2: performance data filtering and search lowest S11 with associated antenna no./length/ stirring position (as variances later) for each variance of each combinations, choose best two of all combination variances to perform field strength calibration and stress level testing.
- Step 3: switch the antenna to power amplifier, call the variances combination of last step to calibrate field strength with average of multi-probes' reading at low power level for example 1watt, record the field strength of each probes, perform field uniformity analysis using [Formula \(F.2\)](#):

$$U_F = 20 \log_{10} \left( \frac{\max(|E_{tot,n} - \langle E_{tot,n} \rangle|)}{\langle E_{tot,n} \rangle} \right) \quad (F.2)$$

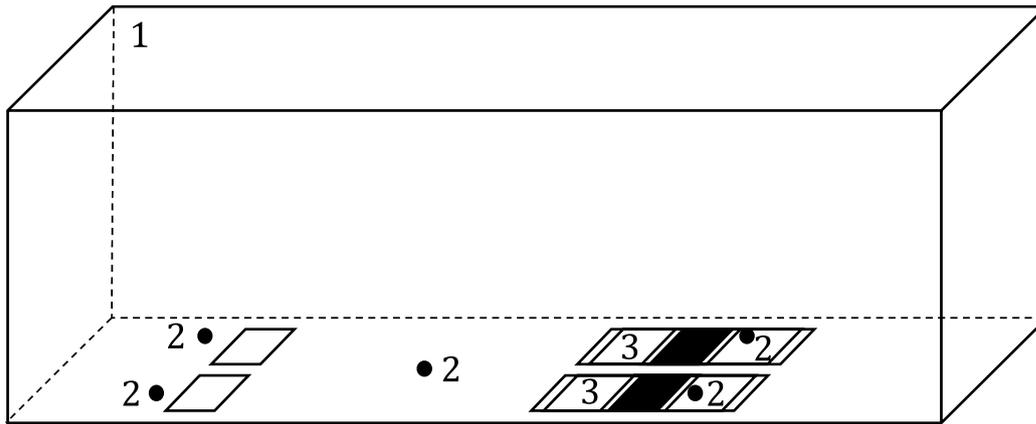
where

$n$  is the field probe number;

$E_{tot,n}$  is the measured total electric field strength by the  $n$  th probe.

Field probes distributes inside test volume either along longitude line like red dot or centre plus four corners like blue rectangle indicating at the height of 1 m, but ensure 2 m clearance to any wall of chamber.

Typically,  $U_F < 6$  dB for 90 % of frequency points. See Figure F.3 for a test setup for calibration.



**Key**

- 1 working volume
- 2 probe mast locations
- 3 dynamometer

**Figure F.3 — Test setup for calibration**

- Step 4: repeat steps 1 and 2 with vehicle inside chamber for the selected two combination because vehicle presented inside chamber requires re-tune of the mode at the frequency.
- Step 5: switch to power amplifier, then call the variances combination of last step to perform stress testing. Scale factor as below using [Formula \(F.3\)](#):

$$S_F = \left( \frac{E_{\text{test}}}{\langle E_{\text{tot},n} \rangle} \right)^2 \tag{F.3}$$

where

- $E_{\text{test}}$  is the test level in V/m;
- $\langle E_{\text{tot},n} \rangle$  is the mean value of the total electric fields in V/m measured in the field probes.

Typically, only less than 200 W is needed to achieve 100 V/m inside test volume.

Steps 1/2/3 need to be carried on for significant change of chamber, only repeat step 4 for different vehicle testing.

Network analyser pre-scan helps find the tuner position for mode under a combination of antenna location/length at each test frequency, then test system call for the status directly to inject the power, the procedure accelerates the testing operation.

**NOTE** Stirred mode can also be used for calibration and test, and helps to increase calibration and/or test efficiency. Compared to the reverb method in stirred mode, the field levels between the maxima become lower and the durations between maxima become longer.

## Annex G (informative)

### Reverb method with closed-loop power control

#### G.1 General

The reverb method with closed-loop power control is based upon the use of a field probe measurement system that allows the measurement of the electric field strengths and the calculation of the test level and the field uniformity in real time.

The applicable frequency range of the reverb method with closed-loop power control is LUF to 18 000 MHz.

This method is performed in a single phase:

- test of the vehicle.

#### G.2 Levelling parameter

Implementing the power control loop for closed-loop testing based directly on measurements of  $E_{RC}$  might lead to either an unacceptable long levelling time or to the risk of over-testing if the stirring speed is not fast enough. Therefore, using mean values or CDF-values (e.g. 80 % percentile) for the power control loop and correcting by the proper maximum to mean or maximum to CDF value is allowed. The proper ratio may be determined experimentally by measurements or by calculations (analytically or by statistical computer experiments assuming a Rayleigh distribution). Nevertheless, the test level shall be defined by one of the definitions of [Annex B](#).

NOTE 1 The VNA method of [Annex I](#) also applies this concept.

NOTE 2 The determination of statistical properties or the electric fields (or power levels) like the CDF together with the dwell time allows conclusions of how long the electric field strength actually was above or below a specific field value. For example, if the dwell time chosen is 10 s and the 80 %-percentile (field value at which 80 % of the measurement value were below or equal to this value) is 75 V/m, then for at least 2 s the electric field strength is at least 75 V/m.

#### G.3 Vehicle reverb test with closed-loop power control

Place the field generating device at the intended location. Place eight calibrated isotropic field probes at the reverb reference points.

The vehicle and associated equipment are installed in the working volume as described in the main body in [Clause 7](#) ([Figures 1](#) to [6](#)).

The position of the charging cable between the vehicle and the HV-AN(s)/AMN(s), if any, shall remain unchanged regardless of the vehicle orientation, antenna location(s) and stirring configurations.

The vehicle shall be operated according to the test plan.

The output power of the amplifier shall be increased until the required test level is indicated by the field measurement system. The mean forward power, the mean reverse power, the mean of the 24 maximum field components and the four standard deviations as required for field uniformity evaluation shall be recorded. In case the field uniformity requirement is not met, this shall be stated in the test report.

NOTE 1 A field probe can be placed in or outside the vehicle during the test.

Tests shall be conducted for all stirring configurations over the test frequency range. Any exceptions to this practice shall be specified in the test plan. The number of stirring configurations shall be at least 12 and at least 6 above  $3f_{LUF,veh}$  or  $3f_{LUF,maxload}$ .

For stirred mode testing the minimum dwell time defined in ISO 11451-1, might need to be extended to ensure at least 12 or 6 independent stirring configurations (see C.4). For example, the coherence time (see C.3) is 540 ms then the minimum dwell time is 6,48 s and above  $3f_{LUF,veh}$  or  $3f_{LUF,maxload}$  it is 3,24 s.

Scan the frequency range at the test level noting any anomalies.

Continue testing until all frequencies, modulations, stirring configurations and vehicle orientations specified in the test plan are completed.

For pulse modulation, it shall be checked that the pulse duration is long enough to reach a steady-state of the fields in the chamber and the switch-on transients have decayed. This can be easily checked with an oscilloscope or a spectrum analyser in zero-span mode connected to a receiving antenna in the working volume. The pulse duration of the pulse modulation shall be extended so that the steady-state time equals the required pulse duration.

NOTE 2 The switch-on and switch-off transients typically last for a few hundred nanoseconds to a few microseconds and can be easily distinguished from the "steady-state" that can change due to a stirred mode.

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## Annex H (informative)

### Chamber time constant method

#### H.1 General

The substitution method is based upon the use of forward power as the reference parameter used for field calibration and during test.

The applicable frequency range of the reverb method using the chamber time constant is LUF to 18 000 MHz.

This method is performed in two phases:

- field calibration (see [H.2](#));
- vehicle test (see [H.3](#)).

The field calibration of a vehicle class needs to be performed only once, and is valid for all vehicles of this class. Classes may be, for example, small, mid-size, and large vehicles, or based on the vehicle type. The applicability of the classification shall be demonstrated by sample calibrations. The needed number of classes depends on the differences in sizes of the vehicles tested and the size and instrumentation of the reverberation chamber.

The RF power required to achieve the required test level for the test of the vehicle is determined from the results of the field calibration phase.

#### H.2 Field calibration

This annex describes two field calibration procedures that are based on the measurement of the chamber time constant:

- the measurement of the chamber time constant with vehicle present allows directly to calculate the necessary input power and hence  $G_{RC}$  (see [H.2.1](#));
- if the mean absorption cross section (ACS) of the vehicle is known, the power requirement can be calculated directly without measuring the chamber time constant with vehicle (see [H.2.2](#)).

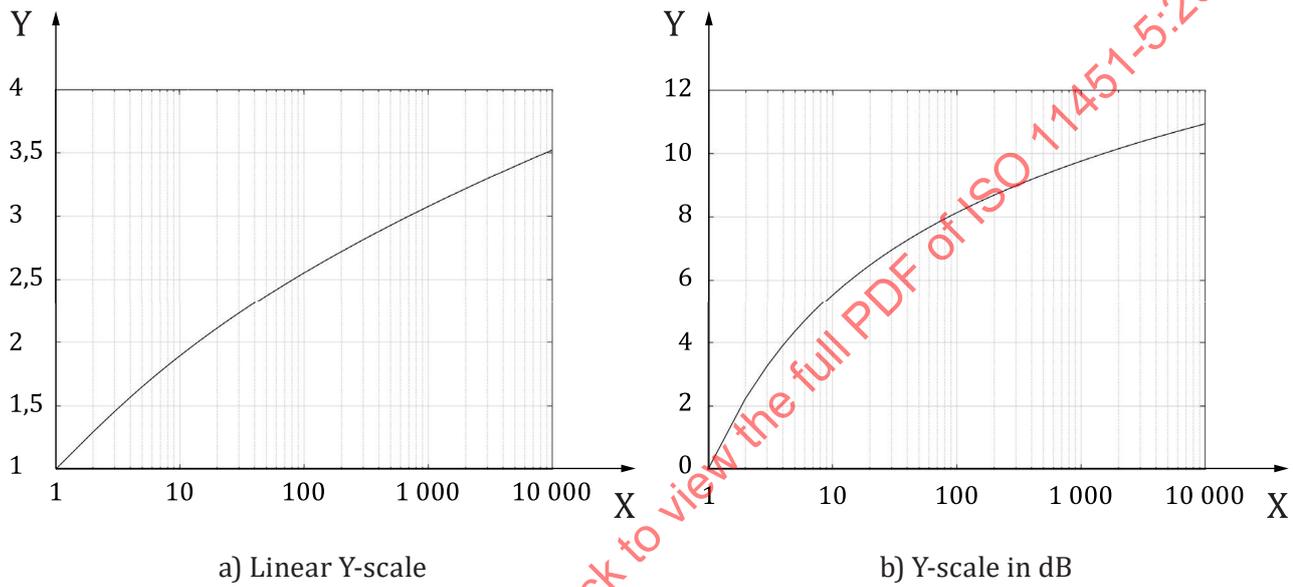
##### H.2.1 Field calibration with vehicle present

Measure the chamber time constant  $\tau_1$  of the loaded chamber with vehicle present according to [Annex L](#).

Determine the maximum to mean ratio  $\alpha$  of the electric field components either from experiments with similar vehicles, or from the number of independent stirring configurations  $N_{ind}$  by evaluating the following expression using [Formula \(H.1\)](#):

$$\alpha(N_{ind}) = \frac{\int_0^{\infty} N_{ind} x^2 \left[ 1 - \exp\left(\frac{-x^2}{2}\right) \right]^{N_{ind}-1} \exp\left(\frac{-x^2}{2}\right) dx}{\sqrt{\pi/2}} \tag{H.1}$$

[Figure H.1](#) gives graphs for  $\alpha$  in linear and in dB scale. For tuned mode,  $N_{ind}$  is the number of stirring configurations used (e.g. 6 or 12), for stirred mode, this needs to be determined by evaluating the autocorrelation function (see [C.2](#)).



**Key**  
 X  $N_{ind}$   
 Y  $\alpha(N_{ind})$

**Figure H.1 — The ratio of the expected maximum value and the expected value from  $N_{ind}$  independent samples**

[Table H.1](#) gives some values rounded to three significant digits.

**Table H.1 — The ratio of the expected maximum value and the expected value from  $N_{ind}$  independent samples**

$N_{ind}$	$\alpha(N_{ind})$ (linear)	$\alpha(N_{ind})$ in dB
1	1,00	0,00
2	1,29	2,23
5	1,65	4,35
10	1,89	5,53
20	2,11	6,48
50	2,37	7,50
100	2,55	8,14
200	2,72	8,69

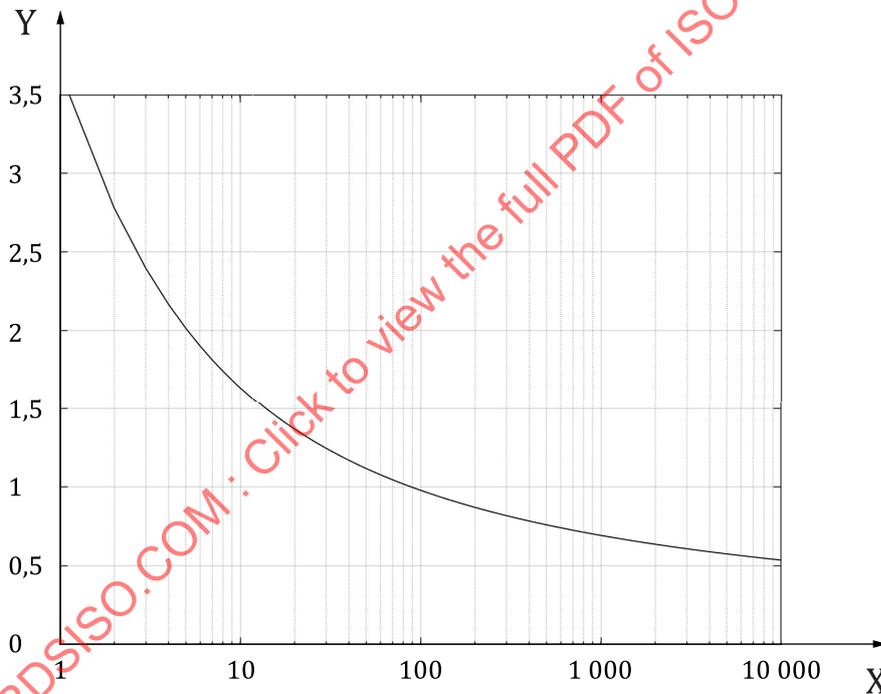
Table H.1 (continued)

$N_{\text{ind}}$	$\alpha(N_{\text{ind}})$ (linear)	$\alpha(N_{\text{ind}})$ in dB
500	2,93	9,33
1 000	3,08	9,76
2 000	3,22	10,2
5 000	3,39	10,6
10 000	3,52	10,9

Figure H.2 shows the relative standard deviation of the maximum electric field component with respect to the expectation value of the maximum electric field component on a logarithmic scale using Formula (H.2):

$$\sigma = 20 \log_{10} \left( \frac{\langle E_{i,\text{max}} \rangle + \text{std}(E_{i,\text{max}})}{\langle E_{i,\text{max}} \rangle} \right) \quad (\text{H.2})$$

as a function of the number of independent stirring configurations.



**Key**

X N

Y  $(\langle E_{i,\text{max}} \rangle + \text{std}(E_{i,\text{max}})) / \langle E_{i,\text{max}} \rangle$  in dB

**Figure H.2 — Relative standard deviation of the maximum electric field component**

The mean electric field component  $\langle E_{x,y,\text{or } z} \rangle$  can be calculated from the mean forward power  $\langle P_f \rangle$  in W and the chamber constant  $\tau_1$  in s of the loaded chamber with vehicle using Formula (H.3):

$$\langle E_i \rangle = \pi \sqrt{\frac{10 c_0 \tau_1 \eta_{\text{tx,tot}} \langle P_f \rangle}{V}} \quad (\text{H.3})$$

where

- $i$  is any direction of the probe axis  $i \in \{x, y, z\}$ ;
- $V$  is the volume of the reverberation chamber;
- $c_0$  is the speed of light (approximately  $3 \cdot 10^8$  m/s);
- $\eta_{\text{tx,tot}}$  is the total antenna efficiency of the transmitting antenna. The total antenna efficiency can be either estimated from the reflection coefficient of the transmitting antenna in free space and an assumed antenna efficiency of 0,9 for horn antennas and 0,75 for logarithmic periodic antennas, or measured using the method described in [Annex L](#).

The expectation value of the maximum of an electric field component can be estimated using  $\alpha(N_{\text{ind}})$  using [Formula \(H.4\)](#):

$$E_{\text{RC}} = \alpha(N_{\text{ind}}) \langle |E_i| \rangle = \alpha(N_{\text{ind}}) \pi \sqrt{\frac{10 c_0 \tau_1 \eta_{\text{tx,tot}} \langle P_f \rangle}{V}} \quad (\text{H.4})$$

Hence, the chamber gain with vehicle  $G_{\text{RC,veh}}$  is given by [Formula \(H.5\)](#):

$$G_{\text{RC,veh}} = \frac{E_{\text{RC}}}{\sqrt{\langle P_f \rangle}} = \alpha(N_{\text{ind}}) \pi \sqrt{\frac{10 c_0 \tau_1 \eta_{\text{tx,tot}}}{V}} \quad (\text{H.5})$$

## H.2.2 Calculation of the power requirement from the ACS

### H.2.2.1 Chamber time constant of the empty chamber

The chamber time constant  $\tau_u$  of the empty (unloaded) chamber without vehicle present shall be measured according to [Annex L](#).

### H.2.2.2 Calculation of the chamber gain from the ACS

If the ACS of the vehicle itself or an applicable class of vehicles is not known, measure the time constant  $\tau_l$  of the loaded chamber with vehicle present according to [Annex L](#) and calculate the ACS  $A_{\text{acs}}$  according to [Annex L](#).

Estimate the loaded chamber time constant  $\tau_l$  using [Formula \(H.6\)](#):

$$\tau_l = \tau_u \frac{V}{c_0 A_{\text{acs}} \tau_u + V} \quad (\text{H.6})$$

where  $V$  is the volume of the reverberation chamber,  $\tau_u$  is the chamber time constant of the unloaded empty chamber without vehicle present, and  $c_0$  is the speed of light.

Calculate the chamber gain according to [H.2](#).

NOTE If  $\tau_l$  needs to be measured first, it is not necessary first to calculate the ACS. The chamber gain can be calculated directly.

Also, the chamber loading factor  $F_{CLF}$  as defined in [8.5.2.3](#) can be calculated from the ACS by using [Formula \(H.7\)](#):

$$F_{CLF} = \frac{A_{ACF}}{A_{CCF}} = \frac{Q_{unloaded}}{Q_{loaded}} = \frac{\tau_u}{\tau_l} = \frac{A_{acs,empty} + A_{acs}}{A_{acs,empty}} \quad (H.7)$$

where  $A_{acs,empty}$  is the absorption cross section of the empty chamber, which can be calculated from the volume of the chamber, the speed of light and the empty chamber time constant using [Formula \(H.8\)](#):

$$A_{acs,empty} = \frac{V}{c_0 \tau_u} \quad (H.8)$$

This method therefore describes an alternative method to the method of [8.5.2.3](#).

### H.3 Vehicle test

The vehicle and associated equipment are installed in the working volume as described in the main body in [Clause 7](#) ([Figures 1](#) to [6](#)).

The position of the charging cable between the vehicle and the HV-AN(s)/AMN(s), if any, shall remain unchanged regardless of the vehicle orientation, antenna location(s) and stirring configurations.

The vehicle shall be operated according to the test plan.

The test is conducted by subjecting the vehicle to the test signal based on the calibrated value as predetermined in the test plan. Calculate for each test frequency the necessary forward power  $P_{f,test}$  into the transmitting antenna for the required test level  $E_{RC,test}$  using [Formula \(H.9\)](#):

$$P_{f,test} = \left( \frac{E_{RC,test}}{G_{RC,veh}} \right)^2 \quad (H.9)$$

Monitor the forward power into the transmitting antenna(s) and record the average value over all stirring configurations. Variations greater than 3 dB shall be noted in the test report.

NOTE 1 A field probe can be placed in or outside the vehicle during the test.

Tests shall be conducted for all stirring configurations over the test frequency range. Any exceptions to this practice shall be specified in the test plan. The number of stirring configurations shall be at least 12 and at least 6 above  $3f_{LUF,veh}$  or  $3f_{LUF,maxload}$ .

For stirred mode testing the minimum dwell time defined in ISO 11451-1, might need to be extended to ensure at least 12 or 6 independent stirring configurations (see [C.4](#)). For example, the coherence time (see [C.3](#)) is 540 ms then the minimum dwell time is 6,48 s and above  $3f_{LUF,veh}$  or  $3f_{LUF,maxload}$  it is 3,24 s.

Interpolation methods may be used between calibration levels to determine the specific forward power to be used for a test. From a practical viewpoint, the increment between calibration levels when the amplifier is operating in a linear range may be larger than when operating in a region where compression occurs.

Scan the frequency range at the test level noting any anomalies.

Continue testing until all frequencies, modulations, stirring configurations and vehicle orientations specified in the test plan are completed.

For pulse modulation, it shall be checked that the pulse duration is long enough to reach a steady-state of the fields in the chamber and the switch-on transients have decayed. This can be easily checked with an oscilloscope or a spectrum analyser in zero-span mode connected to a receiving antenna in the

working volume. The pulse duration of the pulse modulation shall be extended so that the steady-state time equals the required pulse duration.

NOTE 2 The switch-on and switch-off transients typically last for a few hundred nanoseconds to a few microseconds and can be easily distinguished from the “steady-state” that can change due to a stirred mode.

#### H.4 MATLAB code for calculating $\alpha$

The following MATLAB code was used to calculate  $\alpha$  numerically and create [Table H.1](#) and [Figures H.1](#) and [H.2](#):

```
clear;clc;close all;
Nno=101;
NList=unique([floor(logspace(0,4,Nno)) 1 2 5 10 20 50 100 200 500 1000 2000 5000 10000]);
AlphaN=zeros(1,numel(NList));stdN=zeros(1,numel(NList));
x=linspace(0,6,1001);
for ti=1:numel(NList)
    N=NList(ti);
    maxPDFN=N/2*pi*x.*exp(-x.^2*pi/4).*(1-exp(-x.^2*pi/4)).^(N-1);
    AlphaN(ti)=trapz(x,x.*maxPDFN);
    temp=trapz(x,x.*x.*maxPDFN);
    stdN(ti)=sqrt(temp-AlphaN(ti)^2)/AlphaN(ti);
end
figure;
yyaxis left;
plot(NList,AlphaN,'linewidth',2);
xlabel('N');ylabel('\alpha(N_{ind}) (linear)');
set(gca,'YLim',[1 4])
yyaxis right;
plot(NList,20*log10(AlphaN),'linewidth',2);
set(gca,'YLim',[0 12])
ylabel('\alpha(N_{ind}) (dB)');
set(gcf,'Color','w');grid on;
set(gca, 'XScale', 'log');
set(findall(gcf,'-property','FontSize'),'FontSize',24);
set(gcf,'position',[68 216 1222 653]);
figure(gcf);
figure;
plot(NList,20*log10(1+stdN));
set(gcf,'Color','w');grid on;
xlabel('N');ylabel(' (<E_{i,max}>+std(E_{i,max}))/<E_{i,max}> (dB)');
set(gca, 'XScale', 'log');ylim([0 3.5]);
set(findall(gcf,'-property','FontSize'),'FontSize',24);
set(gcf,'position',[68 216 1222 653]);
figure(gcf);
```



## Annex I (informative)

### VNA method

#### I.1 General

This annex describes the method when using a vector network analyser (VNA) for calibration of the reverberation chamber (RC) when loaded by the DUT. The method bases the calibration on average received power (instead of maximum electrical field) during either mode-tuning or mode-stirring.

The applicable frequency range of this reverb method using the VNA method is LUF to 18 000 MHz.

The test level is determined from the average power, and to reduce the risk of over-testing the test level is adjusted towards an upper quantile (output power is reduced). For example, a test level can be set to 90 %, which would mean that 10 % for the samples inside the RC will be equal to or above the test level and 90 % will be below.

In general, during both test and calibration, receiving antennas shall be placed at least  $\lambda/4$  at the RC LUF from any conducting surface. Except from the floor, as the vehicle is placed on the floor (see Reference [7]).

It is preferable to aim the transmitting and receiving antennas at tuners or corners of the RC, and always avoid a direct line-of-sight path between these antennas.

The analysis in this method assumes uncorrelated samples (see C.2), homogenous (i.e. field uniformity), and isotropic field.

The method is divided into four steps:

- field uniformity validation (see I.4);
- calibration of the RC when loaded with DUT (see I.5);
- calculation of the transmit (forward) power (see I.6);
- test of the vehicle (see I.7).

I.2 and I.3 contain definitions, and I.10 lists major uncertainty budget contributions.

#### I.2 Chamber transfer function

The average of the transferred power from the transmitting antenna to the receiving antenna inside the RC is defined by the chamber transfer function ( $H$ ). For the intended frequency range,  $H$  is calculated using Formula (I.1):

$$H_f = \frac{1}{N} \sum_{n=1}^N |S_{21,n,f}|^2 \quad (\text{I.1})$$

where  $N$  is the number of uncorrelated samples,  $n$  is sample index, and  $f$  is frequency. In short form we denote the average in Formula (I.1) as:

$$H_f = \langle |S_{21,n,f}|^2 \rangle \quad (\text{I.2})$$

where  $\langle \cdot \rangle$  denotes the linear average.

### I.3 Maximum load

The verification of the RC setup will implicitly give an upper limit on the permitted DUT load inside the RC. This is defined as the maximum loaded RC (MLRC). If the DUT loads the RC more, a new set of field uniformity measurements with more load inside the RC shall be performed.

The DUT can be tested if the relation  $H_{f,DUT} \geq H_{f,MLRC}$  is true for at least 90 % of the frequency samples.

### I.4 Field uniformity validation

Repeat the steps in [I.3](#) for all eight reference positions,  $i = \{1, \dots, 8\}$ , as defined in [8.5.1](#) and record the chamber transfer function  $H_{f,i}$ . Then calculate the standard deviation ( $\sigma$ ) using [Formula \(I.3\)](#):

$$\sigma_f = \sqrt{\frac{1}{8} \sum_{i=1}^8 (H_{f,i} - \langle H_{f,i} \rangle)^2} \quad (\text{I.3})$$

The verification shall be performed twice: on empty RC, and on MLRC. Maximum of standard deviation of the empty or the MLRC shall be put into the uncertainty budget.

The standard deviation shall be expressed in terms of dB relative to the mean of chamber transfer function over reference positions ( $\langle H_{f,i} \rangle$ ) using [Formula \(I.4\)](#):

$$\sigma_{f,dB} = 10 \log_{10} \left( \frac{\sigma_f + \langle H_{f,i} \rangle}{\langle H_{f,i} \rangle} \right) \quad (\text{I.4})$$

Chamber transfer function of MLRC is defined as the average:  $H_{f,MLRC} = \langle H_{f,i,MLRC} \rangle$ .

### I.5 Calibration of the RC

Calibration is fast and is performed with the DUT (vehicle) inside the RC.

For the intended frequency range, with the VNA sample  $S_{21}$  and calculate the chamber transfer function  $H$  according to [I.2](#).

Prior to RC calibration the VNA ports needs to be defined and calibrated. Typically, the VNA calibration plane is defined at the transmit and receive antenna ports.

It is sufficient to make use of one reference position as field uniformity variations are considered in the field uniformity analysis. If more reference positions are used, it is necessary to calculate their mean.

If the DUT loads the RC more than the MLRC, the field uniformity procedure in [I.4](#) shall be repeated with the DUT installed in the RC (this implies an update of the uncertainty budget).

## I.6 Average test level

The magnitude of the total electrical field can be expressed using [Formula \(I.5\)](#):

$$|E_{\text{tot}}| = \sqrt{|E_x|^2 + |E_y|^2 + |E_z|^2} \quad (\text{I.5})$$

In the RC, the average electric field is assumed to be independent of orientation. This implies that using [Formulae \(I.6 and I.7\)](#):

$$|E_x| = |E_y| = |E_z| \quad (\text{I.6})$$

and

$$|E_{\text{tot}}| = \sqrt{3} |E_{x,y,\text{ or }z}| \quad (\text{I.7})$$

According to Reference [\[12\]](#) the magnitude of the electric field can be expressed using [Formula \(I.8\)](#):

$$\langle |E_{x,y,\text{ or }z}| \rangle = \frac{4\pi}{\lambda} \sqrt{\frac{5\pi \langle P_{\text{rx}} \rangle}{\eta_{\text{rx,tot}}}} \quad (\text{I.8})$$

Given the calibration with the DUT inside the RC, received power can be related to transmit power according to [Formula \(I.9\)](#):

$$\langle P_{\text{rx}} \rangle = H_f \langle P_{f,\text{tx}} \rangle \quad (\text{I.9})$$

Where  $\eta_{\text{rx,tot}}$  is the total radiation efficiency of the receiving antenna ([Annex J](#)).

Combining [Formulae \(I.8\)](#) and [\(I.9\)](#), the required output power for the average test level can be calculated using [Formula \(I.10\)](#):

$$P_{f,\text{tx,avg}} = \frac{\eta_{\text{rx,tot}} \lambda^2 \langle |E_{x,y,\text{ or }z}|^2 \rangle}{80\pi^3 H_f} \quad (\text{I.10})$$

## I.7 Adjusted test level

The adjusted test level is based on the average of the transferred power in combination with an offset determined by the probability,  $p$ , where  $1-p$  is the probability that an electrical field sample is equal to or above the test level. For numerical examples, see Table I.1.

The absolute value of an electric field component,  $|E_{x,y,\text{ or }z}|$ , is assumed Rayleigh distributed. With the theoretical Rayleigh distribution one can adjust the transmit power to affect the density of the electrical field samples above a certain test level  $E_{\text{test}}$  [V/m]. This power bias can be calculated according to [Formula \(I.11\)](#):

$$\Delta_{p,\text{dB}} = 10 \log_{10} \left( \ln \left( \frac{1}{1-p} \right) \right) \quad (\text{I.11})$$

Where  $1-p$  is the probability that an electrical field sample is equal to or above the test level.