

# INTERNATIONAL STANDARD

# NORME INTERNATIONALE



INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE  
COMITÉ INTERNATIONAL SPÉCIAL DES PERTURBATIONS RADIOÉLECTRIQUES

BASIC EMC PUBLICATION  
PUBLICATION FONDAMENTALE EN CEM

**Specification for radio disturbance and immunity measuring apparatus and methods –**

**Part 1-6: Radio disturbance and immunity measuring apparatus – EMC antenna calibration**

**Spécifications des méthodes et des appareils de mesure des perturbations radioélectriques et de l'immunité aux perturbations radioélectriques –**

**Partie 1-6: Appareils de mesure des perturbations radioélectriques et de l'immunité aux perturbations radioélectriques – Étalonnage des antennes CEM**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION  
INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE

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**SPECIFICATION FOR RADIO DISTURBANCE AND IMMUNITY  
MEASURING APPARATUS AND METHODS –**

**Part 1-6: Radio disturbance and immunity measuring apparatus –  
EMC antenna calibration**

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International Standard CISPR 16-1-6 has been prepared by CISPR subcommittee A: Radio-interference measurements and statistical methods.

It has the status of a basic EMC Standard in accordance with IEC Guide 107, *Electromagnetic compatibility – Guide to the drafting of electromagnetic compatibility publications*.

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

|                   |                  |
|-------------------|------------------|
| FDIS              | Report on voting |
| CISPR/A/1087/FDIS | CISPR/A/1098/RVD |

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

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

A list of all parts of CISPR 16 series, under the general title *Specification for radio disturbance and immunity measuring apparatus and methods*, can be found on the IEC website.

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

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- withdrawn,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

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

## SPECIFICATION FOR RADIO DISTURBANCE AND IMMUNITY MEASURING APPARATUS AND METHODS –

### Part 1-6: Radio disturbance and immunity measuring apparatus – EMC antenna calibration

#### 1 Scope

This part of CISPR 16 provides procedures and supporting information for the calibration of antennas for determining antenna factors (AF) that are applicable to antennas intended for use in radiated disturbance measurements.

It has the status of a basic EMC Standard in accordance with IEC Guide 107, *Electromagnetic compatibility – Guide to the drafting of electromagnetic compatibility publications*.

The AF of an antenna is influenced by nearby surroundings and by its position in space relative to the radiating source. This standard focuses on antenna calibrations that provide the AF in a free-space environment in the direction of the boresight of the antenna. The frequency range addressed is 9 kHz to 18 GHz. The relevant antenna types covered in this standard are monopole, loop, dipole, biconical, log-periodic dipole-array (LPDA), hybrid and horn antennas.

Guidance is also provided on measurement uncertainties associated with each calibration method and configuration, and the test instrumentation used.

#### 2 Normative references

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

CISPR 16-1-4:2010, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-4: Radio disturbance and immunity measuring apparatus – Antennas and test sites for radiated disturbance measurements*  
CISPR 16-1-4:2010/AMD 1:2012

CISPR 16-1-5:2014, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-5: Radio disturbance and immunity measuring apparatus – Antenna calibration sites and reference test sites for 5 MHz to 18 GHz*

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

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

### 3 Terms, definitions and abbreviations

#### 3.1 Terms and definitions

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

NOTE Full terms for abbreviations not already given in 3.1 are listed in 3.2.

##### 3.1.1 Antenna terms

###### 3.1.1.1

###### **antenna**

transducer that converts the guided electromagnetic energy of the feed line into a radiated wave in space and vice versa

Note 1 to entry: In the context of this standard, for antennas for which a balun is intrinsic to the functioning of the antenna, the term “antenna” includes the balun.

###### 3.1.1.2

###### **biconical antenna**

symmetric antenna formed by two conical radiating elements having a common axis, and adjacent vertices at which they are fed

Note 1 to entry: For use in the VHF band, biconical antennas are usually made of two conical-shaped wire cages. Often each cage has a cross-bar connecting the centre conductor and one of the peripheral wires to remove a narrowband resonance. Such shorting cross-bars can affect the characteristics of the antenna above 215 MHz. For more details, see also A.4.3.

Note 2 to entry: For the purpose of this standard, a biconical antenna for which the tip-to-tip length is between 1,3 m and 1,4 m (based on the MIL-STD-461 design with tip-to-tip length of 1,37 m [45]<sup>1)</sup>), is referred to as a classical biconical antenna, to distinguish from small biconicals whose upper frequency is above 300 MHz.

###### 3.1.1.3

###### **broadband antenna**

antenna having acceptable characteristics over a wide range of radio frequencies

###### 3.1.1.4

###### **calculable antenna**

dipole-like antenna of which the antenna factor of a single antenna, and the site insertion loss between a pair of antennas, may be calculated using either analytical or numerical (method of moments) techniques based on the dimensions, load impedance and geometrical parameters, and that can be verified by measurement

Note 1 to entry: The calculable dipole antenna is a special case of calculable antenna; the good agreement between the analytical and numerical formulations confirms the very low uncertainties achievable with the linear dipole. A calculable dipole antenna is described in CISPR 16-1-5.

###### 3.1.1.5

###### **horn antenna**

antenna consisting of a waveguide section in which the cross-sectional area increases towards an open end, which is known as the aperture

Note 1 to entry: Rectangular-waveguide pyramidal horn antennas are popular in the microwave frequency range above about 1 GHz. Double-ridged-waveguide horn antennas (DRH; sometimes also referred to as DRG horn, for double-ridged-guide) cover a very wide frequency range. The mainlobe of some DRH antennas splits into several beams at higher frequencies; for other details see the NOTE in 9.5.1.3.

---

1) Numbers in square brackets refer to the Bibliography.

### 3.1.1.6

#### hybrid antenna

antenna consisting of a wire-element log-periodic dipole array section and a broadband dipole section

Note 1 to entry: The longest element of the LPDA (see 3.1.1.7) section is typically resonant at approximately 200 MHz, and the boom is lengthened at the open-circuit (rear) end to feed the connected broadband dipole (e.g. biconical or bowtie) section. Over the range 30 MHz to 200 MHz, the broadband dipole exhibits a performance similar to a biconical antenna, notably in the variation of  $F_a(h,p)$ .

Note 2 to entry: A common-mode choke is typically used at the open-circuit end (i.e. rear) of the boom, to minimize parasitic (unintended) RF currents on the outer conductor of the coaxial cable flowing into the measuring receiver.

### 3.1.1.7

#### log-periodic dipole array antenna

##### LPDA antenna

antenna comprising an array of linear dipole elements whose lengths and spacings increase logarithmically with frequency from the tip to the larger end of the antenna

### 3.1.1.8

#### monopole antenna

linear vertical antenna that is normally placed on a large horizontal conducting ground plane, which then has characteristics like a vertically polarized dipole antenna

Note 1 to entry: The monopole antenna is a combination of a vertical rod and matching unit at its base. Provided that the combined height is less than  $\lambda/8$ , the ESCM is a valid method for measuring the AF.

Note 2 to entry: The term “rod” describes the metal rod that is detachable from the matching unit at the point where it is replaced by the dummy antenna in the ESCM.

### 3.1.1.9

#### resonant dipole antenna

##### tuned dipole antenna

antenna consisting of two straight collinear conductors of equal length, placed end to end, separated by a small gap constituting a balanced feed, with each conductor approximately a quarter-wavelength long such that at the specified frequency the input impedance of the antenna measured across the gap has zero reactance when the dipole is located in free space

Note 1 to entry: A resonant dipole antenna is also a calculable antenna (see 3.1.1.4). In this standard the term “linear dipole” implies “two straight collinear conductors,” in contrast to the biconical dipole, or array of dipoles as in the LPDA antenna.

### 3.1.1.10

#### standard antenna

##### STA

antenna for which the AF is calculated or measured precisely

Note 1 to entry: An STA may be a calculable antenna (see 3.1.1.4) such as specified in 4.3 of CISPR 16-1-5:2014; alternatively an STA can be an antenna of a type similar to the AUC that has been calibrated to lower uncertainties than is required for the AUC. The three antenna method (TAM) is an example of methods for precise measurement of the AF of an STA.

Note 2 to entry: An STA is used for measurements by the standard antenna method (SAM) (see 4.3.5, etc.). An STA is mechanically robust such that reproducibility of AF to better than  $\pm 0,2$  dB is maintained with continuous use of the STA. Balance and cross-polar criteria applicable to the STA are found in 6.3.2 and 6.3.3.

### 3.1.1.11

#### antenna under calibration

##### AUC

antenna being calibrated, and as distinguished from the paired antenna(s) that are used in calibration measurements of the antenna under calibration

Note 1 to entry: See also 3.1.1.12 paired antenna.

**3.1.1.12****paired antenna**

antenna used in antenna calibration that covers the frequency range of the AUC and has similar directivity as the AUC

Note 1 to entry: Example antenna pairs for the TAM include biconical-biconical, biconical-dipole, biconical-hybrid, LPDA-hybrid, LPDA-LPDA, LPDA-horn.

Note 2 to entry: The distinction in the function of a paired antenna in the TAM and the SAM is given in 6.2.1.

Note 3 to entry: See 8.3.3 for description of similarity of antennas.

**3.1.1.13****balun**

device for transforming an unbalanced transmission line to a balanced transmission line and vice-versa

Note 1 to entry: A balun is used, for example, to couple balanced antenna elements to an unbalanced feed line, such as a coaxial cable. A balun may exhibit inherent impedance transformation differing from unity.

Note 2 to entry: In this standard the word balun is also used to refer to the handle of biconical or hybrid antennas, usually in the form of a metal tube or pole.

**3.1.1.14****antenna directivity**

ratio of the radiation intensity of an antenna in its boresight direction to the average radiation intensity

Note 1 to entry: See also 3.1.1.18 boresight direction, and 3.1.1.15 radiation pattern.

Note 2 to entry: The default definition of directivity is relative to the isotropic radiation condition (i.e. for the average radiation intensity, as in this definition), with the unit symbol dBi. When the reference is a half-wave dipole, which has a directivity of 1,64, the unit symbol is dBd ( $y \text{ dBd} = x \text{ dBi} - 2,15 \text{ dB}$ ).

**3.1.1.15****radiation pattern**

directional dependence of the relative intensity of radiation at a fixed distance from the phase centre of a transmit antenna

Note 1 to entry: See also 3.1.1.14 antenna directivity. The radiation patterns of interest for EMC testing are the co-polarized E-plane (see 3.1.1.16) and H-plane (see 3.1.1.17) radiation patterns.

**3.1.1.16****principal E-plane**

plane containing the electric field vector and the direction of maximum radiation, for a linearly-polarized antenna

Note 1 to entry: The principal E-plane pattern can be obtained by rotating in azimuth a horizontally-polarized AUC about its centre and measuring its output voltage, using a co-polarized transmit antenna situated in the far-field of the AUC, in a horizontal plane containing the centres of the AUC and the transmit antenna.

**3.1.1.17****principal H-plane**

plane containing the magnetic field vector and the direction of maximum radiation, for a linearly-polarized antenna

Note 1 to entry: The principal H-plane pattern can be obtained by rotating in azimuth a vertically-polarized AUC about its centre and measuring its output voltage, using a co-polarized transmit antenna situated in the far-field of the AUC, in a horizontal plane containing the centres of the AUC and the transmit antenna.

**3.1.1.18****boresight direction**

the axis of an antenna determined by its radiation properties, which for EMC antennas is the direction of maximum radiation from the antenna

Note 1 to entry: For EMC antennas the direction of maximum signal is usually: a) coincident with the direction in line with the mechanical longitudinal axis of LPDA antennas; b) orthogonal to the elements of monopole, dipole, and biconical antennas; c) orthogonal to the front aperture of horn antennas. In each of these cases, the orthogonal line is coincident with the centre of the antenna.

### 3.1.1.19

#### null

node in signal level resulting from the vector sum of the direct and ground-reflected signals at the receive antenna and with the level being considerably lower than the in-phase sum of these signals

Note 1 to entry: The depth of a null is measured from the in-phase sum of the direct and ground reflected signals. A null in the received signal occurs when the antennas are above a ground plane at heights such that the direct and ground reflected signal are in anti-phase, which can result in large errors in the calculation of AF. A null extends from 90° to 180° out of phase. At 90° the null depth is 6,02 dB. The depth is compared to the nearest adjacent maximum signal in the swept frequency response (or height scan of one antenna at a fixed frequency). Accurate AF results can be obtained in a null deeper than 6 dB, but the operator needs to confirm the quality of their ground plane, e.g. by using a calculable dipole antenna.

Note 2 to entry: The dip in signal level on boresight for some DRH antennas is sometimes referred to as a null. This definition does not apply to such dips.

Note 3 to entry: IEC 60050-726:1982, 726-02-07 defines standing-wave minimum, with synonym node (of a standing wave), as the location in a propagation medium where the vectorial sum of a specified field quantity of two waves creating a standing wave is a minimum.

## 3.1.2 Antenna factor terms

### 3.1.2.1

#### antenna factor

$F_a$

ratio of the electric field strength of a plane wave, incident from the direction corresponding to the mechanical boresight (i.e. the main axis of the antenna), to the voltage induced across a specified load connected to the antenna, measured in a free-space environment

Note 1 to entry: See 4.2 for further details. In this standard, the symbol  $F_a$  is synonymous with free-space antenna factor. Antenna factor is also used as a generic term, signified by AF, which includes free-space AF and height-dependent AF (see 3.1.2.4). AF has the physical dimension (unit) of inverse metres ( $\text{m}^{-1}$ ), and measured AF data are normally expressed in  $\text{dB}(\text{m}^{-1})$  [i.e.  $F_a$ ,  $F_{ac}$ ,  $F_a(h)$ ,  $F_a(h,p)$ , or  $F_a(d)$ ]. Plane wave incidence implies far-field conditions; see C.4. See also C.2 and C.3 for a generalized description of AF, antenna gain, and insertion loss measurements.

### 3.1.2.2

#### antenna factor for monopole antenna calibrated in plane wave conditions

$F_a$

ratio of the electric field strength of a plane wave, incident from a direction orthogonal to the antenna rod, to the voltage induced across a specified load connected to the antenna, measured with the bottom surface of its matching unit on, and in electrical contact with, the ground plane of an OATS

Note 1 to entry: The symbol  $F_a$  is used only when antenna factor is expressed in dB.

Note 2 to entry: The relationship between AF and gain for a monopole differs from that for other antennas; i.e. see C.2.2.

### 3.1.2.3

#### antenna factor for monopole antenna calibrated by the ECSM

$F_{ac}$

antenna factor measured by the Equivalent Capacitance Substitution Method

Note 1 to entry: The symbol  $F_{ac}$  is used only when antenna factor is expressed in dB.

Note 2 to entry: See 5.1.2. A method to correct  $F_{ac}$  for the influence of the matching unit to arrive at  $F_a$  is given in 5.1.2.2. The relationship between AF and gain for a monopole differs from that for other antennas; i.e. see C.2.2.

#### 3.1.2.4

##### height-dependent antenna factor

$F_a(h,p)$ ,  $F_a(h)$

antenna factor, as a function of height,  $h$ , and polarization,  $p$ , of an antenna located at a specified height  $h$  above the ground plane of an ideal OATS

Note 1 to entry: When the designator  $p$  is omitted, as in  $F_a(h)$ , horizontal polarization is assumed. Horizontal polarization is made explicit for example by  $F_a(h,H)$  as in B.4.2.

#### 3.1.2.5

##### magnetic field antenna factor

$F_{aH}$

ratio of the strength of an incident magnetic field component that is orthogonal to the area encircled by a loop element to the voltage induced across a specified load connected to the antenna

Note 1 to entry: The symbol  $F_{aH}$  is used only when antenna factor is expressed in dB. The quantity  $F_{aH}$  is expressed in dB( $\Omega^{-1}\text{m}^{-1}$ ).

Note 2 to entry: CISPR 16-1-4 specifies loop antennas for magnetic field measurements in the frequency range of 9 kHz to 30 MHz.

### 3.1.3 Measurement site terms

#### 3.1.3.1

##### anechoic chamber

shielded enclosure that is lined with radio-frequency absorbers to reduce reflections from the internal surfaces

Note 1 to entry: There are two different types of anechoic chamber, i.e. fully-anechoic room (see 3.1.3.5) and semi-anechoic chamber (see 3.1.3.8).

Note 2 to entry: An anechoic chamber suitable for antenna calibration has a more strict RF performance specification compared with a chamber for EMC radiated disturbance measurements (for details, see CISPR 16-1-5).

#### 3.1.3.2

##### calibration site

any site at which an antenna is calibrated

Note 1 to entry: Calibration sites include a CALTS (see 3.1.3.3) on which the ground reflection is intentionally used, a FAR (see 3.1.3.5), and an open-area calibration site (see Clause 6 of CISPR 16-1-5:2014) at which the antennas are high enough above the ground to reduce the ground reflection. For each of these, the reflections from all directions meet the appropriate site acceptance criteria for antenna calibration.

#### 3.1.3.3

##### calibration test site

##### CALTS

calibration site with a metallic ground plane and tightly specified site insertion loss in horizontal electric field polarization

Note 1 to entry: A CALTS is used for the measurement of height dependent AF, and to measure free-space AF by the standard site method.

Note 2 to entry: A CALTS can also be validated for: a) vertical polarization using the method of 4.7 of CISPR 16-1-5:2014; and b) other specific antenna calibration methods using the methods of 4.9 and 4.10 of CISPR 16-1-5:2014.

#### 3.1.3.4

##### free space

environment where it has been shown that the effect of any obstacle, including the ground, on the direct radiated signals passing directly between two antennas is below a specified uncertainty contribution for the measurement of  $F_a$

**3.1.3.5****fully-anechoic room****FAR**

an enclosure, the six internal surfaces of which are lined with radio-frequency absorbing material (i.e. RF absorber) that attenuates electromagnetic energy in the frequency range of interest

Note 1 to entry: A FAR suitable for antenna calibration has a tighter field uniformity specification compared with that for EMC radiated disturbance measurement specified in CISPR 16-1-4. If ambient RF interference prevents the required SNR, the FAR should be built inside a shielded enclosure.

**3.1.3.6****ideal open-area test site****ideal OATS**

open-area test site having a perfectly flat, perfectly conducting ground plane of infinite area, and with no reflecting objects except the ground plane

Note 1 to entry: An ideal OATS is a theoretical construct that is used in the calculation of the theoretical normalized site insertion loss  $A_i$  for ground-plane sites and in the modelling of antennas. See also 3.1.3.7 open-area test site.

**3.1.3.7****open-area test site****OATS**

facility for measurements and calibrations in which the ground reflection is made reproducible by a large flat electrically conducting ground plane

Note 1 to entry: An OATS can be used for radiated disturbance measurements, where it is also designated as a COMTS. An OATS can also be used for antenna calibrations, where it is designated as a CALTS.

Note 2 to entry: An OATS is an uncovered outdoor site, and is far enough away from buildings, electric lines, fences, trees, underground cables, pipelines, and other potential reflective objects, so that the effects due to such objects are negligible. See also 3.1.3.3 definition of a CALTS, and 3.1.3.6 definition of an ideal OATS. See CISPR 16-1-4 for guidance on the construction of an OATS.

**3.1.3.8****semi-anechoic chamber****SAC**

shielded enclosure, in which five of the six internal surfaces are lined with radio-frequency absorbing material (i.e. RF absorber) that attenuates electromagnetic energy in the frequency range of interest, and the bottom horizontal surface is a conducting ground plane for use with OATS test set-ups

Note 1 to entry: A SAC suitable for antenna calibration has a tighter normalized site attenuation specification for the purposes of antenna calibration compared with that for EMC radiated disturbance measurement. If ambient RF interference prevents the required SNR, the SAC should be built inside a shielded enclosure; see also 3.1.3.5 fully-anechoic room.

**3.1.4 Other terms****3.1.4.1****measuring receiver**

signal measuring instrument, such as a stepping receiver, a spectrum analyzer, or the receiving part of a network analyzer, that fulfils the selectivity and linearity requirements of the relevant calibration method

Note 1 to entry: The term measuring receiver may also imply the full functions of a vector network analyzer. In this standard, the term "signal" means a sinusoidal signal with constant amplitude; see 6.2.1 for other details. For the purposes of antenna calibration, this definition is a modification of that found in CISPR 16-1-1 [1] and CISPR 16-2-3 [2].

**3.1.4.2****site attenuation****SA** $A_s$ 

minimum site insertion loss measured between two polarization-matched antennas located above a conducting ground plane on a calibration site when one antenna is moved vertically over a specified height range and the other is set at a fixed height

Note 1 to entry: The terms site insertion loss (see 3.1.4.3) and site attenuation describe essentially the same measurement quantity, however the term SA is used in the context of finding the minimum value of the site insertion loss (SIL) measured for a pair of antennas when one antenna was scanned in height above a ground plane.

**3.1.4.3****site insertion loss****SIL** $A_i$ 

transmission loss between two polarization matched antennas when a direct electrical connection via cables and attenuators between the signal generator output and the measuring receiver input is replaced by a transmit antenna and a receive antenna placed at specified positions on a calibration site

Note 1 to entry: Refer to 7.2 for other details.

Note 2 to entry: The symbol  $A_i$  uses  $A$  as the conventional symbol for attenuation, with the subscript  $i$  denoting insertion; for  $A_i$  the subscript is not to be confused with usage in this standard of  $i$  as an index symbol, e.g.  $i = 1, 2, 3$ .

**3.2 Abbreviations**

The following are abbreviations used in this standard that are not already given in 3.1.

|      |                                                                   |
|------|-------------------------------------------------------------------|
| AF   | antenna factor                                                    |
| DANL | displayed average noise level                                     |
| DVM  | digital voltmeter                                                 |
| DRH  | double-ridged horn                                                |
| EM   | electromagnetic                                                   |
| EMC  | electromagnetic compatibility                                     |
| ECSM | equivalent capacitance substitution method                        |
| EUT  | equipment under test                                              |
| GTEM | gigahertz transverse electromagnetic                              |
| HP   | horizontal polarization                                           |
| LNA  | low-noise amplifier                                               |
| NEC  | Numerical Electromagnetics Code (wire antenna modelling software) |
| NSA  | normalized site attenuation                                       |
| RF   | radio frequency                                                   |
| RSS  | root-sum-square (square root of the sum of the squares)           |
| SAM  | standard antenna method                                           |
| SNR  | signal-to-noise ratio                                             |
| SSM  | standard site method                                              |
| TAM  | three antenna method                                              |
| TEM  | transverse electromagnetic                                        |

VNA      vector network analyzer  
 VP        vertical polarization  
 VSWR    voltage standing wave ratio

## 4 Fundamental concepts

### 4.1 General

This standard specifies methods to calibrate antennas that are used to perform radiated disturbance measurements. The main calibration parameter is antenna factor,  $F_a$ , which can be equivalently converted to realized gain (see Annex C).

It is recognized that when used in accordance with the test methods defined in CISPR 16-2-3 [2], the measurement antenna may not be in free space, being located instead above a metallic ground plane at a height of between 1 m and 4 m. Methods are specified in Annex B to measure the antenna factor as a function of height and polarization above a metallic ground plane,  $F_a(h,p)$ . These methods allow the differences between the  $F_a$  and  $F_a(h,p)$  values of an antenna to be quantified and included as a contribution to the uncertainty associated with performing radiated disturbance measurements above a metallic ground plane. See A.1 for rationale of the need for a ground plane, and rationale of a choice of calibration methods based on available test sites, available state-of-the-art knowledge, and a required uncertainty level.

Associated with each antenna calibration method is a method for validating a calibration site, and an acceptance criterion for that site that is related to the uncertainty required of the AF. The relevant site specifications and site validation methods are given in CISPR 16-1-5.

### 4.2 The concept of antenna factor

The antenna factor  $F_a$ , in dB(m<sup>-1</sup>), as defined in 3.1.2.1, is determined by Equation (1):

$$F_a = E - V \quad (1)$$

where

$E$       is the field strength in dB(μV/m) of the incident plane wave that illuminates the antenna;

$V$       is the resultant voltage in dB(μV) across the output terminal of the antenna.

As shown in C.2.1, the AF depends on the load  $Z_0$  connected to the antenna output as well as the impedance  $Z_0'$  seen from the gap between the radiating elements towards the load. An antenna factor is also affected by mutual coupling to its surroundings, for example the proximity of other antennas, the ground, and buildings. However, with the definition of AF as being in a free-space environment, these effects on  $F_a$  are minimized. The quantity  $V$  is normally measured at the receiver end of a cable connecting the antenna to the receiver, therefore  $V$  is to be corrected by the cable loss [see e.g. Equation (48) in 7.4.3.1]. A mismatch loss correction would also be required for a cable with poor match (i.e. see 6.2.2).

This standard assumes that radiated disturbance measurements are made using  $F_a$  (see rationale given in A.4). In radiated emission measurements, the incident field strength,  $E$ , can be calculated from a reading,  $V$ , of a measuring receiver connected to the antenna using  $E = V + F_a$ , where  $E$  is in dB(μV/m),  $V$  is in dB(μV) and  $F_a$  is in dB(m<sup>-1</sup>). The effect of any influence factor within the calibration environment that perturbs  $F_a$  is treated as a source of uncertainty; for other details see 7.3 of CISPR 16-2-3:2010 [2].

Measurements of radiated disturbance from an EUT are made at a fixed distance, e.g. 3 m. Where the distance from the EUT to the demarcated geometrical centre of an LPD antenna

is used, there will be an error in the electric field strength at frequencies not corresponding to that at the centre of the LPDA antenna. The electric field strength can be corrected for the difference between the actual phase centre position and the geometrical centre position as described in A.6.2 and CISPR 16-2-3 [2], or alternatively this correction can be built into the antenna factor.

Use of a horizontally-polarized dipole, biconical or hybrid antenna for EUT radiated disturbance measurements above a metallic ground plane introduces uncertainty caused by mutual coupling with the image of the antenna in the ground plane. This changes the impedance of the radiating elements seen by the balanced terminals of the balun, and changes  $F_a$  into a height dependent AF,  $F_a(h,p)$ . To quantify the uncertainties contributed by the difference of  $F_a(h,p)$  from  $F_a$ , it is acceptable for this difference to be obtained from generic measurements, or simulations of each model of antenna. An antenna manufacturer may be able to provide  $F_a(h,p)$  over the height range 1 m to 4 m.

### 4.3 Calibration methods for 30 MHz and above

#### 4.3.1 General

This subclause provides basic considerations for the antenna calibration methods defined in this standard. Free-space AF,  $F_a$ , and height-dependent AF,  $F_a(h,p)$ , can be measured using either the three antenna method (TAM) or the standard antenna method (SAM).  $F_a$  can also be measured using the standard site method (SSM), including a correction.

By the reciprocity theorem, it is not necessary to specify which antenna shall transmit or receive. The measurement of any AUC requires a second antenna, which shall be referred to as its “paired” antenna (see 3.1.1.12), leaving the calibration laboratory to decide which is most convenient to connect to the signal source or the receiver. An exception is that antennas with preamplifiers shall only be connected to the receiver. All calibration methods are based on the SIL measurement procedure described in 7.2.

#### 4.3.2 Antenna minimum separation distances

For calibrations using the TAM, the separation of the antenna pair shall be precisely known so that it can be used in the equation for the calculation of  $F_a$ . During the calibration of dipole and LPDA antennas, a fixed separation of  $2\lambda$  at the lowest frequency of interest shall be maintained between the phase centres of the antenna pair. For the calibration of biconical and hybrid antennas, a fixed separation of 10 m can be maintained because the longest dipole elements behave as short dipoles below 60 MHz. See C.5 for other details.

NOTE Although 10 m is only one wavelength ( $\lambda$ ) at 30 MHz, the length of a biconical antenna is only  $0,14\lambda$ , and there is negligible mutual coupling between the antennas. The additional uncertainty of the AF due to calibration using a distance of 10 m instead of 20 m is 0,1 dB at 30 MHz, and reducing with frequency to 0,03 dB at 60 MHz.

#### 4.3.3 General considerations for the TAM

The TAM is a method of antenna calibration for which no prior knowledge of the AF of any of the three antennas is needed. The TAM involves the use of three antennas of similar type (“paired antennas,” see 3.1.1.12) that cover a common frequency range. Three unique antenna pairs can be formed from the three antennas, and the SIL of each pair is measured. The TAM is described further in 7.4.1.1, 7.4.1.2, 8.2, 9.2.4, 9.4.2, B.4.3, and B.5.3.

#### 4.3.4 General considerations for the SSM

The SSM is effectively the TAM when performed over a ground plane, as described in 7.4.2 and 8.4. The reflected signal at the ground plane surface undergoes a phase change of  $180^\circ$  for horizontal polarization; the antenna heights (and/or separation distance) are adjusted so that the direct and reflected signals combine to give a signal maximum.

Horizontal polarization is preferred because the uniform H-plane pattern (over the relevant angular range) simplifies the calculation of AF and because reflections from antenna masts

and cables are minimized. To ensure that the measured AF is close in value to  $F_a$  as measured using the other methods of this document, one antenna is at a fixed height of 2 m and located in the far field of the paired antenna that is scanned in height to avoid a null in the received signal (see the null criterion in 3.1.1.19). The separation distance used for the SSM in reference [13] is 10 m. However to be in the far-field, tuned dipoles at 30 MHz should preferably use 20 m separation; see Table B.7 (see B.5.2) including above 30 MHz. If 10 m is used, the uncertainty shall be accounted for. The agreement with  $F_a$  can be improved by adding a correction factor, for example as shown by Equation (59) (see 8.4.3).

#### 4.3.5 General considerations for the SAM

A set of standard antennas (STAs), having antenna factors accurately determined, is required for the SAM. The STA can be an antenna that has been calibrated either using the TAM or using substitution with a calculable antenna. For the calibration of a single antenna, the SAM involves just two measurements of SIL, whereas the TAM needs three measurements of SIL.

NOTE In some literature the SAM has been referred to as the reference antenna method, which employs a reference antenna whose geometry, structure and AF are rigorously specified by standards such as ANSI C63.5 [13] or CISPR 16-1-5. Apart from this, the reference antenna method is synonymous with the SAM.

The SAM is more tolerant of field non-uniformities caused by the site than the TAM, which implies that the quality of the site can be relaxed over that required for the TAM (see A.1 and A.9.4 for other details). This consideration assumes that the STA and AUC are of the same type (e.g. the classical biconical antenna design; see 3.1.1.2), from which it follows that they will have similar mechanical dimensions and therefore similar radiation patterns. Ideally, the STA used is the same model of antenna as the AUC, but it may not be practicable for a calibration laboratory to have numerous STAs. See 8.3.3 for guidance on determining similarity of antennas in SAM calibrations. A calculable dipole antenna as the STA is ideally suited for calibrating dipole antennas. Providing the field incident on the antennas is uniform, as described in 4.9 of CISPR 16-1-5:2014, a calculable dipole can be used to calibrate a biconical antenna; e.g. see 9.3 and A.9.4.

#### 4.4 Measurement uncertainties for antenna calibration measurement results

Measurement uncertainties shall be estimated for each antenna calibration results set, using methods consistent with ISO/IEC Guide 98-3:2008. Measurement uncertainty is a function of the properties of the calibration measurement set-ups, the instrumentation and the general characteristics of the AUC. See also A.9.2 about typical measurement uncertainty ranges. Each calibration laboratory shall quantify its own measurement uncertainties.

Example measurement uncertainty budgets are given for each method of calibration contained in this standard (i.e. see Clause 8 and Annex B). In the column headings, “Value” is the best estimated value of  $X_i$ , “Probability distribution” is the probability distribution function, “Sensitivity” is the sensitivity coefficient  $c_i$ , and  $u_i$  is the uncertainty contribution  $u_i(y)$ . Numerical values are included for illustration purposes only. The symbol  $u_i$  signifies the “standard uncertainty” applying to each term in the budget. These examples should help laboratories prepare measurement uncertainty budgets specific to their needs, facilities, and instrumentation. The examples include all of those influence quantities that are common to all antenna calibration sites, but some calibration laboratories and sites may have additional influence quantities that are not listed. In this case, the additional influence quantities shall be added to the model and accordingly to the measurement uncertainty budget. See also Annex C for information about certain antenna characteristics useful for uncertainty analysis.

NOTE The “law of propagation of uncertainty” is approximate when an input quantity, here site imperfection, is dominant and has a distribution that is non-linear. It is far from easy to say what error will be committed. ISO/IEC Guide 98-3:2008/SUP (GUM) [7], which uses a Monte Carlo method for the propagation of (probability) distributions, is applied in any cases of doubt.

Uncertainty budgets can often overestimate the expanded uncertainty, because they comprise many estimated component uncertainties. A way to test the correctness of a budget is to compare the AF measured by at least two independent methods. This could alternatively be achieved by an international intercomparison. The smaller the difference in results, the more

different methods, the greater the confidence in the outcome. If the difference in the AFs of method A and method B is no larger than the individual “combined standard uncertainty” for the results of method A or method B, this points to the possibility that some of the larger components in the budgets have been overestimated and are worthy of further investigation.

#### 4.5 Summary of methods of measurement to obtain AF

Many different antenna types are available for use in radiated disturbance measurements. These antennas can be calibrated with either the TAM or the SAM that require SIL measurements, or with the SSM that requires SA measurements. The antenna calibration methods for frequencies above 30 MHz are summarized in Table 1, with a corresponding subclause number for details of the method. The detailed measurement procedures specific to each calibration method are specified in Clause 8 and Annex B, where the equations for obtaining AF as specific to each calibration method are also provided.

Table 1 is a lookup table by antenna type and frequency range, and shows also the type of site, either with a ground plane or with absorber, the antenna heights and separation distance, and the polarization used. See also A.1 for other background concerning the multiple methods described in this standard.

Additionally, methods for measuring the height-dependent antenna factor,  $F_a(h,p)$ , are described in B.4 (see also 4.2), applicable for horizontally-polarized tuned dipole and biconical antennas, and the broadband dipole (e.g. biconical) portion of hybrid antennas.

The information in Table 1 is presented instead by subclause number in Table 2, the purpose of which is to aid the choice of method by highlighting one method for each class of antenna. Table 2 is intended to be like a flowchart in which the suggested method is straightforward and time efficient; however if the calibration laboratory does not have the facility for the suggested method, an alternative method is available. For example, if the laboratory does not have a FAR, horn antennas can equally be calibrated using the outdoor method of 9.4.2. The column headed “Method not requiring an STA” includes methods with the lowest uncertainties that are not dependent on possessing an STA, and that use horizontal polarization. Such methods may be more time consuming than some other methods.

**Table 1 – Summary of calibration methods above 30 MHz for  $F_a$**

| Calibration site                                                                                                                   | Antenna under calibration                            | Calibration method        | Frequency range MHz                     | Antenna set-up <sup>a</sup>                                                                  | Pol. <sup>b</sup> | Subclause                     |
|------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|---------------------------|-----------------------------------------|----------------------------------------------------------------------------------------------|-------------------|-------------------------------|
| CALTS or SAC, utilizing the ground plane                                                                                           | Tuned dipole                                         | TAM                       | 30 to 1 000                             | $d = 10 \text{ m}$ , <sup>c</sup><br>$h_1, h_2$ depend on $f$                                | HP                | B.5.3                         |
|                                                                                                                                    |                                                      | SAM                       | 30 to 1 000                             | $d = 10 \text{ m}$ ,<br>$h_1, h_2$ depend on $f$                                             | HP                | B.5.2                         |
|                                                                                                                                    |                                                      | SAM with averaging        | 30 to 300                               | $d = 10 \text{ m}$ ,<br>$h_1, h_2$ depend on $f$                                             | HP                | B.4.2                         |
|                                                                                                                                    |                                                      | SSM                       | 30 to 1 000                             | $d = 10 \text{ m}$ , $h_2 = 2 \text{ m}$ ,<br>$h_1 = 1 \text{ m}$ to $4 \text{ m}$<br>(scan) | HP                | 8.4                           |
|                                                                                                                                    | Biconical,<br>(also biconical part of hybrid by 9.3) | SSM                       | 30 to 300                               | $d = 10 \text{ m}$ , $h_1 = 2 \text{ m}$ ,<br>$h_2 = 1 \text{ m}$ to $4 \text{ m}$<br>(scan) | HP                | 8.4                           |
|                                                                                                                                    |                                                      | SAM                       | 30 to 300                               | $d = 15 \text{ m}$ ,<br>$h_1 = 1,75 \text{ m}$ ,<br>$h_2 = 0 \text{ m}$ <sup>d</sup>         | VP                | 9.3                           |
|                                                                                                                                    |                                                      | SAM or TAM with averaging | 30 to 300                               | $d = 10 \text{ m}$ ,<br>$h_1, h_2$ depend on $f$                                             | HP                | B.4.2 SAM<br>B.4.3 TAM        |
|                                                                                                                                    | LPDA                                                 | SSM                       | 200 to 1 000                            | $d = 10 \text{ m}$ , $h_2 = 2 \text{ m}$ ,<br>$h_1 = 1 \text{ m}$ to $4 \text{ m}$<br>(scan) | HP                | 8.4                           |
| Free-space environment<br><br>FAR or minimizing ground reflections by height or absorber<br><br>$h_1, h_2, h_3$ apply above ground | Tuned dipole                                         | SAM                       | 60 to 1 000                             | $d_{\min}$ dependent on frequency, use FAR                                                   | HP<br>VP          | 9.2.2                         |
|                                                                                                                                    | Biconical,<br>(also biconical part of hybrid)        | SAM                       | 30 to 300                               | $d = 4 \text{ m}$ minimum                                                                    | HP<br>VP          | 9.2.2<br>B.4.2 with averaging |
|                                                                                                                                    | LPDA<br>(LPDA part of hybrid)                        | TAM<br>SAM                | 200 to 18 000;<br>$\geq 1 000$ for horn | $d = 2,5 \text{ m}$ ,<br>$h_1 = h_2 = h_3 \sim 4 \text{ m}$ <sup>f</sup>                     | VP                | 9.4.2<br>9.4.3                |
|                                                                                                                                    | Horn                                                 | TAM<br>SAM                | 200 to 18 000                           | $d = 2,5 \text{ m}$ ,<br>$h_1 = h_2 \sim 2,5 \text{ m}$ <sup>f</sup>                         | VP<br>HP          | 9.4.4                         |
|                                                                                                                                    | Horn<br>LPDA                                         | TAM                       | 1 000 to 18 000                         | $d = 1 \text{ m}$ or $3 \text{ m}$ ,<br>use FAR                                              | VP<br>HP          | 9.5.1.3                       |
|                                                                                                                                    |                                                      | SAM                       | 1 000 to 18 000                         | $d = 1 \text{ m}$ or $3 \text{ m}$ ,<br>use FAR                                              | VP<br>HP          | 9.5.2                         |

NOTE 1 The AUC is at height  $h_1$ .

NOTE 2 See A.4.2 regarding the optimum crossover frequency between biconical and LPDA antennas.

NOTE 3 If a set of standard antennas is available, the SAM may be preferable to SSM or TAM.

NOTE 4 In a FAR, the result is expected to be the same whether antennas are oriented HP or VP; see also A.2.5.

- <sup>a</sup>  $d$  is the separation distance between the transmit and receive antennas.  
 $h_1$  is the height of an AUC.  
 $h_2$  and  $h_3$  are the heights of other AUCs or paired antennas.  
 For SSM normally the AUC shall be the height scanned antenna; by request of a calibration laboratory's client the AUC can be the fixed height antenna [i.e. see A.5 a)].
- <sup>b</sup> Pol. is polarization.  
 HP = All antennas positioned for horizontal polarization.  
 VP = All antennas positioned for vertical polarization.
- <sup>c</sup> Below 60 MHz  $d = 20$  m will be used to ensure a separation of at least  $2\lambda$  to avoid an additional uncertainty of approximately 0,25 dB for one wavelength separation; see Table B.7 (see B.5.2).
- <sup>d</sup> An antenna height of  $h_2 = 0$  m signifies that the antenna is a monocone with its feed at ground plane level.
- <sup>e</sup> A hybrid antenna can also be calibrated by a combination of the methods for biconical and LPDA antennas.
- <sup>f</sup> The height depends on meeting the site acceptance criterion and may be increased when lower uncertainties for  $F_a$  are required.

Table 2 – Calibration methods above 30 MHz by subclause number

| Antenna type, frequency, MHz                                                                            | Suggested method                                         | Alternative method, frequency, MHz                                                                                                                      | Method not requiring an STA      |
|---------------------------------------------------------------------------------------------------------|----------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------|
| Biconical, 30 to 300<br>Biconical part of hybrid, 30 to 240                                             | 8.4 SSM CALTS                                            | 9.3 VP CALTS<br>9.1 SAM FAR<br>B.4.2 HP SAM height-averaging                                                                                            | B.4.3 HP TAM height-averaging    |
| LPDA, 200 to 3 000 <sup>a</sup><br>LPDA part of hybrid, 140 to 3 000 <sup>a</sup><br>Horn, $\geq 1 000$ | 9.4.2 TAM high above ground                              | 9.4.3 SAM high above ground<br>9.4.4 TAM or SAM in FAR or with absorber on ground<br>8.4 SSM CALTS, 140 to 1 000<br>9.5.1.3 TAM in FAR, 1 000 to 18 000 | 9.4.2                            |
| Horn, 1 000 to 18 000<br>LPDA, 1 000 to 18 000                                                          | 9.5.1.3 TAM in FAR                                       | 9.5.2 SAM in FAR<br>9.4.2 TAM high above ground                                                                                                         | 9.5.1.3                          |
| Tuned dipole                                                                                            | B.5.2 SAM at "free-space" height using calculable dipole | B.4.2 HP SAM height-averaging<br>8.4 SSM CALTS, 30 to 1 000                                                                                             | B.5.3 TAM at "free-space" height |
| <sup>a</sup> The upper frequency depends on the manufacturer's specification.                           |                                                          |                                                                                                                                                         |                                  |

## 5 Calibration methods for the frequency range 9 kHz to 30 MHz

### 5.1 Calibration of monopole antennas

#### 5.1.1 General

Monopole antennas, sometimes called rod antennas, are used typically in the frequency range 9 kHz to 30 MHz. The recommended calibration frequency increments are given in Table 3. Because of the long wavelengths associated with frequencies below 30 MHz, methods in this standard used to calibrate or characterize antennas at higher frequencies are not applicable to monopole antennas. A standard uncertainty of less than 1 dB can be achieved using the plane wave method and the Equivalent Capacitance Substitution Method (ECSM) described in the following subclauses and in Annex G.

**Table 3 – Frequency increments for monopole antenna calibration**

| Frequency range    | Increments |
|--------------------|------------|
| 9 kHz to 10 kHz    | 1 kHz      |
| 10 kHz to 150 kHz  | 10 kHz     |
| 150 kHz to 200 kHz | 50 kHz     |
| 200 kHz to 1 MHz   | 100 kHz    |
| 1 MHz to 30 MHz    | 1 MHz      |

In the plane wave method, the entire antenna is illuminated by a plane wave on a large ground plane; a method is described in G.1. In most cases the matching unit is above the ground plane; RF currents flow in the housing, and the taller the housing the larger the effect this has on the AF.

NOTE 1 “Matching unit” is used as a generic term for the metal housing containing the connection between the monopole radiating element (i.e. metal rod) and the input of a measuring receiver. The housing can contain a matching circuit and amplifier. Good electrical contact of the metal base of the housing with the ground plane is a condition for an effective and reproducible performance of a monopole antenna. Models of monopole antenna with rubber feet usually also have a metal foot (spacer) of slightly greater height to ensure electrical contact with the ground plane. For units without such a metal foot, a short metal braid strip of width at least 15 mm is used in electrical contact with the ground plane and the bottom of one vertical side of the matching unit, using screws if necessary to ensure good RF contact.

In contrast to the plane wave method, in the ECSM the rod is substituted by a capacitor equal to the self-capacitance of the monopole. The principle of this method is briefly explained in Annex G. Each model of monopole antenna requires the design of a dummy antenna (i.e. see 5.1.2.4). It is essential to verify the dummy antenna at the design stage by comparing the AFs measured by the ECSM with those measured using a plane wave method. In this way the design can be improved, and potential uncertainty contributions of up to 4 dB, for example, can be reduced [36]. The  $F_{ac}$  obtained by the ECSM can be confirmed by the  $F_a$  obtained by the plane wave method.

NOTE 2 A further method that can be used to verify the ECSM is to compare the field strength measured with an ECSM-calibrated monopole antenna on a large ground plane in the far field of a strong AM transmitter with that of a precisely calibrated loop antenna. However, this method can verify AFs only at spot frequencies. For each spot frequency it is verified that the monopole and loop antennas receive the dominant direct wave from one direction, with any other signals being weaker by greater than 30 dB.

NOTE 3 The ECSM can work well for antennas whose total length from the base of the matching unit to the top of the rod is shorter than  $\lambda/8$  (i.e. see G.2.1).

NOTE 4 A monopole antenna is sometimes mounted on a counterpoise (e.g. a vestigial ground plane of dimensions 0,6 m by 0,6 m) on a tripod, and the AF can be several dB lower than the AF measured with the matching unit on the ground plane or by the ECSM (i.e. see G.2.2). Monopole antennas on tripods used outdoors can be accurately calibrated by the plane wave method. Other configurations are with the vestigial ground plane connected to a conducting bench earthed to a wall in a shielded room, or with the antenna on the bench that would require more elaborate calibration methods; calibration methods are not given for such other configurations, but to improve the reproducibility of the results, the manufacturer's instructions or recommendations regarding the use of a counterpoise or ground plane are followed, including bonding (i.e. earthing) the antenna matching unit to the ground plane.

## 5.1.2 Calibration by the ECSM

### 5.1.2.1 General

The output from the matching unit is measured using the test configuration shown in Figure 1 or Figure 2. The antenna factor  $F_{ac}$  in dB(m<sup>-1</sup>) (see 3.1.2.3) is given by Equation (2).

$$F_{ac} = V_D - V_L - L_h \quad (2)$$

where

$V_D$  is the measured output of the signal generator, in dB(μV);

- $V_L$  is the measured output of the matching unit, in dB(μV);  
 $L_h$  is the height correction factor (for the effective height), in dB(m).

For the monopole antenna with a 1 m long rod that is commonly used in EMC measurements, the effective height  $h_e$  is 0,5 m, the height correction factor  $L_h$  is –6 dB(m) and the self-capacitance  $C_a$  is 12 pF, which assumes a rod radius of 3,6 mm [40].

NOTE Formulas for the effective height, height correction factor, and self-capacitance of monopole antennas with different lengths and radii are shown in 5.1.2.2. For example, one commercial antenna with a rod of relatively large diameter has  $C_a = 16$  pF.

Either of two set-ups and procedures can be used, i.e. 5.1.2.3.2 using a network analyzer, or 5.1.2.3.3 using a measuring receiver and signal generator. The same dummy antenna is used in both procedures. See 5.1.2.4 for guidance in making a dummy antenna. Measurements shall be made at a sufficient number of frequencies (i.e. see Table 3) to obtain a smooth curve of antenna factor versus frequency over the operating range of the antenna, or 9 kHz to 30 MHz, whichever is smaller.

### 5.1.2.2 Monopole antenna parameter equations

The following equations are used to determine the effective height, self-capacitance and height correction factor of monopole antennas.<sup>2)</sup> The equations are valid only for cylindrical rods shorter than  $\lambda/8$  [56]. To calculate the correct value of self-capacitance to use for ECSM, the frequency dependent ratio in Equation (4) may be ignored since it is close to unity when the  $\lambda/8$  condition is met.

$$h_e = \frac{\lambda}{2\pi} \tan \frac{\pi h}{\lambda} \quad (3)$$

$$C_a = \frac{55,6 h}{\ln(h/a) - 1} \frac{\tan(2\pi h/\lambda)}{2\pi h/\lambda} \quad (4)$$

$$L_h = 20 \lg(h_e) \quad (5)$$

where

- $h_e$  is the effective height of the rod, in m;  
 $h$  is the actual height (i.e. length) of the rod, in m;  
 $\lambda$  is the wavelength, in m;  
 $C_a$  is the self-capacitance of the rod, in pF;  
 $a$  is the radius of the rod, in m;  
 $L_h$  is the height correction factor, in dB(m).

A graphical presentation of Equation (4) for various rod diameters is given in Figure G.3 (see G.2.1), and for Equation (5) with two antenna lengths is given in Figure G.4. The ECSM does not take into account the effect on  $F_{ac}$  of the contribution by the matching unit; an empirical correction is to add half the height of the housing to the monopole length when calculating the height correction factor, as shown in Equation (6). A typical reduction in  $F_{ac}$  is 0,8 dB. In the calibration of a monopole antenna to be used according to CISPR 25 [4], in which the matching unit is placed beneath the ground plane, Equation (5) applies.

<sup>2)</sup> Equation (4) is the same as shown in CISPR 16-1-4:2010-12 Corrigendum 1, which supersedes Equation (B.2) of CISPR 16-1-4:2010-04. Future maintenance will remove Annex B of CISPR 16-1-4:2010-04 and replace it with appropriate cross-reference to this 5.1.2 of CISPR 16-1-6.

$$L_h = 20 \lg \left( h_e + \frac{h_b}{2} \right) \quad (6)$$

where  $h_b$  is the height of the matching unit, in m.

Other details concerning Equation (3) are available in [28], [32], and [59], and for Equation (4) in [29], [39], [58], [59], and [68].

NOTE References [13] and [36] refer to an expression for  $C_a$  different from Equation (4), having the term  $[\ln(h/a)-1]$  in the denominator replaced by  $[\ln(2h/a)-1]$ . However, theoretical and experimental analysis [40] show that Equation (4) is more appropriate.

### 5.1.2.3 Calibration procedures

#### 5.1.2.3.1 General instructions

Two alternative calibration procedures are described: use of a network analyzer in 5.1.2.3.2 and use of a signal generator and receiver in 5.1.2.3.3.

The 50  $\Omega$  termination used in the calibration is recommended to have a return loss greater than 32 dB (i.e. VSWR < 1,05:1) because this is realistically achievable and achieves a small uncertainty contribution. The measuring receiver shall be calibrated and have a return loss greater than 20,9 dB (VSWR < 1,2:1). The output of the signal generator shall be stable in frequency and amplitude.

The dummy antenna specified in 5.1.2.4 is connected as close as possible to the antenna port on the matching unit, and the T-connector is connected as close as possible to the dummy antenna. The outer conductor of the T-connector shall be electrically connected to the matching unit, if necessary by a short flat wire braid. The matching unit shall be earthed via the outer conductor of the coaxial cable to the measuring receiver. If the return losses of the receiver and signal generator are high, additional pads may not be needed at the receiver input port and the generator output port.

#### 5.1.2.3.2 Network analyzer procedure

The procedure is as follows:

- a) Calibrate the network analyzer with the cables to be used in the measurements.
- b) Set up the matching unit to be characterized and the measuring equipment as shown in Figure 1. The dummy antenna is connected as close to the antenna port as possible and the T-connector is connected as close to the dummy antenna as possible. The same length and type of cables are used between the T-connector port A and the port  $V_D$ , and between the 50  $\Omega$  port R and the port  $V_L$ . Voltage measurements shall be made at the port  $V_D$  and the port  $V_L$ .
- c) Subtract the signal level,  $V_L$ , in dB( $\mu$ V), from the signal level,  $V_D$ , in dB( $\mu$ V), and subtract  $L_h$  (–6 dB for the 1 m rod) to obtain  $F_{ac}$  in dB( $m^{-1}$ ), as shown in Equation (2).

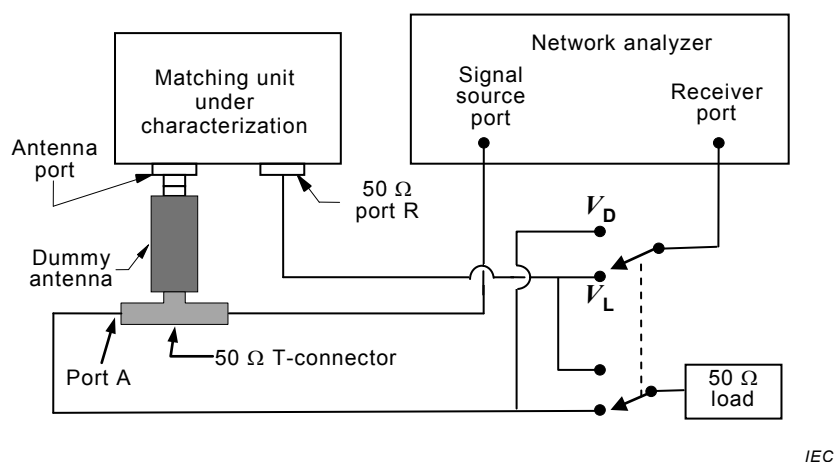


**Figure 1 – Set-up for AF determination using a network analyzer**

#### 5.1.2.3.3 Measuring receiver and signal generator procedure

The procedure is as follows:

- Set up the matching unit to be characterized and the measuring equipment as shown in Figure 2.
- With the equipment connected as shown and a 50 Ω termination on the T-connector, measure the received signal voltage  $V_L$ , in dB(μV), at the 50 Ω port R.
- Leaving the RF output of the signal generator unchanged, transfer the 50 Ω termination to the 50 Ω port R and transfer the receiver input cable to the T-connector. Measure the drive signal voltage  $V_D$  in dB(μV).
- Subtract  $V_L$  from  $V_D$  and subtract  $L_h$  (e.g. –6 dB for the 1 m rod) to obtain  $F_{ac}$  in dB(m<sup>-1</sup>), as shown in Equation (2).

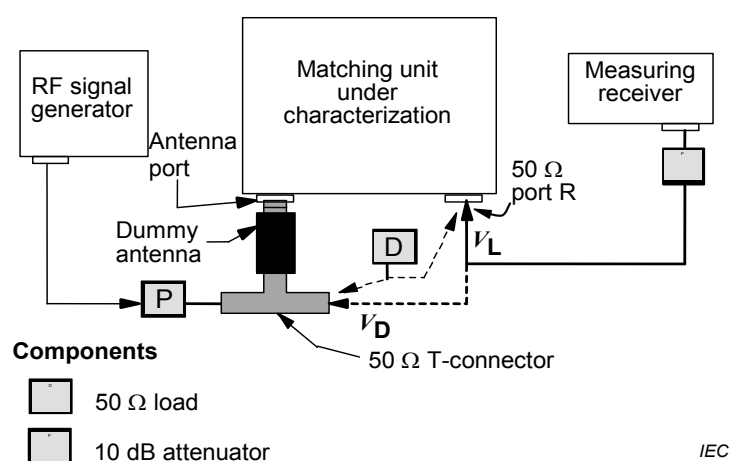


**Figure 2 – Set-up for AF determination using a measuring receiver and signal generator**

#### 5.1.2.4 Dummy antenna considerations

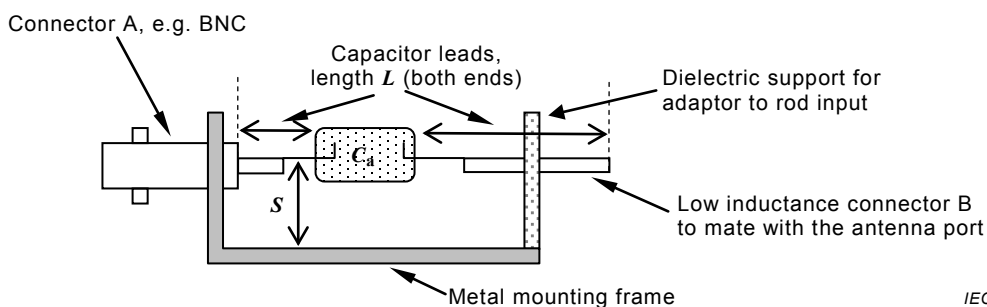
The key consideration of the dummy antenna design is to reduce any deviation in the RF impedance of the dummy antenna such that the calculated capacitor value is equivalent to the

actual rod when on an infinite ground plane. The key component of the dummy antenna is the capacitor, which shall be mounted such that the risk is minimized of any unintended added impedance between the capacitor and the matching unit.

If the mounting frame shown in Figure 3 is metallic, the side that supports connector B shall be dielectric; furthermore the mounting frame shall be electrically connected to the metal matching unit by a metal braid at least 15 mm wide to ensure a low inductance; see NOTE 1 of 5.1.1.1.

If the entire mounting frame is dielectric, the outer conductor of connector A shall be similarly connected to the matching unit by a braid. Ensure that connector B is at least 10 mm from any metallic part of the mounting frame. The capacitor leads shall be kept as short as possible to reduce additional inductance, but no longer than 8 mm, and spaced at least 10 mm from the surface of the metal mount. Also, the connecting wires should be sufficiently far from the adaptor shell, or ground plane of the monopole, to avoid capacitive coupling that distorts the calculated impedance value of the adaptor. Connector B may be in the form of a threaded brass bolt which can be screwed into the antenna port of the matching unit, shown in Figure 1 and Figure 2, where the rod would normally be attached. Any matching network incorporated into the dummy antenna shall be evaluated for losses associated with resistive voltage dividers, and these shall be accounted for in the calculation of  $F_{ac}$ .

NOTE An alternative dummy antenna is described in G.2.6 that uses a resistor circuit to simulate the monopole length such that  $F_{ac} = V_D - V_L$ , rather than as in Equation (2); see G.2.6. If the antenna uses a telescoping rod, the rod is extended to the length requested by the calibration laboratory's client, or as specified in the manufacturer's instructions.



#### Key

- $C_a$  antenna capacitance calculated from Equation (4), 5 % tolerance; a silver mica capacitor is recommended;
- $S$  lead spacing, 5 mm to 10 mm (10 mm from all surfaces if enclosed in a box);
- $L$  lead length, as short as possible; total lead length not greater than 40mm, including both capacitor leads and the length of connector B.

**Figure 3 – Example of mounting a capacitor in the dummy antenna**

#### 5.1.2.5 Uncertainty evaluation for ECSM calibration

This uncertainty evaluation applies to the ECSM calibration from 9 kHz to 30 MHz of monopole antennas with rods of length less than 1,1 m. See Annex G and [65] for a detailed analysis. The ECSM antenna factor applies to the case where the top of the matching unit is beneath, and in electrical contact with, a large ground plane, with only the rod projecting above the ground plane. However, in typical usage of monopole antennas, the base of the matching unit sits on, and is in electrical contact with the ground plane, in which case the AF of the whole antenna assembly will be lower than that calculated by Equation (2).

NOTE 1 The AF is dependent on the dimensions of the matching unit, particularly the height, and can be approximated by using an effective height calculated for the length of the rod increased by half the height of the matching unit. For a 1,0 m monopole antenna with a housing height of 0,1 m, the decrease in AF is approximately 0,8 dB.

NOTE 2 A sudden change in behavior is common at the extreme ends of a specified frequency range for broadband devices, and extending the range at each end beyond 9 kHz to 30 MHz, e.g. 100 Hz to 35 MHz, will give useful information about the uncertainty and reproducibility of  $F_a$  at the ends of the specified range.

Equation (2) implies that the antenna factor given by the ECSM is strongly affected by various parameters influencing the two voltage measurements for  $V_D$  and  $V_L$ , as well as by the deviation of the correction factor  $L_h$  from its expected value. A first-order Taylor expansion of Equation (2) about the expected values of the parameters yields:

$$F_{ac} = (V_D + \delta V_{D \text{ meas}} + \delta V_{D \text{ mismatch}}) - (V_L + \delta V_{L \text{ meas}} + \delta V_{L \text{ mismatch}} + \delta V_{L \text{ Ca}} + \delta V_{L \text{ amp}}) - (L_h + \delta L_{Lh}) \quad (7)$$

where

$$\delta V_{D,L \text{ meas}} = \delta V_{D,L \text{ linear}} + \delta V_{D,L \text{ res}} \quad (8)$$

and  $\delta V_{D \text{ meas}}$  and  $\delta V_{L \text{ meas}}$  represent the effects of the characteristics of the measuring receiver on measured  $V_D$  and  $V_L$ , respectively. The important characteristics are linearity and resolution, and their respective effects are denoted by  $\delta V_{D,L \text{ linear}}$  and  $\delta V_{D,L \text{ res}}$ . The terms  $\delta V_{D \text{ mismatch}}$  and  $\delta V_{L \text{ mismatch}}$  are the changes in  $V_D$  and  $V_L$ , respectively, caused by mismatch in cable connection, as briefly explained in 6.2.2. The terms  $\delta V_{L \text{ Ca}}$  and  $\delta V_{L \text{ amp}}$  are the results of small changes in the antenna capacitance  $C_a$  and the gain of the matching unit amplifier, if present, respectively. The term  $\delta L_{Lh}$  is the effect on the height correction factor  $L_h$ , which is caused by deviation of the effective height of the antenna from its expected value.

When a VNA is employed, as in Figure 1, the value of  $\Delta V = V_D - V_L$  in dB is directly measured by a single measurement, in which case Equation (7) can be simplified as

$$F_{ac} = (\Delta V + \delta V_{\Delta \text{ meas}} + \delta V_{D \text{ mismatch}} - \delta V_{L \text{ mismatch}} - \delta V_{L \text{ Ca}} - \delta V_{L \text{ amp}}) - (L_h + \delta L_{Lh}) \quad (9)$$

where

$$\delta V_{\Delta \text{ meas}} = \delta V_{\Delta \text{ noise}} + \delta V_{\Delta \text{ linear}} + \delta V_{\Delta \text{ res}} \quad (10)$$

In Equation (10),  $\delta V_{\Delta \text{ meas}}$  represents the effect of the characteristics of the VNA on the measured  $\Delta V$ . The uncertainty contributions attributed to the noise and the linearity might be combined and indicated as the uncertainty for  $|S_{21}|$  measurements in a data sheet of the network analyzer.

In terms of Equation (9), uncertainty components and example values are shown in Table 4. All the components have a sensitivity coefficient of unity. It is assumed that only the rod projects above the ground plane. Usually, uncertainty attributed to the VNA resolution may be ignored compared with other components. The tolerance on the value of  $C_a$  can be that supplied by the manufacturer, or for frequencies below 1 MHz,  $C_a$  can be measured from the gradient of  $|S_{11}|$  with frequency.

Although it is possible to analyze the uncertainty above 10 MHz as a separate component, it is much more practical to give one uncertainty for the whole range. For 1 m monopoles, the increase in uncertainty above 10 MHz is not large, but for other designs the difference could be very significant. In these cases, the user should evaluate the uncertainties as most appropriate.

**Table 4 – Example measurement uncertainty budget for  $F_{ac}$  of a monopole antenna calibrated by the ECSM using Equation (9)**

| Source of uncertainty or quantity $X_i$                                                                                                                                                                                                                                                                                                                                                                                                                                               | Value dB | Probability distribution | Divisor    | Sensitivity | $u_i$ dB | Note <sup>a</sup> |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|--------------------------|------------|-------------|----------|-------------------|
| VNA characteristics affecting $ S_{21} $ measurements                                                                                                                                                                                                                                                                                                                                                                                                                                 | 0,07     | Normal                   | 2          | 1           | 0,04     | N1)               |
| Mismatch in $V_D$ measurement                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 0,27     | U-shaped                 | $\sqrt{2}$ | 1           | 0,19     | N2)               |
| Mismatch in $V_L$ measurement                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 0,27     | U-shaped                 | $\sqrt{2}$ | 1           | 0,19     | N2)               |
| Accuracy of capacitance $C_a$ : e.g. $\pm 1,3$ pF in 11 pF                                                                                                                                                                                                                                                                                                                                                                                                                            | 1,09     | Rectangular              | $\sqrt{3}$ | 1           | 0,62     | N3)               |
| Stability of amplifier gain                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 0,05     | Normal                   | 1          | 1           | 0,05     | N4)               |
| Accuracy of effective height, 4 %                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 0,34     | Rectangular              | $\sqrt{3}$ | 1           | 0,20     | N5)               |
| $\Delta V$ measurement repeatability                                                                                                                                                                                                                                                                                                                                                                                                                                                  | 0,02     | Normal                   | 1          | 1           | 0,02     | N6)               |
| Combined standard uncertainty, $u_C$                                                                                                                                                                                                                                                                                                                                                                                                                                                  |          |                          |            |             | 0,71     | N7)               |
| <b>Expanded uncertainty, <math>U</math> (<math>k = 2</math>) <sup>b</sup></b>                                                                                                                                                                                                                                                                                                                                                                                                         |          |                          |            |             | 1,42     |                   |
| <sup>a</sup> Numbered notes are as given by the numbered items in E.2.<br><sup>b</sup> If the major uncertainty components in this table do not follow a normal distribution function, the expanded uncertainty should be evaluated using a computer simulation such as Monte-Carlo method. However, this table shows the combined standard uncertainty given by the RSS calculation, because some calibration laboratories may not routinely perform Monte-Carlo method simulations. |          |                          |            |             |          |                   |

## 5.2 Calibration of loop antennas

### 5.2.1 General

Loop antennas used for EMC radiated disturbance measurements over the frequency range 9 kHz to 30 MHz are typically up to 0,6 m in diameter. They are usually mounted on a small box containing matching and tuning networks, and some designs contain an amplifier. To measure the RF magnetic field strength using a loop antenna, its magnetic field antenna factor needs to be known.

Several techniques have been developed for calibrating loop antennas or measuring its magnetic field antenna factor; reference [18] gives a useful overview, [15] gives a simplified version of the standard field method in [32] and [16], and the three-antenna method is described in [35]. In this subclause and in Annex H, two methods are described that are straightforward to implement. The TEM cell method has the advantage of wide frequency coverage, but with a minimum uncertainty of antenna factor of approximately  $\pm 0,5$  dB. The Helmholtz coil method [34] is accurate to 0,7 % (0,06 dB) up to 150 kHz, and better than  $\pm 0,5$  dB up to 10 MHz, and is a valuable check for implementing the TEM cell method (see Annex H). Provided the TEM cell is used well below the onset of its first resonant frequency and the loop is well shielded, validation of the result up to 150 kHz using the Helmholtz coil method validates the calibration in the TEM cell to 30 MHz.

A well designed loop antenna is symmetric in the plane of the loop, and is shielded from picking up electric fields. The absence of, or poor, shielding can affect the reproducibility of antenna factor in the calibration of loop antennas.

### 5.2.2 TEM (Crawford) cell method

#### 5.2.2.1 Measurement procedure

TEM cells are fully shielded, and intended not to emit energy that may be hazardous to personnel or cause interference with nearby electronic equipment. The basic TEM cell is a

section of two-conductor transmission line that is operating in the transverse electromagnetic (TEM) mode, hence the name [34].

In a TEM cell, the field strength at the centre point between the centre conductor (septum) and outer conductor can be calculated from:

$$E = \frac{V}{b} = \frac{\sqrt{P_{\text{net}} Z_0}}{b} \quad (11)$$

$$H = \frac{E}{377 \, \Omega} \quad (12)$$

where

|                  |                                                                                 |
|------------------|---------------------------------------------------------------------------------|
| $E$              | is the electric field strength, in V/m;                                         |
| $H$              | is the magnetic field strength, in A/m;                                         |
| $V$              | is the voltage at the input or output port of the TEM cell, in V;               |
| $Z_0$            | is the real part of the characteristic impedance of the TEM cell, in $\Omega$ ; |
| $P_{\text{net}}$ | is the net power at the input of the TEM cell, in W;                            |
| $b$              | is the distance from the upper wall to the centre plate (septum), in m.         |

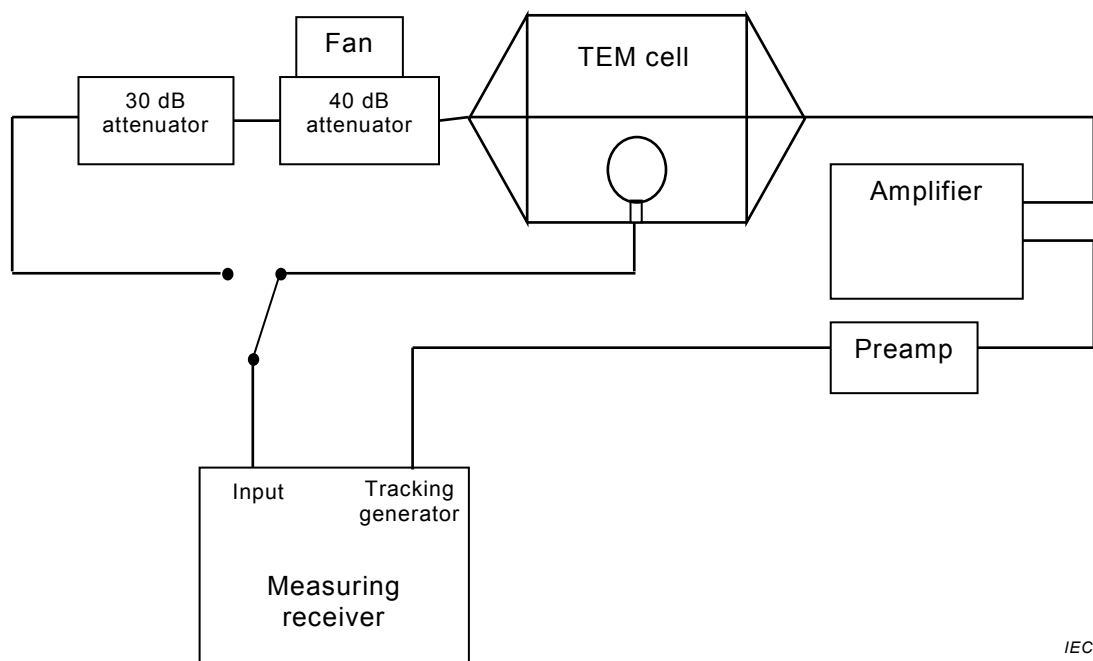
These field strength equations apply only at the centre point for a well-matched TEM cell, and significant variation will be seen closer to or farther from the septum. However the average field strength over the area of the loop is close to the value of the field strength at the centre. As the frequency is increased, above a certain frequency higher order modes will be generated. The calibration shall only be performed before the onset of the first cell resonance, which can be identified by a sharp change in the field detected by a probe placed inside the TEM cell. When the cell is loaded the resonant frequency can change, and it is advisable to use the cell well below the resonant frequency; sometimes this means well below the maximum frequency specified by the manufacturer.

**NOTE** The characteristic impedance of the system is assumed to be 50  $\Omega$ , but the impedance of the TEM cell at the position of the loop, and loaded with the loop, can differ by about 2 %. The uncertainty related to  $Z_0$  at the centre of the loaded cell can be reduced by measuring the impedance at this point and including that value in Equation (11). The impedance can be measured using a time domain reflectometer.

A typical set-up is shown in Figure 4. Blocks of polystyrene foam can be used to support the loop centrally between the plates; this serves the essential function of insulating the base of the loop from the TEM cell conductor surface. To get sufficient output signal from a passive loop, an amplifier is needed to create a sufficiently high field strength in the TEM cell. The field is calibrated by first switching the direct line, via attenuators, to the measuring receiver; then the loop output is switched to the measuring receiver. An amplifier is not needed for an active loop, whose set-up is shown in Figure 5. For a particular model of loop antenna whose amplifier module is included in a tripod support, the loop only is lowered through a hole in the upper plate (outer conductor) of the cell to enable the tripod to remain outside the cell. The metallic part that protrudes shall not touch the outer conductor of the cell. It is easier to access the connections to this loop from the top. For other models of loop antenna it may be possible to place the whole antenna inside the cell, on the bottom plate, as shown in Figure 4, or on the central plate. The routing of the cable in the top or side of the TEM cell has negligible effect provided a good quality screened cable is used.

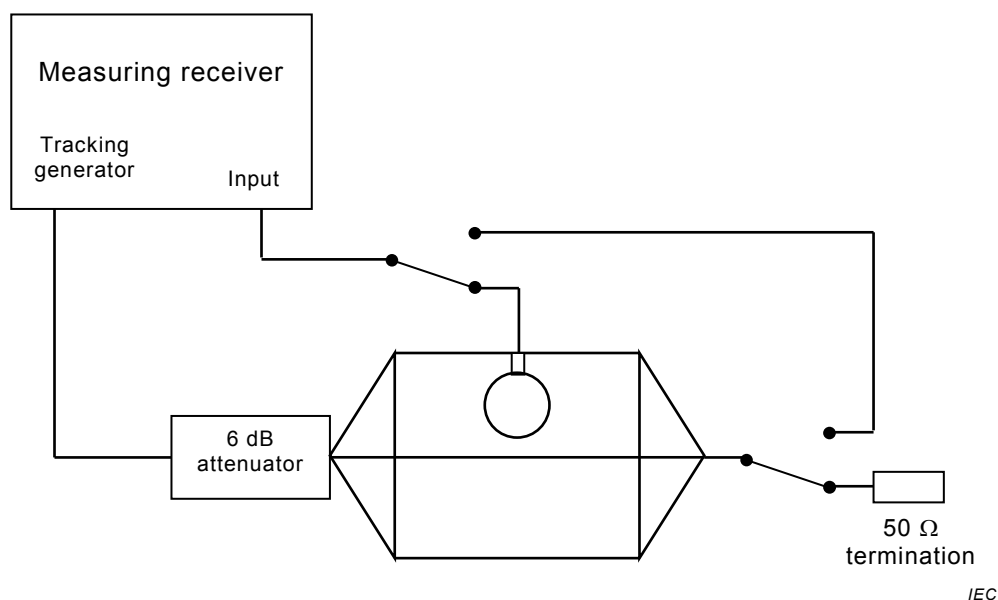
Only loops that are shielded from the electrical component of a TEM wave can be calibrated using a TEM cell. If the loop is not shielded, and the two halves (semi-circle with diameter through input connector) of the loop are not exactly balanced, the loop will respond to the electric component of the electromagnetic field. The effectiveness of the shielding can be tested by rotating the loop 180° about its vertical diameter which causes a 180° phase change between the pickup of the electric and magnetic fields; any change in the output signal should be included in the measurement uncertainty budget. This is the “electric field rejection” component in Table 5.

As an example of utilizing most of the spacing between the plates of the TEM cell, loops up to approximately 0,63 m diameter can be calibrated in a TEM cell that has a plate separation (i.e. septum height) of 0,915 m.



IEC

**Figure 4 – Block diagram of TEM cell set-up for passive loop antennas**



IEC

**Figure 5 – Block diagram of TEM cell set-up for active loop antennas**

### 5.2.2.2 Uncertainties

An example measurement uncertainty budget for magnetic field antenna factor at frequencies above 9 kHz is shown in Table 5. The measurement uncertainty of a loop under test depends mainly on the ratio of septum height and loop size. Measurement uncertainties of less than 1 dB are achievable for small loops in large cells, but can become worse for loops with size greater than two-thirds of the septum height.

**Table 5 –Example measurement uncertainty budget for  $F_{aH}$  of a loop antenna measured in a TEM cell**

| Source of uncertainty or quantity $X_i$                          | Value dB | Probability distribution | Divisor    | Sensitivity | $u_i$ dB | Note |
|------------------------------------------------------------------|----------|--------------------------|------------|-------------|----------|------|
| Cell line impedance                                              | 0,17     | Rectangular              | $\sqrt{3}$ | 1           | 0,10     | –    |
| Field uniformity                                                 | 0,25     | Rectangular              | $\sqrt{3}$ | 1           | 0,14     | –    |
| Septum height                                                    | 0,02     | Rectangular              | $\sqrt{3}$ | 1           | 0,01     | –    |
| Receiver sensitivity <sup>a</sup>                                | 0,1      | Rectangular              | $\sqrt{3}$ | 1           | 0,06     | –    |
| Receiver linearity                                               | 0,30     | Rectangular              | $\sqrt{3}$ | 1           | 0,17     | –    |
| Receiver resolution 0,1 dB                                       | 0,05     | Rectangular              | $\sqrt{3}$ | 1           | 0,03     | –    |
| System stability                                                 | 0,10     | Rectangular              | $\sqrt{3}$ | 1           | 0,06     | –    |
| Electric field rejection                                         | 0,10     | Rectangular              | $\sqrt{3}$ | 1           | 0,06     | –    |
| Cable loss                                                       | 0,10     | Rectangular              | $\sqrt{3}$ | 1           | 0,06     | –    |
| Load reflections                                                 | 0,34     | U-shaped                 | $\sqrt{2}$ | 1           | 0,24     | –    |
| Attenuators                                                      | 0,14     | Rectangular              | $\sqrt{3}$ | 1           | 0,08     | –    |
| Mismatch                                                         | 0,18     | U-shaped                 | $\sqrt{2}$ | 1           | 0,13     | –    |
| Loop positioning                                                 | 0,10     | Rectangular              | $\sqrt{3}$ | 1           | 0,06     | –    |
| <b>Combined standard uncertainty, <math>u_C</math></b>           |          |                          |            |             | 0,42     | –    |
| <b>Expanded uncertainty, <math>U</math> (<math>k = 2</math>)</b> |          |                          |            |             | 0,84     |      |

<sup>a</sup> For receiver sensitivity, refer to 6.2.4 and A.8.1. If the S/N ratio is above 17 dB (average detection) the influence is below 0,1 dB.

## 6 Frequencies, equipment and functional checks for calibrations at or above 30 MHz

### 6.1 Calibration frequencies

#### 6.1.1 Calibration frequency ranges and increments

Measurements of  $F_a$  of broadband antennas used at or above 30 MHz shall be made by swept frequency methods, or the equivalent of the maximum frequency increments shown in Table 6. Discrete frequencies for calibration of tuned dipoles are given in B.3.

**Table 6 – Frequency increments for broadband antenna calibration**

| Frequency range     | Maximum increment |
|---------------------|-------------------|
| 30 MHz to 1 000 MHz | 2 MHz             |
| 1 GHz to 3 GHz      | 10 MHz            |
| Above 3 GHz         | 50 MHz            |

If measurements are made at an outdoor site, there may be some frequencies at which ambient signals cause significant interference. For one such frequency designated as  $f_1$ , find a frequency,  $f_2$ , where the ambient signal is at least 30 dB below the received measurement signal. Measurements shall be made at  $f_2$  within the frequency range  $f_1 \pm \Delta f$ , where  $\Delta f$  is 1 MHz in the frequency range from 30 MHz to 150 MHz, 3 MHz from 151 MHz to 300 MHz, and 5 MHz from 301 MHz to 1 000 MHz. The frequency  $f_2$ , and the reason for deviating from the specified frequency, shall be documented in the calibration report. Above 1 GHz, ambient signals can be avoided by measuring in a shielded anechoic chamber.

Some antennas exhibit resonances seen as spikes in a plot of antenna factor versus frequency, an example of which is shown in Figure 6. A calibration increment of 2 MHz is sufficient to indicate the presence of a sharp resonance, but may not capture its peak. Either the calibration shall be performed with a small frequency increment (i.e. see A.8.6), or a statement shall be added to the certificate of calibration that the uncertainty could be higher in the frequency range  $0,985 f_{\text{res}} < f < 1,015 f_{\text{res}}$ , where  $f_{\text{res}}$  is the resonant frequency.

NOTE Some models of LPDA or hybrid antennas, whose dipole elements are not welded or protected from oxidation, develop resonances due to breakdown of RF contact of some of the dipole elements, typically increasing  $F_a$  by between 2 dB and 5 dB. This occurs particularly for LPDA antennas that have also been used for transmitting relatively high power levels for immunity testing.

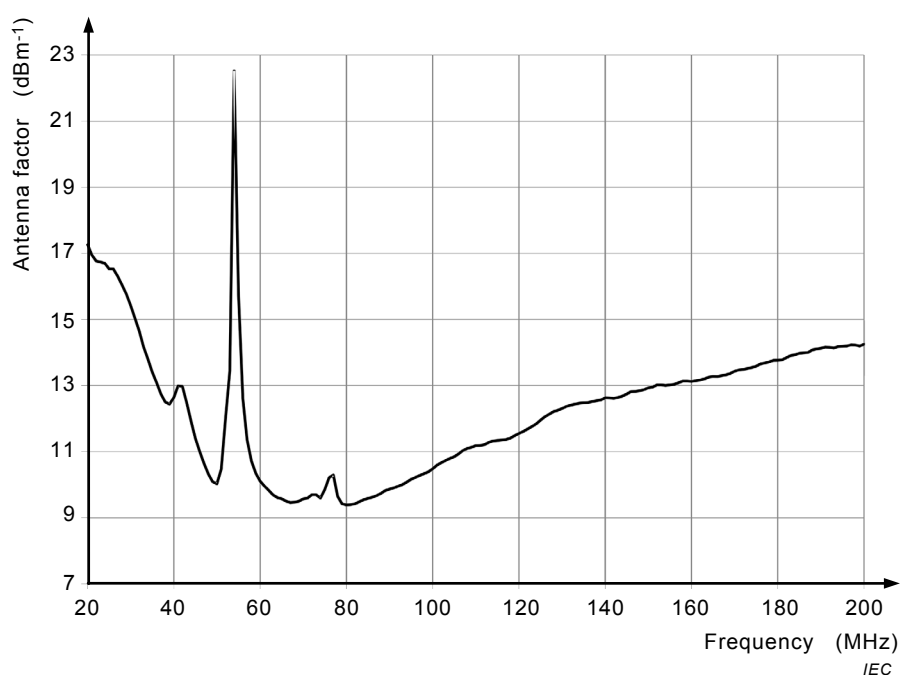


**Figure 6 – Example of resonant spike due to poor biconical element connections, using 2 MHz increment**

### 6.1.2 Transition frequency for hybrid antennas

The design principle of a hybrid antenna is the combination of a conventional biconical antenna and a LPDA antenna so as to cover the frequency range from 30 MHz to 1 GHz or higher. A hybrid antenna with a specified frequency range of 30 MHz to 1 GHz can be calibrated against two paired hybrid antennas. However, in the case that a lower uncertainty in  $F_a$  is required, a hybrid AUC can be calibrated in two stages by the TAM: the first stage against two paired biconical antennas, and the second stage against two paired LPDA antennas. In this case the two sets of  $F_a$  data need to be joined at a suitable transition frequency. Alternatively the first stage can be carried out by the SAM using one biconical STA up to 240 MHz; because the wavelength is larger than the element dimensions, the STA does not have to be identical to the AUC, whereas for non-identical LPDAs the TAM should be

used. If the SSM is used, note that for frequencies above 1 GHz other calibration procedures of Clause 8 or Clause 9 shall be used, as applicable. See also 5.3.2 of CISPR 16-1-5:2014 about validating a FAR to use with this calibration approach.

The optimum transition frequency is obtained by overlaying the plots of  $F_a$  against frequency, and choosing by inspection the frequency band where there is a close fit between the two plots. Experience with a large number of models of hybrid antenna has shown that this can occur in the frequency range 140 MHz to 240 MHz, most typically near 180 MHz. At lower frequencies, effects of mutual coupling with the ground plane, while at higher frequencies effects of antenna directivity, may each be responsible for deviations between the two sets of results.

## 6.2 Measurement instrumentation requirements for antenna calibrations

### 6.2.1 Equipment types

All instrumentation shall have a nominal impedance of 50  $\Omega$ . The preferred instrument for antenna calibrations is a network analyzer, incorporating a swept-frequency signal source and a tracking receiver. Alternatives are a spectrum analyzer with tracking generator, or a computer-controlled combination of a signal generator and a receiver. The generic term “measuring receiver” (i.e. 3.1.4.1) is used for the receiving part of these suitable instrument types.

The sweep time shall be established using the following procedure to ensure there is sufficient dwell time for the signal to be fully measured at the measuring receiver [1], especially in the case of long cable runs. Set up a pair of antennas on a CALTS at fixed heights of 2 m and the separation to be used for antenna calibration, e.g. 10 m. Configure the measuring receiver as for an antenna calibration, including sweep time, RF bandwidth, number of averages, and number of frequency points; these set-up parameters could be adapted for a faster sweep time in a FAR. Gradually increase the sweep time to  $T_{\min}$  until no change is seen in the response. The sweep time  $T_{\min}$  or longer can be used for calibrations.

At frequencies at which there is a signal null, as defined in 3.1.1.19, the comparison between responses may be unreliable. It is recommended to observe the differences in responses only for a signal-to-{receiver noise} ratio greater than 17 dB if using a receiver with an average detector, or a signal-to-{receiver noise} ratio greater than 34 dB if using a VNA; see A.8.1 for other considerations.

NOTE 1 Decreasing the RF bandwidth increases the dynamic range and reduces the influence of ambient signals, but also may necessitate a longer dwell time.

NOTE 2 When measuring SA (i.e. 8.4) it is assumed that the speed of the motorized mast allows the sweep of the frequency range to complete before the mast has moved more than 2 cm for frequencies above 300 MHz, and 5 cm for frequencies below 300 MHz. If the mast speed is too fast, errors can occur in the calculated AF caused by the height at which the signal maximum is actually recorded differing from the height at which it is calculated in  $e_0(i,j)|_{\max}$  in Equation (C.27) (see C.3.3). In a height scan where there are multiple maxima lobes, particularly at the higher frequencies, the calculated and measured maxima can be from different lobes and the error in AF can be of the order of 0,5 dB, showing as an uncharacteristic step in a plot of AF against frequency.

When calibrating an antenna by the TAM or by the SSM, two other similar antennas (i.e. paired antennas) that cover the frequency range are required (see 8.2 and 8.4). These can be either other AUCs, or antennas owned by the calibration laboratory. In the case of three unknown antennas, a suitability check is recommended to verify that there are no faults with the measurements or an unstable antenna. This can be done by replacing one antenna by an STA as a one-off exercise at the start of a session of calibrations. Confidence in the attainment of traceable results is gained by including at least one of the three antennas whose AF is known through a history of several calibrations.

Paired antennas serve different functions for measurements by the TAM or by the SAM. In the case of the TAM the antenna has to be similar, as defined in 3.1.1.12. In the case of the SAM, the function of the paired antenna is to set up a uniform field over the aperture of the AUC and the STA. When a ground plane is used, the radiation patterns of the AUC and STA have

to be very similar. The definition of SIL in 3.1.4.3 introduces the description of an antenna as receive or transmit; this is an alternative to description as AUC and paired antenna. The designation “receive and transmit” reduces one degree of freedom for the operation, because the measured result is the same whichever antenna is connected to the receiver or signal generator.

At appropriate intervals, for traceability the linearity of the instrumentation is verified using calibrated attenuators. Measurements are performed with calibrated attenuators, e.g. 10 dB, 30 dB, or 50 dB, and mismatch standards. The results are compared to the values from the calibration certificate by the  $E_n$  criterion [8].

A traceable distance-measuring instrument (e.g. tape measure or laser meter) is needed to measure the antenna separation and height. The RF measurement result is more sensitive to height above a ground plane than to separation. For the TAM the absolute heights and separation distances are crucial, whereas for the SAM the crucial measurement is the positioning of the AUC with respect to the STA; the position tolerance for the SAM is given in 8.3.2. The height should be set within a tolerance of  $\pm 10$  mm; higher deviations lead to higher measurement uncertainties. The tolerance and uncertainties can be quantified by performing a sensitivity test of SIL magnitude by varying the height.

The accuracy with which separation needs to be measured depends on the absolute distance; the smaller the separation, the smaller the tolerance is allowable. For example, for a 10 m separation, an error in position of 10 mm for both antennas leads to an uncertainty contribution in field strength in free space of  $20 \lg(9,98/10)$  dB = 0,017 dB; an uncertainty contribution of 0,1 dB implies an error in separation of 114 mm. An error in separation is more critical where the ground plane reflection is included, as in the SSM, because the phase of the signals is involved. Height scanning partially compensates for an error in distance, because it searches for the in-phase condition. In this case, an error in separation of less than  $\pm \lambda/30$  is preferred. The upper frequency for SSM is 1 GHz, at which  $\lambda/30$  is 10 mm.

The time interval between the AUC and STA SIL measurements shall be kept to a minimum to reduce signal generator and receiver drift and effects of temperature changes. The transmission loss of cables used in antenna calibration will vary with temperature. It is recommended that cables that are exposed to direct sunlight have white skins, or are fitted with a white sheath, to reduce the effect of temperature fluctuations arising from variations in direct sunlight due to changing cloud cover.

Time should be allowed for the cable temperatures to stabilize in cases where cables are taken from a warm room to a cold outdoor site, and where cables are left outdoors warming up in the transition from night-time to day-time temperatures. The maximum time interval shall be assessed for local conditions by observing the change in received signal, while neither the source nor the measurement set-up (including cables and antennas) are in any way disturbed.

### 6.2.2 Mismatch

Measurement uncertainty budgets given in this standard include mismatch uncertainties. This subclause covers the uncertainty due to the mismatch of the receiver and signal source with the cables, attenuators, and mismatch of antennas with the connected cables. The equations for the mismatch uncertainties are derived in Annex F.

NOTE 1 Despite that the use of slotted lines is obsolete, VSWR is often used to denote mismatch of equipment such as attenuators and measuring receivers, but it is more common to cite measurements of mismatch as return loss. The quantity “return loss” is favoured over VSWR for the measured magnitude of mismatch of antennas.

The receive antenna shall appear to the receiver to have a return loss  $> 20,9$  dB, which can usually be achieved by connecting a 6 dB attenuator to the cable connecting the antenna to the receiver. Note that the cable attenuation itself is part of the padding attenuation; there is a trade-off in the level of padding attenuation between achieving an acceptable SNR and an acceptable mismatch uncertainty.

It is preferred to use single cables, rather than several cables interconnected together, because each connection will contribute a mismatch uncertainty. For more accurate measurements, especially above 1 GHz, a VNA can be used to measure complex reflection coefficients, to facilitate correcting for mismatch uncertainty arising if impedances different from 50  $\Omega$  are presented to the transmit and receive antennas. The application of error correction techniques shall be done very carefully in configurations where there is the possibility of movement of cables, which may negate the error correction.

When performing the SIL measurement between two antennas (i.e. see 7.2.2), two separate sections of cable are used, i.e. one section (labelled T) connects the output port of the signal source with the antenna port of the transmit antenna; the other cable section (labelled R) connects the antenna port of the receive antenna with the input port of the measuring receiver. Equations (13) and (14) are derived in Annex F, and apply to a section of cable with a connected attenuator, as measured with a full two-port calibrated VNA. The section of cable may include a padding attenuator as required, which is usually at the end of the cable connected to the antenna.

The value of the limit for the mismatch uncertainty (see NOTE 2) associated with the power transfer between the signal source and the transmit antenna is given by Equation (13). The value of the limit for the mismatch uncertainty associated with the power transfer between the receiver and the receive antenna is given by Equation (14).

$$M_T^{\pm} = 20 \lg \left[ 1 \pm \left( |\Gamma_{aT}| |S_{11}| + |\Gamma_T| |S_{22}| + |\Gamma_{aT}| |\Gamma_T| |S_{11}| |S_{22}| + |\Gamma_{aT}| |\Gamma_T| |S_{21}|^2 \right) \right] \text{ in dB} \quad (13)$$

$$M_R^{\pm} = 20 \lg \left[ 1 \pm \left( |\Gamma_{aR}| |S_{11}| + |\Gamma_R| |S_{22}| + |\Gamma_{aR}| |\Gamma_R| |S_{11}| |S_{22}| + |\Gamma_{aR}| |\Gamma_R| |S_{21}|^2 \right) \right] \text{ in dB} \quad (14)$$

The reflection coefficients and  $S$ -parameters are measured, where

- $\Gamma_{aR}$  is the reflection coefficient of the receive antenna port;
- $\Gamma_{aT}$  is the reflection coefficient of the transmit antenna port;
- $\Gamma_T$  is the reflection coefficient of the output port of the signal source;
- $\Gamma_R$  is the reflection coefficient of the input port of the measuring receiver;
- $S_{11}$  is the reflection coefficient of the cable section R or T that connects with the ports of the receive and transmit antennas respectively, applied to Equation (13) or Equation (14), respectively;
- $S_{21}$  is the transmission coefficient (i.e. loss) of the cable section R or T that connects with the ports of the receive and transmit antennas respectively, applied to Equation (13) or Equation (14), respectively;
- $S_{22}$  is the reflection coefficient of the cable section R or T that connects with the input port of the measuring receiver; or the output port of the signal source respectively, applied to Equation (13) or Equation (14), respectively.

For example, if an antenna and the measuring receiver have a return loss of 20,9 dB (i.e.  $|\Gamma_{aR}| = |\Gamma_R| = 0,091$ ), and the connecting cable has  $|S_{11}| = |S_{22}| = 0,024$  and  $|S_{21}| = 0,5$ , then Equation (14) yields an error bound of  $M_R^{\pm} = 0,056$  dB.

NOTE 2 A correction could be applied to reduce an error, but where no correction is applied, the value of the error is taken to be the value of the uncertainty, which is  $M_R / \sqrt{2}$ .

In cases where  $S_{11}$  and  $S_{22}$  of the cables are negligibly small, e.g. at frequencies below 200 MHz, Equations (13) and (14) can be simplified by setting all terms multiplied by  $S_{11}$  and  $S_{22}$  to zero.

### 6.2.3 Dynamic range and reproducibility of SIL measurement

The main requirement for the accurate measurement of SIL between two antennas is amplitude linearity (sometimes referred to as dynamic accuracy). The aim for linearity should be better than  $\pm 0,1$  dB per decade, but account should be taken in the measurement uncertainty budget of the actual linearity achieved. Antenna measurements generally need a dynamic range of 60 dB or more, or a null detection method can be used together with a precision step attenuator. For a description of the null detection method, also known as a substitution method, see 4.4.4.3.2 of CISPR 16-1-5.

Coaxial cables shall not be bent tighter than their specified minimum bend radius because this could introduce a mismatch; furthermore for cables that are not in a permanent fixed layout, excessive bending can reduce the reproducibility of cable performance. If the cables do get overly bent, the cable-through measurement should be repeated, to check that the SIL has not changed by more than 0,2 dB.

The typical attenuation between two antennas 10 m apart is in the order of 40 dB, thus the use of two fixed attenuators (e.g. 6 dB) is recommended to reduce the mismatch uncertainties, and a sufficient signal-to-{receiver noise} ratio of at least 34 dB is required to obtain low measurement uncertainties. Adding cable loss, this adds up to roughly 90 dB in total. The value (dB) of attenuator can be reduced according to the amount of attenuation contributed by the cable. Dynamic range is usually defined as the ratio between maximum reading and noise floor. A further method to improve the mismatch uncertainty is the use of a calibrated VNA, and removal of the attenuators if more dynamic range is needed. In this case, the effective source and load match shall be used to calculate the mismatch uncertainty. The effective source and load match of calibrated VNAs are better than 30 dB return loss. This can involve full tow-port calibration (12-term correction) of the VNA, which may only be suitable for methods using shorter cables.

### 6.2.4 Signal-to-noise ratio

The signal generator shall provide output power sufficient to produce a signal, via the cables and antennas, at the measuring receiver input well above the noise level of the receiver. Assuming the use of a VNA, the signal-to-{receiver noise} ratio should be 34 dB or more, however in the case of a receiver using an average detector the ratio can be reduced to 17 dB or more. The signal-to-interference ratio should be 30 dB or more, to minimize the impact of a sinusoidal ambient signal. Receiver noise can be decreased by reducing the resolution bandwidth as required. See also A.8.1 for other considerations.

Power amplifiers may be used at the signal generator output to raise the signal above both the ambient and receiver noise. However, care shall be taken to comply with radio regulations.

In addition, preamplifiers may be used at the measuring receiver input to raise the signal above the receiver noise. However, care shall be taken to avoid overloading the preamplifier input, as well as the input of the measuring receiver. The linearity of each preamplifier shall be verified, particularly when high level ambient signals are present. Filters may be used to prevent out-of-band signals from saturating the preamplifiers. Out-of-band and saturation errors shall be evaluated, and included in the uncertainty analysis of the antenna calibration. The problems posed by ambient interference in the calibration of antennas can be avoided by using a shielded FAR or SAC.

If an ambient signal is present within the bandwidth of the measuring receiver during the calibration process, together with the test signal, the resulting error depends on the nature of the ambient signal. In case the ambient signals contain sinusoidal components (e.g. analogue broadcasts), a greater value of {signal-plus-ambient}-to-ambient ratio may be required. For example, a sinusoidal ambient signal that is 20 dB below a sinusoidal test signal would cause an uncertainty contribution of about 0,9 dB. To reduce this uncertainty contribution, the level of the test signal will have to be increased accordingly. Sinusoidal ambient signals will yield

larger uncertainty contributions than noise-like or broadband signals; see also the second paragraph of 6.1.1 about avoiding measurements on ambient frequencies.

### 6.2.5 Antenna masts and cables

Unwanted reflections from the antenna support structures, and antenna cables and control cables, contribute to the systematic uncertainties of an antenna calibration. To constrain the uncertainty caused by these reflections to no more than  $\pm 0,5$  dB, lightweight non-metallic masts should be selected (motorized masts for the SSM may be more robust), in accordance with the guidance presented in A.2.3.

Antenna cables shall be orthogonal to the antenna dipole elements, and routed horizontally by at least 1 m behind the antenna before routing vertically to ground. For a vertically-polarized antenna, the antenna cable should be extended horizontally behind the antenna for at least 5 m before routing vertically to ground. For distances smaller than 5 m, the measurement uncertainty shall be evaluated and applied accordingly. See A.2.3 for means to quantify this effect. These guidelines apply mainly to dipole and biconical antennas, because the effects are less for more directive antennas such as LPDA antennas.

## 6.3 Functional checks of an AUC

### 6.3.1 General

Prior to performing a calibration, the integrity of the AUC shall be verified. Unless the antenna is new, it shall be visually inspected to ensure it does not have mechanical or structural damage or any oxidation on the electrical contact surfaces. Measurement of the return loss is optional, but it is a quick test and is strongly recommended before the AF is measured, because gross departure from the manufacturer's data can identify whether it is worth proceeding with the longer measurement of antenna factor.

If the return loss is not measured first, and if the measured AF departs obviously from the previous calibration or the manufacturer's data, it is recommended to then measure the return loss, because deviation from the manufacturer's data can confirm a faulty antenna and help to identify the cause of the fault. A method of measurement of return loss is given in A.8.7. Checking the connector pin-depth (i.e. see A.8.2), and checking for sharp resonances in the frequency response (i.e. see A.8.6), are also recommended but are optional.

### 6.3.2 Balance of an antenna

In antenna calibration and radiated disturbance measurements, the receive antenna balun may give rise to common-mode currents on the cable attached to the receive antenna. Such common-mode currents create EM fields that may be picked up by the receive antenna, and that consequently may cause a systematic uncertainty in the radiated disturbance measurement results and in the measurement of antenna factor. A method of measuring the imbalance is given in 4.5.4 of CISPR 16-1-4:2010. If there is any indication that the balun has poor balance, thus exciting common mode currents on the outer conductor of the cable, ferrite clamps placed on the cable are partially effective in damping these currents.

**NOTE** It can be difficult to achieve good balance on high power baluns and the use of these in receive antennas is discouraged. Where the balance of a receive antenna degrades, typically at the low frequency end, repair is encouraged.

### 6.3.3 Cross-polar performance of an antenna

When an antenna is placed co-polarized in a linearly-polarized plane-wave field and then rotated through  $90^\circ$ , its cross-polar rejection shall be at least 20 dB. Alignment with the electric field vector of the plane wave (co-polarized) is defined to be the condition when a mechanical reference line of the antenna is parallel to the field vector. The reference line is the physical dipole axes for dipole, biconical, LPDA and hybrid antennas, and a physical plane for horn antennas. For example in a vertically-polarized field, the side-wall of a horn antenna, or the central vane of a DRH antenna, is vertically aligned.

Generally it is not necessary that cross-polar performance be measured each time an antenna is calibrated, but it is strongly recommended that at minimum the cross-polar rejection data should be available from the antenna manufacturer. Usually dipole, biconical and horn antennas inherently comply with the 20 dB requirement; however, LPDA dipole elements are in echelon, such that many LPDA antennas, and the LPDA part of hybrid antennas, do not meet the 20 dB requirement, especially at the top end of their operating frequency bands (see A.7). The additional uncertainty due to cross-polar rejection of less than 20 dB shall be calculated, to be available for use in the measurement uncertainty budget for an EMC disturbance test.

The measurement of cross-polar response to better than 20 dB requires identifying a paired antenna which itself has a cross-polar rejection of greater than 40 dB, such as a standard waveguide horn antenna. Generally the cross polar of LPDA antennas degrades with increase in frequency. For example, an LPDA antenna with a specified upper frequency of 2 GHz is likely to meet the cross-polar rejection of 20 dB below 1 GHz, in which case it is necessary to measure cross-polar response above 1 GHz; see 4.5.5 of CISPR 16-1-4:2010 about measurement procedures. A linear dipole antenna can be used, but it is more practicable to use a horn antenna, whose directivity provides a big advantage in reducing reflected signals. Horn antennas also generally cover wider frequency ranges than dipoles. One of the antennas has to be rotatable through slightly greater than 90° (see also [14] for other details about test procedures).

#### 6.3.4 Radiation patterns of an antenna

The radiation pattern is a key parameter of an antenna, especially for calibrations based on ground-plane reflection methods. Generally, antennas used for EMC testing have a broad main lobe in the antenna boresight direction, but for some antennas, in particular horns, at frequencies approaching the upper end of their operating frequency range, the main lobe can become narrow, or decrease (exhibiting a dip, i.e. a shallow null) on boresight. These pattern characteristics can affect the precision that is required in the alignment of an antenna for calibration.

In general, for antennas mounted in a free-space set-up without a ground plane, the pattern has an insignificant effect on the uncertainty of the resulting antenna factor obtained in a calibration (except see the NOTE in 9.5.1.3 about DRH antennas). When the method of calculating antenna factor includes a ground-plane reflection, as in Equation (23) (see 7.3.2) in combination with Equation (C.22) (see C.3.2), there can be a significant uncertainty contribution for antennas with a narrow-beam pattern. Equation (23) alone is a simplified version of Equation (C.22), assuming a uniform radiation in all directions, and applies in calibrations where the ray transmitted directly between the antennas has the same amplitude in the radiation pattern as the ray that passes from one antenna to the other via the ground plane; this is the assumption of the simplified calculation of AF, e.g. Equation (39) (see 7.4.1.2.1). An example is a uniform H-plane pattern of a horizontally-polarized biconical antenna.

Normally, in the case of a horizontally-polarized LPDA antenna using 10 m separation, the uncertainty contribution due to the radiation pattern is negligible. However in the case of a separation of 3 m, or a more directive antenna, the uncertainty contribution could be significant. As an example, if the reflected signal is 2 dB down from the peak of the beam, the uncertainty in the AF is 0,46 dB.

The magnitude of the uncertainty can be evaluated from knowledge of the radiation pattern and the geometry of the antenna set-up. The separation and heights of the antenna pair are used to calculate the angles from boresight of the direct and reflected rays between the antennas. The uncertainty can be reduced by including the radiation pattern data in the calculation of AF, i.e. using Equation (C.29) (see C.3.3).

Measurements of omnidirectional antennas, such as biconicals, require tighter site validation criteria than for directional antennas, such as horns, because for the latter unwanted reflections are suppressed in directions of low directivity of the antenna.

Radiation patterns are measured by rotating the antenna around its phase centre in a free-space environment. Most commonly the antenna is rotated in a horizontal plane, i.e. azimuth rotation, and the amplitude response recorded against angle of rotation from boresight.

## 7 Basic parameters and equations common to antenna calibration methods for frequencies above 30 MHz

### 7.1 Summary of methods for measurements to obtain AF

The antenna calibration set-up and site type, with a corresponding subclause number, are summarized in Table 1 in 4.5. General considerations for the main types of calibration methods are given in 4.3. The basic SIL measurement procedure and common measurement uncertainty components are described in 7.2, which are a basis for measurements described in Clauses 8 and 9. General equations to calculate AF from SIL or SA are described in 7.3. The equations of 7.3 are applied to the TAM, SSM and SAM in 7.4. A detailed example measurement uncertainty evaluation is given in 7.4.1.1.2, following the steps of ISO/IEC Guide 98-3:2008 starting with a model equation. The parameters related to phase centres and antenna positioning are described in 7.5.

### 7.2 Site insertion loss measurements

#### 7.2.1 General

The measurement of SIL is common to all radiated field methods of antenna calibration. The measurement procedures for SIL, and the common measurement uncertainty components, are described in 7.2.2 and 7.2.3, respectively.

#### 7.2.2 SIL and SA measurement procedure

The SIL,  $A_i(i,j)$ , for an antenna pair  $(i,j)$  shall be measured according to the following steps, using set-ups as shown in Figure 7 and Figure 8, in a free-space environment or at a calibration site with a ground plane, respectively. A free-space environment can be created either by absorber lining, or by having the antennas elevated at a large height above the ground. The antennas are either horizontally or vertically polarized, as specified by the calibration method. The calibration frequencies are as described in 6.1.1. When over a ground plane, the antenna heights shall be such that a signal null is not produced (e.g. see 7.4.1.2.1).

- a) Adjust a signal generator connected to antenna  $i$  to produce an electromagnetic field at a level to ensure a sufficient SNR at the position of the paired antenna  $j$ . Connect a measuring receiver to antenna  $j$  and tune to the frequency of the signal generator. Adjust the output of the signal generator according to the criteria of 6.2.3. Measure the output voltage derived from antenna  $j$ ,  $V_S(i,j)$  in dB( $\mu$ V). The measurement is normally performed with a VNA, but the same principles of ensuring a sufficient SNR apply (see also the definition of “measuring receiver,” 3.1.4.1).
- b) Detach the cables from the antennas and connect directly to each other with an adaptor. Measure the output voltage as  $V_D$  in dB( $\mu$ V). The frequency and output level of the signal generator shall be kept constant during the measurements of  $V_S(i,j)$  and  $V_D$ .
- c) Calculate the SIL between the two antennas using Equation (15).

$$A_i(i,j) = V_D - V_S(i,j) \text{ in dB} \quad (15)$$

When a measuring receiver gives power readings in dBm, Equation (15) is equivalent to the difference of the power readings ( $P$ ), as given in Equation (16):

$$A_i(i,j) = P_D - P_S(i,j) \text{ in dB} \quad (16)$$

- d) For the TAM: Follow the procedure of steps a) and b). To minimize the time lapse between the antenna pair and the cable connection measurements, carry out step a) consecutively for the three antenna pairs, and then repeat the cable connection measurement of step b). Note the difference between the two cable connection readings:

if the difference exceeds the tolerance set by the laboratory to achieve a given uncertainty for AF, all measurements shall be repeated. A recommended maximum tolerance is  $\pm 0,25$  dB. Although a VNA has minimal drift in amplitude, a significant drift can be caused by variations in temperature of the cables; also variations in connector repeatability can occur.

- e) For the SSM: Measure the maximum output voltage induced in antenna  $j$ ,  $V_S(i,j)|_{\max}$  in dB( $\mu$ V), during the height scan from 1 m to 4 m of antenna  $j$  using the set-up as shown in Figure 8. Calculate the site attenuation,  $A_s$ , between the two antennas using Equation (17).

$$A_s(i,j) = V_D - V_S(i,j)|_{\max} \quad \text{in dB} \quad (17)$$

It is not necessary to identify which antenna of the measured pair is kept at a fixed height, and which one is height scanned (i.e. see 7.4.2.2 and A.5, but for better reproductibility see footnote "a" in Table 1).

- f) For the SAM: Measure the SIL for the STA first, then for the AUC, then repeat the STA measurement. Note the difference between the two STA readings; if the difference exceeds the tolerance set by the laboratory to achieve a given uncertainty for AF, the causes for the unacceptable difference should be investigated and all measurements shall be repeated.

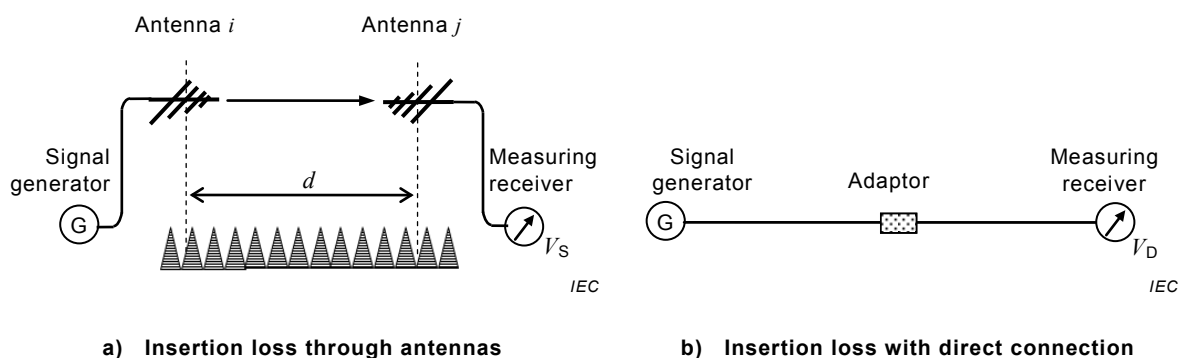


**Figure 7 – Antenna set-up for SIL measurement at a free-space calibration site**

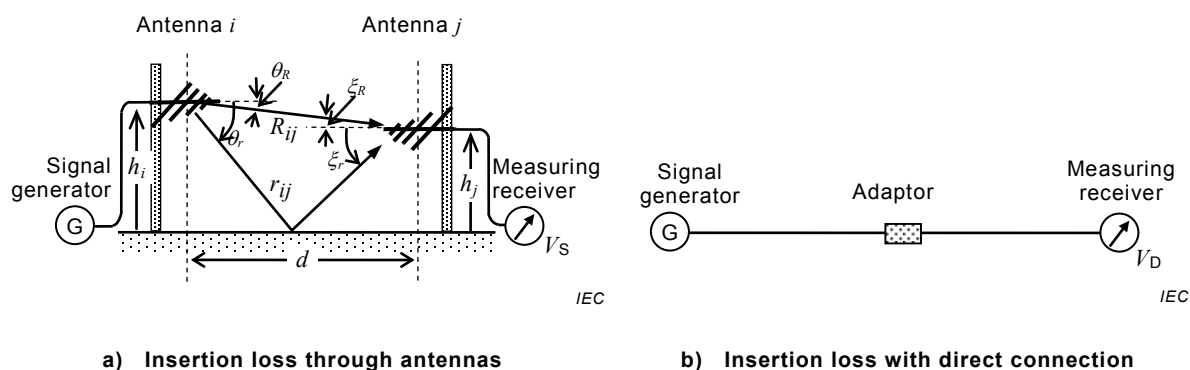


**Figure 8 – Antenna set-up for SIL and SA measurement at a ground-plane calibration site**

### 7.2.3 Common uncertainty components of a SIL measurement

The calibration of an AUC involves the measurement of SIL between the AUC and another antenna. In each SIL or SA measurement, the two voltage measurements, i.e. for  $V_D$  and  $V_S$

in Figure 7 or Figure 8, are affected by various influence parameters, such as stability of the signal generator, accuracy of the voltage measurement, mismatch in cable connection, and measurement repeatability. The symbols in Figure 8 a) are described in 7.3.3. A first-order Taylor expansion of Equation (15) about the expected values of the parameters yields:

$$A_i = (V_D + \delta V_{D SG} + \delta V_{D noise} + \delta V_{D linear} + \delta V_{D res} + \delta V_{D mismatch} + \delta V_{D cable}) - (V_S + \delta V_{S SG} + \delta V_{S noise} + \delta V_{S linear} + \delta V_{S res} + \delta V_{S mismatch} + \delta V_{S cable}) \quad (18)$$

where  $\delta V_{D SG}$  and  $\delta V_{S SG}$  represent variations in measured  $V_D$  and  $V_S$  caused by the stability of the signal generator output, respectively. Deviations of the characteristics of the measuring receiver from the ideal ones affect the measured  $V_D$  and  $V_S$ . The important characteristics are noise, linearity, and resolution, and their respective effects are denoted by  $\delta V_{D,S noise}$ ,  $\delta V_{D,S linear}$  and  $\delta V_{D,S res}$ . If a variable attenuator is used so that the measuring receiver level is changed negligibly during measurements of  $V_D$  and  $V_S$ , the linearity errors in Equation (18) can be excluded, instead, the uncertainty of the attenuation difference, one for  $V_D$  and the other for  $V_S$  measurement, of the variable attenuator shall be included leading to:

$$\delta V_{\Delta linear} = \delta V_{D linear} - \delta V_{S linear} \quad (19)$$

Evaluation of the receiver noise influence is briefly described in 6.2.4. The quantities  $\delta V_{D mismatch}$  and  $\delta V_{S mismatch}$  are the changes in  $V_D$  and  $V_S$  caused by mismatch in cable connection, respectively. The quantity  $\delta V_{S mismatch}$  involves the influences of mismatches of the cable sections T and R, as explained in 6.2.3. Variation in the cable attenuation, due to temperature and cable bending, may introduce significant uncertainty in the SIL or SA measurements; such an influence is taken into account by  $\delta V_{D,S cable}$ .

For the measurement of SIL or SA, if a full two-port calibration of the VNA is performed to reference planes at the antenna ends of the cables, the value of  $\Delta V = V_D - V_S$  in dB is directly measured by one measurement, in which case Equations (18) and (19) can be simplified to:

$$A_i = \Delta V + \delta V_{\Delta meas} + \delta V_{D mismatch} - \delta V_{S mismatch} - \delta V_{\Delta cable} \quad (20)$$

with

$$\delta V_{\Delta meas} = \delta V_{\Delta noise} + \delta V_{\Delta linear} + \delta V_{\Delta res} \quad (21)$$

where  $\delta V_{\Delta meas}$  represents the influence of the VNA characteristics on measured  $\Delta V$ , and  $\delta V_{\Delta cable}$  is the difference in the cable attenuation between  $V_D$  and  $V_S$  measurements.

Referring to Equation (20), uncertainty components and example values for a SIL measurement with a VNA are shown in Table 7. The specific  $u_c$  value of Table 7 is used as a common uncertainty contribution in the uncertainty evaluations for various calibration methods specified in this standard. The uncertainties related to the mismatch,  $\delta V_{D,S mismatch}$ , are excluded from the table because they strongly depend on the antennas connected to the cables, but mismatch is included in the measurement uncertainty budgets for the calibration methods in Clause 9 and Annex B. Uncertainty caused by the receiver resolution,  $\delta V_{\Delta res}$ , is also excluded as it may be negligibly small compared with other components. Equations (20) and (21) imply that all the components have a sensitivity coefficient of unity. The combined standard uncertainty,  $u_c$ , was calculated assuming that all the listed uncertainty components have a sensitivity coefficient of unity.

**Table 7 – Example measurement uncertainty budget for common components of a SIL measurement result evaluated from Equation (20)**

| Source of uncertainty or quantity $X_i$                                | Value dB | Probability distribution | Divisor    | Sensitivity | $u_i$ dB    | Note <sup>a</sup> |
|------------------------------------------------------------------------|----------|--------------------------|------------|-------------|-------------|-------------------|
| VNA characteristics affecting $\Delta V$ measurements                  | 0,18     | Normal                   | 2          | 1           | 0,09        | N8)               |
| Cable attenuation variation due to temperature or flexing              | 0,15     | Rectangular              | $\sqrt{3}$ | 1           | 0,09        | N9)               |
| $\Delta V$ measurement repeatability                                   | 0,04     | Normal                   | 1          | 1           | 0,04        | N6)               |
| Combined standard uncertainty, $u_C$                                   |          |                          |            |             | 0,13        | N7)               |
| <b>Expanded uncertainty, <math>U</math> (<math>k = 2</math>)</b>       |          |                          |            |             | <b>0,26</b> |                   |
| <sup>a</sup> Numbered notes are as given by the numbered items in E.2. |          |                          |            |             |             |                   |

### 7.3 Basic equations for the calculation of AF from SIL and SA measurements

#### 7.3.1 Antenna factor from SIL measurements

Antenna calibration is a process to derive an accurate estimate of the AF from measurements of the site insertion loss or site attenuation. The relationship between the AF and the SIL or SA is introduced in this subclause. The rationale for the equations is briefly described in Annex C. Basic equations are given in 7.3.2 and 7.3.3, and simplified versions of these are given in 7.4.1.1 to 7.4.3 for each calibration method.

In general, uncertainty values in this standard are tabulated using the maximum value in a given frequency range; each calibration laboratory could subdivide the frequency range, to show where lower uncertainties are achievable in any frequency sub-ranges.

#### 7.3.2 Relationship of AF and SIL for a free-space calibration site

At a free-space calibration site, where the ground-reflected wave and any other source of reflection is negligible, the site insertion loss is measured between the two antennas accurately directed toward each other, as shown in Figure 7. The site insertion loss for this antenna pair set-up can be expressed as in Equations (22) to (24).

$$A_i(i, j) = F_a(i) + F_a(j) + K(i, j) \text{ in dB} \quad (22)$$

where the coefficient  $K(i, j)$  is expressed as

$$K(i, j) = 20 \lg \left( \frac{39,8}{f_{\text{MHz}}} \right) - 20 \lg [e_0(i, j)] \text{ in dB(m}^2\text{)} \quad (23)$$

The field strength parameter  $e_0$  is given by

$$e_0(i, j) = \frac{1}{d} \text{ in m}^{-1} \quad (24)$$

where

- $F_a(i)$  is the AF in dB(m<sup>-1</sup>) of antenna  $i$  in its boresight direction;
- $F_a(j)$  is the AF in dB(m<sup>-1</sup>) of antenna  $j$  in its boresight direction;
- $f_{\text{MHz}}$  is the frequency in MHz;
- $d$  is the specified separation distance between the antennas, in m.

Equations (22) to (24) are derived theoretically in C.3.1, i.e. see Equations (C.15) to (C.19). The rigorous expression for  $e_0(i,j)$  is given by Equation (C.17). Equation (23) can be expressed as:

$$K(i,j) = -20\lg(f_{\text{MHz}}) + 20\lg(d) + C \quad (25)$$

where  $C$  is equal to  $20\lg(39,8)$ .

### 7.3.3 Relationship of AF and SIL for a calibration site with a metal ground plane

When the SIL is measured for a pair of antennas facing each other with polarization  $p$  above a metal ground plane, as shown in Figure 8, the SIL can be expressed in the following form:

$$A_i(i,j) = F_a(i | h_i, p) + F_a(j | h_j, p) + K(i, j | p) \quad \text{in dB} \quad (26)$$

with the coefficient  $K(i, j | p)$  given by:

$$K(i, j | p) = 20\lg\left(\frac{39,8}{f_{\text{MHz}}}\right) - 20\lg[e_0(i, j | p)] \quad \text{in dB(m}^2\text{)} \quad (27)$$

where

$F_a(i | h_i, p)$  is the height-dependent AF of antenna  $i$  in  $\text{dB(m}^{-1}\text{)}$  in its boresight direction (i.e.  $\theta_R = 0$ ), where the antenna is elevated at a height  $h_i$  and oriented for polarization  $p$ ;

$F_a(j | h_j, p)$  is the height-dependent AF of antenna  $j$  in  $\text{dB(m}^{-1}\text{)}$  in its boresight direction (i.e.  $\xi_R = 0$ ), where the antenna is elevated at a height  $h_j$  and oriented for polarization  $p$ .

For horizontal polarization (i.e.  $p = \text{H}$ ), the field strength parameter  $e_0(i, j | p)$  in Equation (27) can be expressed as

$$e_0(i, j | \text{H}) = \left| \frac{e^{-j\beta R_{ij}}}{R_{ij}} - \frac{e^{-j\beta r_{ij}}}{r_{ij}} \right| \quad \text{in m}^{-1} \quad (28)$$

where

$\beta$  is the angular wave number,  $2\pi/\lambda$ ;

$e$  base of natural logarithm;  $e \cong 2,718$ .

The propagation distances of the direct and ground-reflected waves,  $R_{ij}$  and  $r_{ij}$ , are given by:

$$\begin{aligned} R_{ij} &= \sqrt{d^2 + (h_j - h_i)^2} \\ r_{ij} &= \sqrt{d^2 + (h_j + h_i)^2} \end{aligned} \quad (29)$$

where

$d$  is the specified separation distance between the antennas, in m;

$h_i, h_j$  are the heights of antenna  $i$  and antenna  $j$ .

Equations (26) and (27) have the same form as Equations (22) and (23), but differ by the inclusion of the  $h_{i,j}$  and  $p$  parameters; Equations (26) and (27) are also given in C.3.2 as

Equations (C.20) and (C.21). As mentioned in C.3.2, Equation (28) for  $e_0(i,j | p)$  is based on the assumptions that the paired antennas have broad beamwidth radiation patterns, encompassing the direct and ground-reflected waves, and with nearly the same values of their respective AFs in the direction of specular reflection as those in their boresight directions [i.e. the condition described in 6.3.4 and given by Equation (C.23)]. The expanded form of Equation (28) is Equation (41) (see 7.4.1.2.1). Where the AF in the ground and boresight directions differ significantly, the rigorous expression for  $e_0(i,j | p)$  given by Equation (C.22) (see C.3.2) should be used.

## 7.4 Equations for AF and measurement uncertainties using the TAM, SSM, and SAM

### 7.4.1 TAM

#### 7.4.1.1 TAM at a free-space calibration site

##### 7.4.1.1.1 SIL measurement basis

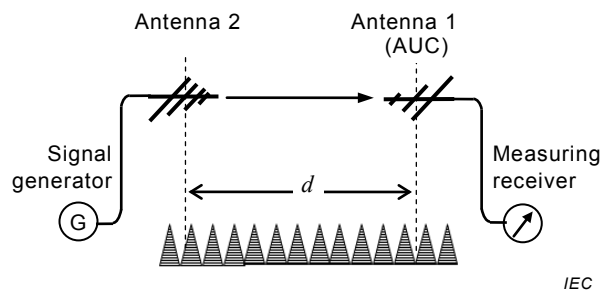
Antenna calibration employing the TAM requires three antennas (numbered as 1, 2, and 3) to form three antenna pairs, for which the SIL is measured. To determine the AF in the boresight direction, the paired antennas are arranged at a free-space calibration site, with their boresight directions precisely pointed to each other, as illustrated in Figure 9. A free-space environment can be created either by absorber lining, or with the antennas elevated at a large height above a metal ground plane. The antenna separation distance,  $d$ , shall be constant for all the antenna pairs. Using Equation (22), a set of three equations is obtained from the three measured values of the SIL (in dB), i.e.  $A_i(2,1)$ ,  $A_i(3,1)$ , and  $A_i(3,2)$ :

$$\begin{aligned} A_i(2,1) &= F_a(1) + F_a(2) + K(2,1) \\ A_i(3,1) &= F_a(1) + F_a(3) + K(3,1) \quad \text{in dB} \\ A_i(3,2) &= F_a(2) + F_a(3) + K(3,2) \end{aligned} \quad (30)$$

$F_a(1)$ ,  $F_a(2)$ , and  $F_a(3)$  are the AFs of the respective antennas in their boresight directions, in dB(m<sup>-1</sup>).  $K(i,j)$  is given by Equation (23).

In actual SIL measurements, antenna positioning and orientation may slightly change and differ from the specified conditions, therefore individual  $K(i,j)$  shall be applied. From Equation (30), each AF can be determined from:

$$\begin{aligned} F_a(1) &= \frac{1}{2} [A_i(2,1) + A_i(3,1) - A_i(3,2) - K(2,1) - K(3,1) + K(3,2)] \\ F_a(2) &= \frac{1}{2} [A_i(2,1) - A_i(3,1) + A_i(3,2) - K(2,1) + K(3,1) - K(3,2)] \quad \text{in dB(m}^{-1}\text{)} \\ F_a(3) &= \frac{1}{2} [-A_i(2,1) + A_i(3,1) + A_i(3,2) + K(2,1) - K(3,1) - K(3,2)] \end{aligned} \quad (31)$$



a) Antenna pair (2,1)

IEC