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Australian/New Zealand Standard™

Specification for radio disturbance and immunity measuring apparatus and methods

Part 1.6: Radio disturbance and immunity measuring apparatus — EMC antenna calibration



AS/NZS CISPR 16.1.6:2015

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- Consumer Electronics Suppliers Association
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- EMC Society of Australia
- Energy Networks Australia
- Engineers Australia
- Free TV Australia
- Lighting Council New Zealand
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Australian/New Zealand Standard™

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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Preface

This Standard was prepared by the Joint Standards Australia/Standards New Zealand Committee TE-003, Electromagnetic Compatibility.

A1 Amendment No. 1 to this Standard was prepared by the Joint Standards Australia/Standards New Zealand Committee TE-003, Electromagnetic Compatibility. **A1**

A2 Amendment No. 2 to this Standard was prepared by the Joint Standards Australia/Standards New Zealand Committee TE-003, Electromagnetic Compatibility. **A2**

The objective of this Standard is to provide 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.

A2 This Standard is identical with, and has been reproduced from CISPR 16-1-6, Ed. 1.0 (2014), *Specification for radio disturbance and immunity measuring apparatus and methods, Part 1-6: Radio disturbance and immunity measuring apparatus—EMC antenna calibration* and its Amendment No. 1 (2017) and Amendment No. 2 (2022), which are consolidated into the source text. **A12**

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- (a) In the source text “this part of CISPR 16” should read “this Australian/New Zealand Standard”.
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References to International Standards should be replaced by references to Australian or Australian/New Zealand Standards, as follows:

<i>Reference to International Standard</i>		<i>Australian/New Zealand Standard</i>	
CISPR		AS/NZS CISPR	
16	Specification for radio disturbance and immunity measuring apparatus and methods	16	Specification for radio disturbance and immunity measuring apparatus and methods
16-1-4:2020 AMD1:2012	Part 1-4: Radio disturbance and immunity measuring apparatus—Antennas and test sites for radiated disturbance measurements	16.1.4:2013	Part 1.4: Radio disturbance and immunity measuring apparatus—Antennas and test sites for radiated disturbance measurements
16-1-5:2014	Part 1-5: Radio disturbance and immunity measuring apparatus—Antenna calibration sites and reference test sites for 5 MHz to 18 GHz	16.1.5:2015	Part 1.5: Radio disturbance and immunity measuring apparatus—Antenna calibration sites and reference test sites for 5 MHz to 18 GHz

Only normative references that have been adopted as Australian or Australian/New Zealand Standards have been listed.

The terms “normative” and “informative” have been used in this Standard to define the application of the annexes to which they apply. A “normative” annex is an integral part of a Standard, whereas an “informative” annex is only for information and guidance.

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INTERNATIONAL ELECTROTECHNICAL COMMISSION
INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE

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

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

FOREWORD

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CISPR 16-1-6 edition 1.2 contains the first edition (2014-12) [documents CISPR/A/1087/FDIS and CISPR/A/1098/RVD], its amendment 1 (2017-01) [documents CISPR/A/1195/FDIS and CISPR/A/1204/RVD] and its amendment 2 (2022-03) [documents CIS/A/1362/FDIS and CIS/A/1365/RVD].

This Final version does not show where the technical content is modified by amendments 1 and 2. A separate Redline version with all changes highlighted is available in this publication.

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*.

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 the base publication and its amendments 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

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- withdrawn,
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- amended.

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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

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 16-1-2, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-2: Radio disturbance and immunity measuring apparatus – Coupling devices for conducted disturbance measurements*

CISPR 16-1-4:2019, *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 16-1-5:2014, *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]¹⁾), 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.

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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

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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 (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(S/m) or dB($\Omega^{-1}\text{m}^{-1}$).

Note 1 to entry: The unit dB(pT/ μV) is used in some standards (but not in CISPR 16-1-6), which can be converted to dB(S/m) by subtracting 2 dB.

Note 3 to entry: CISPR 16-1-4 specifies loop antennas for magnetic field strength 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

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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_1 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
CPM	current probe method
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
SFM	standard field method
SNR	signal-to-noise ratio
SSM	standard site method

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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⁻¹), 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⁻¹). 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 LPDA 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 2λ 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 (λ) 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° 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.

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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

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

a	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)].
b	Pol. is polarization. HP = All antennas positioned for horizontal polarization. VP = All antennas positioned for vertical polarization.
c	Below 60 MHz $d = 20$ m will be used to ensure a separation of at least 2λ to avoid an additional uncertainty of approximately 0,25 dB for one wavelength separation; see Table B.7 (see B.5.2).
d	An antenna height of $h_2 = 0$ m signifies that the antenna is a monocone with its feed at ground plane level.
e	A hybrid antenna can also be calibrated by a combination of the methods for biconical and LPDA antennas.
f	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 Biconical part of hybrid, 30 to 240	8.4 SSM CALTS	9.3 VP CALTS 9.1 SAM FAR B.4.2 HP SAM height-averaging	B.4.3 HP TAM height-averaging
LPDA, 200 to 3 000 ^a LPDA part of hybrid, 140 to 3 000 ^a Horn, $\geq 1 000$	9.4.2 TAM high above ground	9.4.3 SAM high above ground 9.4.4 TAM or SAM in FAR or with absorber on ground 8.4 SSM CALTS, 140 to 1 000 9.5.1.3 TAM in FAR, 1 000 to 18 000	9.4.2
Horn, 1 000 to 18 000 LPDA, 1 000 to 18 000	9.5.1.3 TAM in FAR	9.5.2 SAM in FAR 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 8.4 SSM CALTS, 30 to 1 000	B.5.3 TAM at "free-space" height
^a 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 $\text{dB}(\text{m}^{-1})$ (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 $\text{dB}(\mu\text{V})$;

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.²⁾ 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.

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

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

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

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;
 λ 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.

²⁾ 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 Ω 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 Ω 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(μ V), from the signal level, V_D , in dB(μ 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).

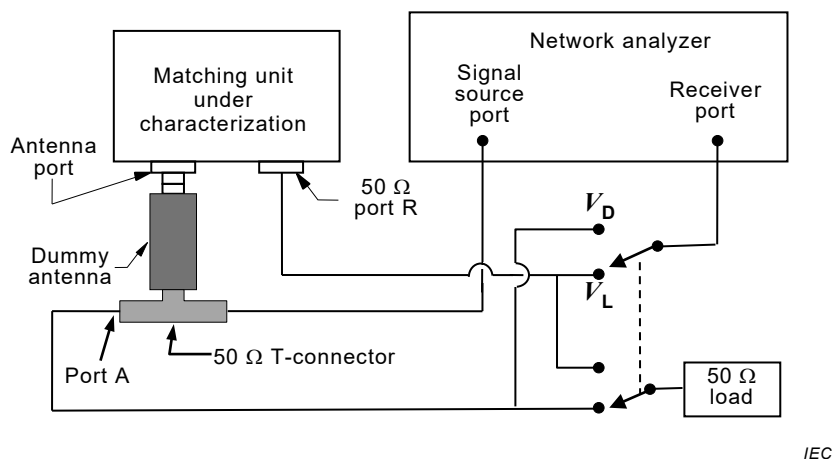


Figure 1 – Set-up for AF determination using a network analyzer

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⁻¹), as shown in Equation (2).

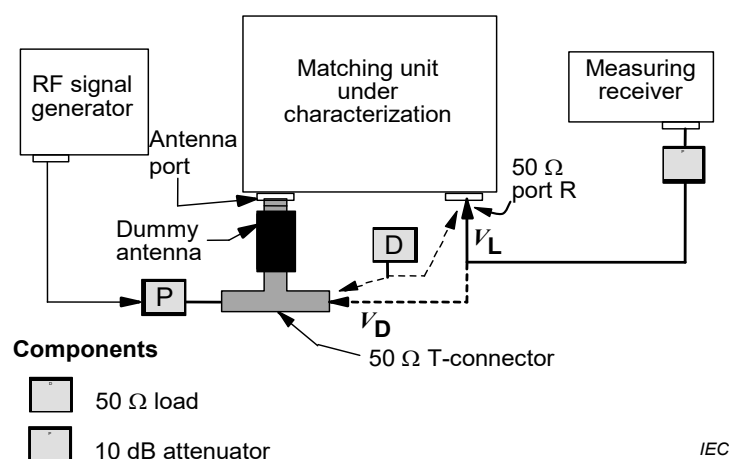


Figure 2 – Set-up for AF determination using a measuring receiver and signal generator

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

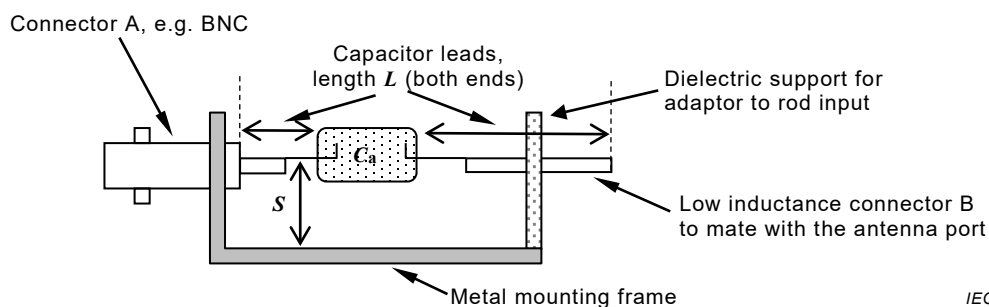
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actual rod when on an infinite ground plane. The key component of the dummy antenna is the capacitor, which shall be mounted such that the risk is minimized of any unintended added impedance between the capacitor and the matching unit.

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.

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 δL_{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 ΔV . 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 ^a
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)
ΔV measurement repeatability	0,02	Normal	1	1	0,02	N6)
Combined standard uncertainty, u_C					0,71	N7)
Expanded uncertainty, $U (k = 2)$ ^b					1,42	
^a Numbered notes are as given by the numbered items in E.2. ^b 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 magnetic field antenna factors [74]. Reference [18] provides a useful overview. Reference [15] provides a simplified version of the standard field method (SFM) ([32] and [16]), and the TAM is described in [35]. This subclause and Annex H specify acceptable calibration methods for loop antennas.

The TAM and the TEM cell method yield a standard uncertainty of measured antenna factor of approximately $\pm 0,5$ dB, while application of the TEM cell method is restricted to the frequency range below the first resonant frequency of the TEM cell.

The current probe method (CPM) [15] is an improved SFM based on IEEE Std 291 [32]. In the original method, the current flowing in the transmit loop antenna was measured using an RF vacuum thermocouple built into the loop element; however, a thermocouple is typically small and fragile, and therefore is not suitable for use in routine calibration measurements.

The Helmholtz coil method [34], categorized as a SFM, is accurate to 0,7 % (0,06 dB) up to 150 kHz, and better than $\pm 0,5$ dB up to 10 MHz (see Annex H), but its applicable frequency range depends on the coil size.

A sufficient signal-to-{receiver noise} ratio of at least 34 dB is necessary to obtain low measurement uncertainties, if using a VNA as described in 6.2.4. In addition, it is important to

attach attenuators to the transmit loop antenna and the receive loop antenna, to reduce mismatch uncertainties if using a signal generator and a receiver. When calibrating a loop antenna in free-space conditions, the distance between the transmit antenna or the receive antenna and any nearby reflecting objects, including any metallic ground plane, should be greater than 1,3 m; the clearance required also depends on the spacing between the 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 Ω ;
P_{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 Ω , 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.

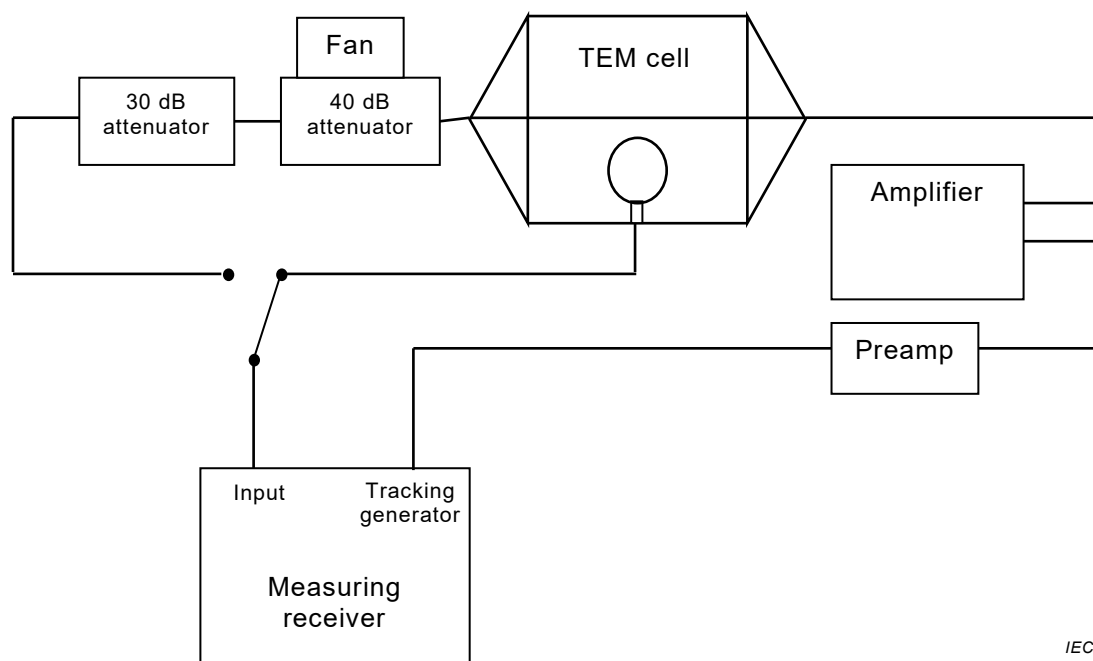
A typical set-up is shown in Figure 4. Blocks of polystyrene foam can be used to support the loop centrally between the plates; this serves the essential function of insulating the base of the loop from the TEM cell conductor surface. To get sufficient output signal from a passive loop, an amplifier 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

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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.



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

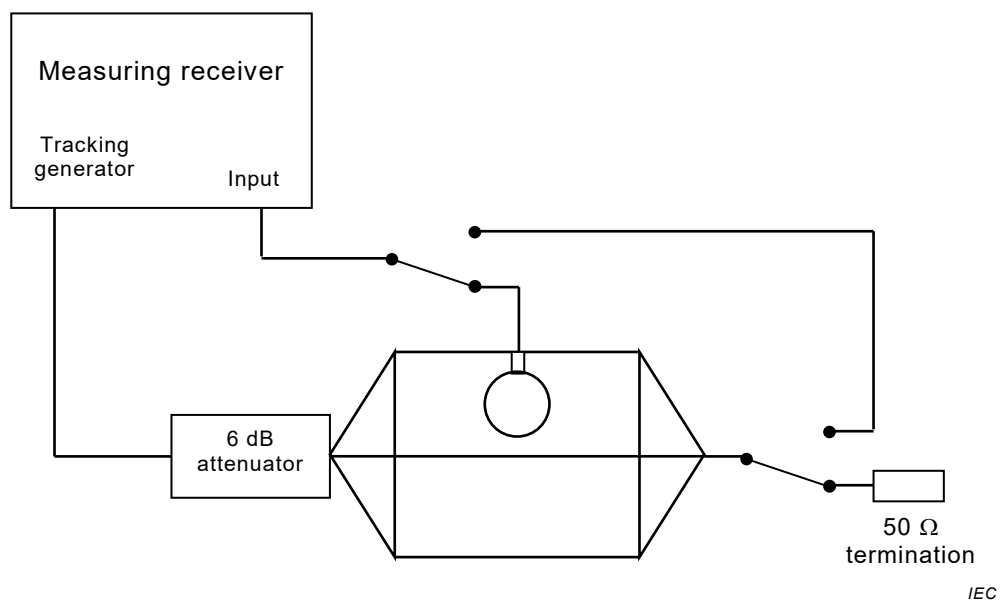


Figure 5 – Block diagram of TEM cell set-up for active loop antennas

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 ^a	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	–
Combined standard uncertainty, u_C					0,42	–
Expanded uncertainty, U ($k = 2$)					0,84	
^a 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.						

5.2.3 Three antenna method (TAM)

5.2.3.1 General

Antenna calibration using the TAM requires three antennas (numbered as 1, 2, and 3) to form three antenna pairs. Prior knowledge of the AF of any of the three antennas is not needed with the TAM (see also 4.3.3 about the TAM).

SIL for antenna calibration is usually measured with a calibrated network analyzer, to reduce mismatch errors that may occur between the signal output port and the transmit loop antenna, as well as between the signal receiving port and the receive loop antenna. Alternatively, a combination of signal/tracking-generator and measuring receiver can be used; in this case, padding attenuators are required to reduce standing waves on the cables.

Different from TAM calibrations above 30 MHz, which are based on the Friis transmission equation, the TAM method for loop antenna calibrations is based on a modified Neumann mutual inductance formula [75], which is approximately expressed by the so-called Greene's formula [70].

The separation distance between the transmit antenna and the receive antenna shall be small compared to the distance to the surroundings. Therefore, coupling between the antennas is

maximized, while coupling to the surroundings is minimized. A specific site validation criterion is not required, but the influences from the site on the magnetic field antenna factor results shall be estimated; see the discussion in 5.2.3.2.

5.2.3.2 Calibration procedure

For antenna pairs coaxially aligned as shown in Figure 21, the site insertion loss, $A_i(i,j)$, between antenna i and antenna j is measured in a free-space environment [35], and is described by Equation (61).

$$A_i(i,j) = F_{aH}(i) + F_{aH}(j) + 45,9 + 20\lg(f_{\text{MHz}}) - 20\lg[K(i,j)] \text{ in dB} \quad (61)$$

From data on the $A_i(i,j)$ for the three antenna pairs, the magnetic field antenna factors F_{aH} of each antenna can be determined using Equations (62).

$$\begin{aligned} F_{aH}(1) &= \frac{1}{2} [-45,9 - 20\lg f_{\text{MHz}} + A_i(1,2) + A_i(1,3) - A_i(2,3) + K(1,2) + K(1,3) - K(2,3)] \\ F_{aH}(2) &= \frac{1}{2} [-45,9 - 20\lg f_{\text{MHz}} + A_i(1,2) - A_i(1,3) + A_i(2,3) + K(1,2) - K(1,3) + K(2,3)] \text{ in dB(S/m)} \\ F_{aH}(3) &= \frac{1}{2} [-45,9 - 20\lg f_{\text{MHz}} - A_i(1,2) + A_i(1,3) + A_i(2,3) - K(1,2) + K(1,3) + K(2,3)] \end{aligned} \quad (62)$$

where

f_{MHz} is the frequency in MHz;

$A_i(i,j)$ is the SIL between antenna i and antenna j ; when it is measured using a network analyzer, the site insertion loss is given by Equation (63).

$$A_i(i,j) = -20\lg|S_{21}(i,j)| \text{ in dB;} \quad (63)$$

$K(i,j)$ is the function shown in Equation (64), based on a modified Neumann equation for antenna pair (i,j)

$$K(i,j) = 20\lg \left(\frac{1}{4\pi S_i S_j} \left| \oint_{C_j} \oint_{C_i} \frac{e^{-j\beta R}}{R} d\mathbf{s}_i \cdot d\mathbf{s}_j \right| \right) \text{ in dB(m}^{-3}\text{)} \quad (64)$$

and

S_i, S_j are the geometric areas ($r^2\pi$) in m^2 of antennas i and j , respectively;

C_i, C_j are the closed curves encircling the loop element of antennas i and j , respectively;

$d\mathbf{s}_i, d\mathbf{s}_j$ are infinitesimal segment vectors of the loop elements of antennas i and j , respectively;

R is the distance in m between the segments $d\mathbf{s}_i$ and $d\mathbf{s}_j$.

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If the three loop antennas are true circles and a homogeneous current distribution along each loop is assumed, Equation (64) can be expressed approximately by the following form:

$$K(i, j) = 20 \lg \left(\frac{\sqrt{1 + \beta^2 R_0^2(i, j)}}{2\pi R_0^3(i, j)} \left[1 + \frac{15}{8} \left(\frac{r_i r_j}{R_0^2(i, j)} \right)^2 + \frac{315}{64} \left(\frac{r_i r_j}{R_0^2(i, j)} \right)^4 \right] \right) \text{ in dB(m}^{-3}\text{)} \quad (65)$$

Equation (65) is called Greene's formula [70], where

$$R_0(i, j) = \sqrt{d_{ij}^2 + r_i^2 + r_j^2} \text{ in m} \quad (66)$$

r_i, r_j are the radii in m of antennas i and j , respectively;

d_{ij} is the distance, in m, between the loop centres of antennas i and j ;

β is the wave number ($=2\pi/\lambda$) in m^{-1} .

Equation (65) is valid under the conditions that $\beta R_0(i, j) \leq 1,0$ and $r_i r_j / R_0^2(i, j) \leq 1/16$. Equation (64) and Equation (65) can be fulfilled if the current distribution on both loop antennas is uniform. To calibrate loop antennas accurately, the radius of the loop antenna driven as the transmit loop shall be within derived limits; for example, Table 15 shows suitable combinations for r_i , r_j , and d_{ij} , and indicates the error of Greene's formula at the highest frequency of 30 MHz. The frequency dependency of the error is shown in Figure 22. The loop centre distance between a pair of antennas, d_{ij} , should be selected to fulfil the conditions, and shall be as small as possible to minimize influences from the surroundings. It should be noted that other uncertainty terms, such as the positioning uncertainty increase as the separation reduces.

An estimate for the influence of a ground plane with different loop separation distances d_{ij} ranging from 0,1 m to 1,0 m is given in Figure 23. Figure 23 is obtained by normalizing the SILs between two loop antennas with 60 cm diameter placed 1,3 m and 2,5 m above a ground plane to the SILs in free space. An OATS or a SAC can be used as the calibration test site, and the particular influence of the calibration test site shall be taken into consideration for the calibration measurement uncertainty estimation. The influence of the ground plane also depends on the position of the feed gaps of the two loop antennas.

Alternatively to Equations (62), Equations (67) can be used, which are based on a numerical simulation approach. The advantage of the numerical simulation approach is that the inhomogeneous current distribution is taken into account. The conditions required for the application of Greene's formula do not apply for the numerical simulation approach. It is not necessary to take into account the error given in Table 15.

$$\begin{aligned} F_{\text{aH}}(1) &= \frac{1}{2} [A_i(1,2) + A_i(1,3) - A_i(2,3) - A_N(1,2) - A_N(1,3) + A_N(2,3)] \\ F_{\text{aH}}(2) &= \frac{1}{2} [A_i(1,2) - A_i(1,3) + A_i(2,3) - A_N(1,2) + A_N(1,3) - A_N(2,3)] \text{ in dB(S/m)} \\ F_{\text{aH}}(3) &= \frac{1}{2} [-A_i(1,2) + A_i(1,3) + A_i(2,3) + A_N(1,2) - A_N(1,3) - A_N(2,3)] \end{aligned} \quad (67)$$

where

$A_i(i,j)$ is the SIL between antenna i and antenna j ; when it is measured using a network analyzer, the site insertion loss is given by Equation (63).

$A_N(i,j)$ is the normalized site insertion loss (NSIL) calculated by NEC. The same loop geometry shall be used for simulation and calibration. Further information about normalized site attenuation calculation is planned for inclusion in future editions of CISPR 16-1-4.³

Greene's formula does not apply if the antennas do not have circular shapes. For square shapes, it is feasible to modify Equation (65) by a correction factor for r_i or r_j where

$$r_i = 1,13(s_i/2) \text{ and } r_j = 1,13(s_j/2) \quad (68)$$

r_i, r_j are the radii, in m, of antennas i and j , respectively;

s_i, s_j are the side lengths, in m, of the square loops i and j , respectively.

To obtain $K(i,j)$ for square shapes accurately, or to obtain $K(i,j)$ for other loop antenna shapes, $K(i,j)$ should be calculated per Equation (64) using numerical integration.

The accuracy of Greene's formula is estimated by calculating the difference per Equation (69) of the magnetic field antenna factor found by the application of Greene's formula and the magnetic field antenna factor found by numerical simulation. The accuracy of the integral formula of Equation (64) is estimated by calculating the difference per Equation (71) of the magnetic field antenna factor found by the application of the integral formula and the magnetic field antenna factor found by numerical simulation. The results are shown in Figure 22, where a decreased accuracy at the upper frequency end can be observed.

$$\Delta F_{aH,G} = F_{aH,G} - F_{aH,num} \quad (69)$$

$$\Delta F_{aH,I} = F_{aH,I} - F_{aH,num} \quad (70)$$

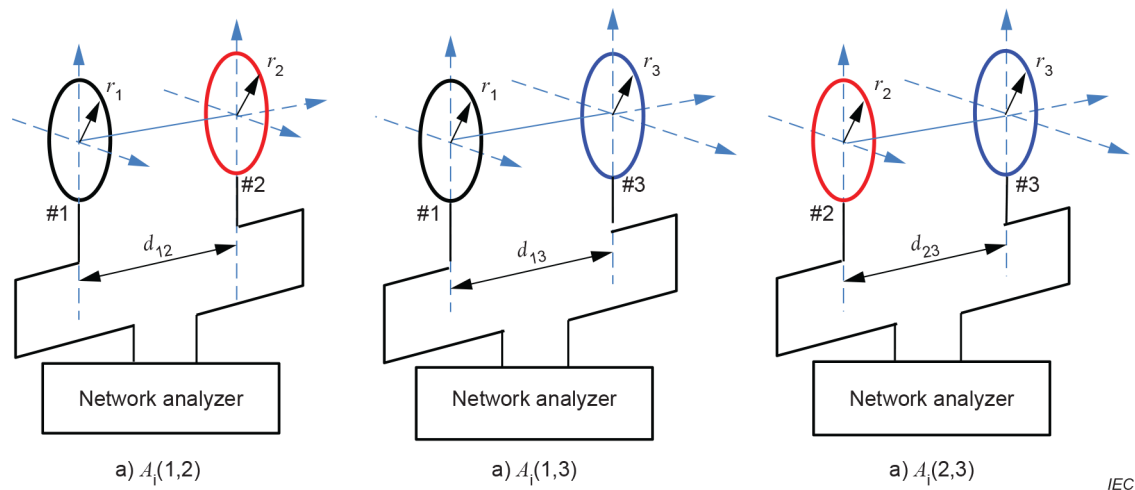
$F_{aH,G}$ is the magnetic field antenna factor found by application of Greene's formula,

$F_{aH,I}$ is the magnetic field antenna factor found by application of the integral formula;

$F_{aH,num}$ is the magnetic field antenna factor found by numerical simulation.

³ As discussed in e.g. 10.6 of CIS/A/1240/RM, a project is ongoing for amending CISPR 16-1-4 to include site validation below 30 MHz; at the time of preparation of this FDIS the most recent documents for that project are CIS/A/1323/CDV and CIS/A/1288/CC.

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NOTE The feed points may be placed at the top of the loop antennas.

Figure 21 – Loop antenna pair arrangements for the TAM

Table 15 – Examples for valid use of Equation (65)

Loop radius r_i [m]	Loop radius r_j [m]	Distance d_{ij} [m]	$\beta R_0(i, j)$	$r_i r_j / R_0^2(i, j)$	Error due to non-constant current distribution at 30 MHz [dB]
0,05	0,3	0,39	0,31	0,061 3	0,13
0,15	0,3	0,78	0,53	0,062 4	0,33
0,05	0,15	0,31	0,22	0,061 9	0,07
0,15	0,15	0,57	0,38	0,060 8	0,18
0,05 (NOTE 1)	0,05	0,2	0,13	0,055 6	0,05
0,3 (NOTE 2)	0,3	1,2	0,8	0,055 6	0,53

NOTE 1 If both loop radii are very small, the accuracy of Greene's formula is excellent and with an error of only 0,05 dB.

NOTE 2 If a transmit antenna and also a receive antenna with a large radius are used, the effect of the inhomogeneous current distribution can lead to a relatively large error of 0,53 dB.

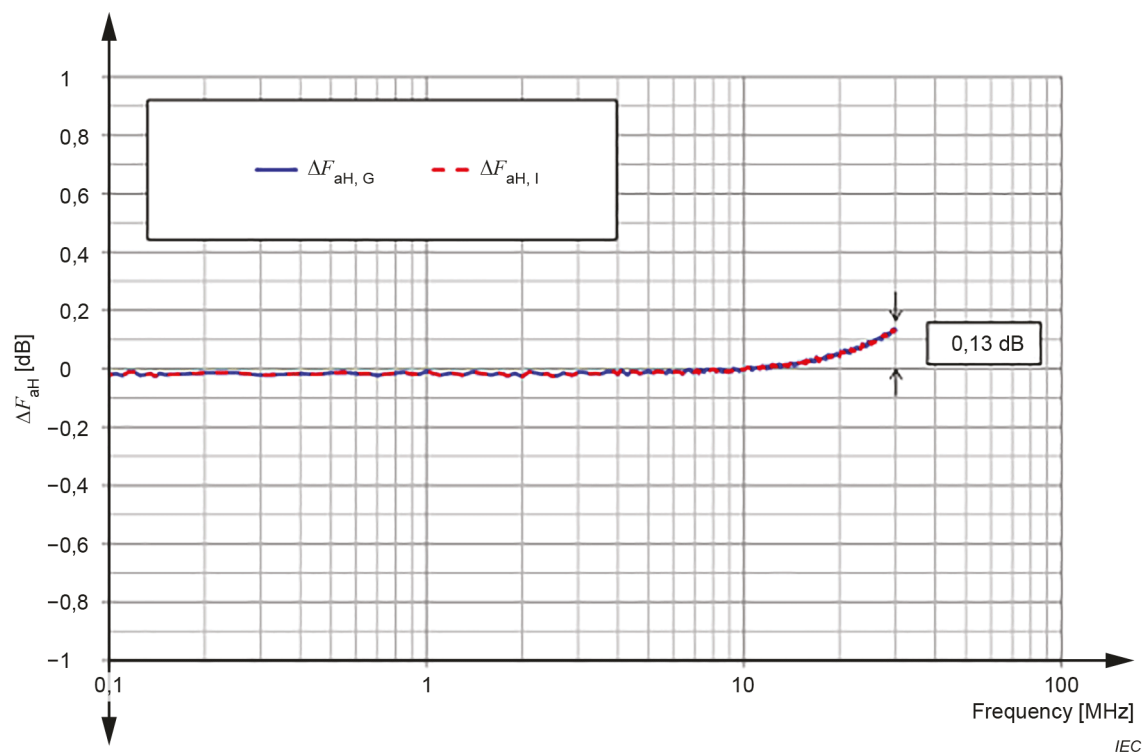
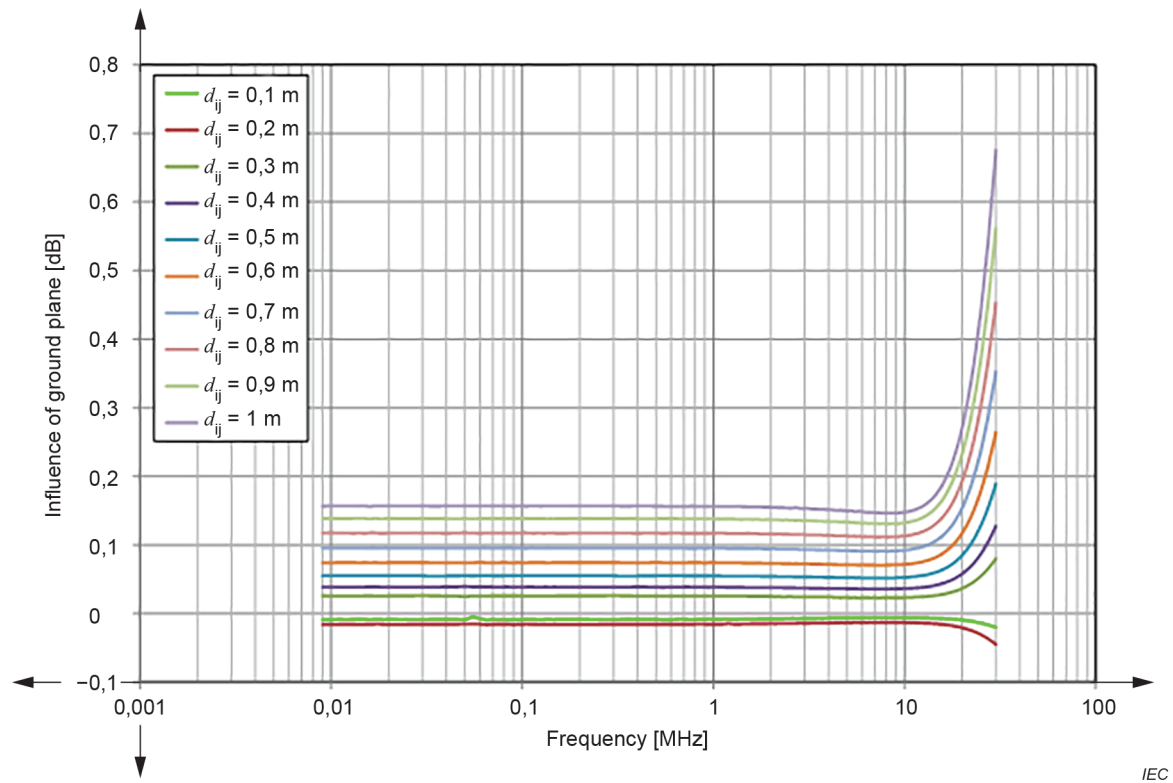
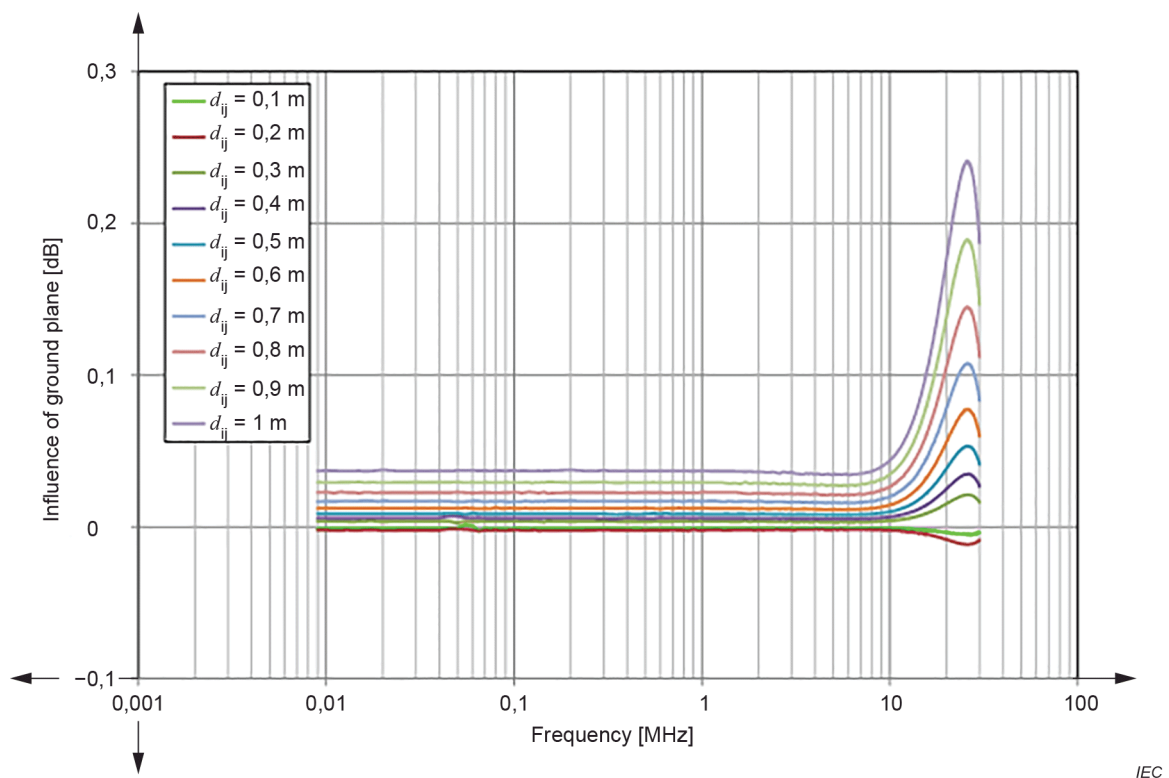


**Figure 22 – Accuracy of Greene's formula and integral formula
vs. frequency for $r_i = 0,05$ m, $r_j = 0,3$ m, and $d = 0,39$ m**

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a) 1,3 m above ground plane



b) 2,5 m above ground plane

Figure 23 – Examples of influence of ground plane on SIL in free-space condition

5.2.3.3 Measurement uncertainties for TAM calibration results

An example of the uncertainty budget estimated for TAM calibration F_{aH} results at 30 MHz is shown in Table 16 and Table 18. The combined standard uncertainties for the $A_i(i,j)$ SIL results and the $K(i,j)$ geometry parameter are used as inputs for the F_{aH} expanded uncertainty in Table 18.

The expanded uncertainty of F_{aH} measurement results depends significantly on the size of the AUC because $K(i,j)$ per Equation (65) is a function of the separation distance, the radii of both of the loop antennas, and misalignment.

Figure 24 shows the definitions of the parameters used in the uncertainty evaluation for $K(i,j)$:

- a) misalignment in the x -axis, uncertainty of m (not shown in Figure 24);
- b) misalignment in the y -axis, uncertainty of d_{ij} ;
- c) misalignment in the z -axis, uncertainty of l (z -axis offset);
- d) misalignment around the x -axis, uncertainty of θ_i and θ_j ;
- e) misalignment around the y -axis, uncertainty of Θ_i and Θ_j (not shown in Figure 24);
- f) misalignment around the z -axis, uncertainty of ϕ_i and ϕ_j (not shown in Figure 24).

It is not possible to derive the influence of misalignment with Greene's formula, so NEC simulations are used instead. The uncertainty component in K (given as δA_{SIL}) is derived from differences in the calculated NEC SIL values.

An easy solution to calculate measurement uncertainty is to use a mixed approach. The uncertainty of K is calculated by a numerical method, while the remaining uncertainty contributions are combined using the propagation of uncertainties law.

The measurement function for F_{aH} is given in Equation (71).

$$F_{aH}(1) = \frac{1}{2} \left[-45,9 - 20 \lg f_{\text{MHz}} + A_i(1,2) + A_i(1,3) - A_i(2,3) + K(1,2) + K(1,3) - K(2,3) \right] \quad (71)$$

Because the frequency inaccuracy can be neglected, the contribution from the term f_{MHz} is neglected in the analysis.

The measurement function for $A_i(i,j)$ is given in Equation (72).

$$\delta A_i(i,j) = \delta A_{\text{LIN}} + \delta A_{\text{M}} + \delta A_{\text{L}} + \delta A_{\text{SNR}} + \delta A_{\text{BS}} \quad (72)$$

The measurement function for $K(i,j)$ is given in Equation (73).

$$\begin{aligned} \delta K(i,j) = & \delta A_{\text{SIL}}(r_1, \delta r_1, r_2, \delta r_2, d_{12}, \delta d_{12}, \delta m, \delta l, \delta \theta_1, \delta \theta_2, \delta \Theta_1, \delta \Theta_2, \delta \phi_1, \delta \phi_2) \\ & + \delta A_{\text{coup}} + \delta A_{\text{approx}} \end{aligned} \quad (73)$$

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An example source code for a measurement uncertainty Monte Carlo simulation (MCS) (e.g. [7]) is given in Annex J.

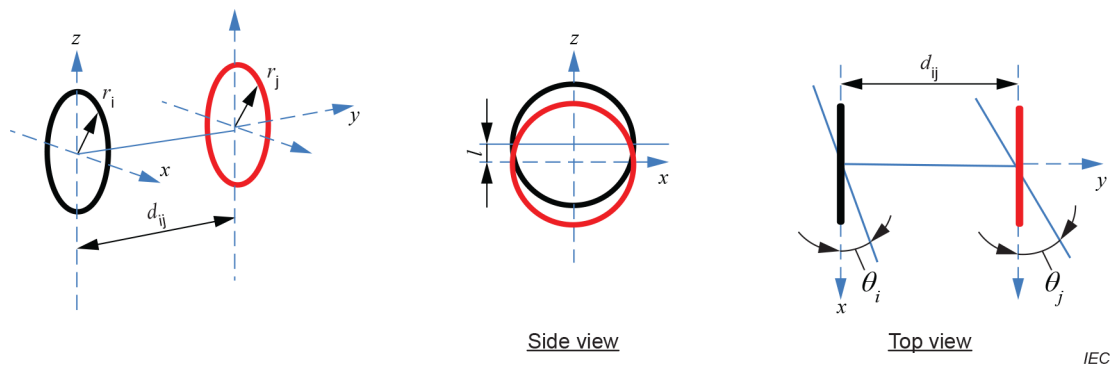


Figure 24 – Definitions of the parameters used in measurement uncertainty evaluation for $K(i,j)$

Table 16 – Example of an uncertainty budget for site insertion loss $A_i(i,j)$

Source of uncertainty or quantity X_i		Value dB	Probability distribution	Divisor	Sensitivity	u_i dB
Linearity of receiver in the network analyzer	δA_{LIN}	0,10	Rectangular	$\sqrt{3}$	1	0,06
Transmit antenna mismatch and receive antenna mismatch	δA_M	0,17	U-shaped	$\sqrt{2}$	1	0,12
Leakage between coaxial cables	δA_L	0,09	Rectangular	$\sqrt{3}$	1	0,05
Signal to noise ratio	δA_{SNR}	0,01	Rectangular	$\sqrt{3}$	1	0,01
Bending and stretching cables	δA_{BS}	0,10	Rectangular	$\sqrt{3}$	1	0,06
Combined standard uncertainty						0,15
NOTE The uncertainty value of signal to noise ratio depends on the measurement frequency, radii of loop antennas, distance between two loop antennas and measuring instruments such as VNA or spectrum analyser with tracking generator. For example, with $r_1 = r_2 = 5$ cm, $d = 10$ cm, frequency of 10 kHz, and a VNA is used, then the uncertainty value of signal to noise ratio can be larger than 1,0 dB.						

Table 17 – Example of an uncertainty budget for $K(i,j)$ as used by the TAM

Source of uncertainty or quantity X_i		Value	Probability distribution
Positioning of loop antennas	δA_{SIL}		
Radius antenna 1 ($r_1 = 0,05$ m)	δr_1	0,002 m	Rectangular
Radius antenna 2 ($r_2 = 0,3$ m)	δr_2	0,002 m	Rectangular
Distance (misalignment in y -axis, $d_{12} = 0,31$ m)	δd_{12}	0,01 m	Rectangular
Misalignment in x -axis	δm	0,01 m	Rectangular
Misalignment in z -axis	δl	0,01 m	Rectangular
Misalignment around x -axis, antenna 1	$\delta \theta_1$	5°	Rectangular
Misalignment around y -axis, antenna 1	$\delta \Theta_1$	1°	Rectangular
Misalignment around z -axis, antenna 1	$\delta \varphi_1$	5°	Rectangular
Misalignment around x -axis, antenna 2	$\delta \theta_2$	5°	Rectangular
Misalignment around y -axis, antenna 2	$\delta \Theta_2$	1°	Rectangular
Misalignment around z -axis, antenna 2	$\delta \varphi_2$	5°	Rectangular
Coupling with ground plane	δA_{coup}	0,1 dB	Rectangular
Approximation error in Equation (65) (NOTE)	δA_{approx}	0,13 dB	Rectangular
Expanded uncertainty, U ($k = 2$)			0,8 dB
NOTE If Greene's formula [Equation (65)] is used, there is an error because the formula is only an approximation of Equation (64). An estimation of this error is shown in Table 15 and Figure 21. This contribution does not apply if a numerical approach is used [see Equation (67)].			

Table 18 – Example of an uncertainty budget for F_{aH} of a loop antenna determined by the TAM – expanded uncertainty at 30 MHz

Source of uncertainty or quantity X_i		Value dB	Probability distribution	Divisor	Sensitivity	u_i dB	Note
SIL	$A_i(1,2)$	0,15	Normal ($k = 1$)	1	1/2	0,08	See Table 16
SIL	$A_i(1,3)$	0,15	Normal ($k = 1$)	1	1/2	0,08	See Table 16
SIL	$A_i(2,3)$	0,15	Normal ($k = 1$)	1	-1/2	0,08	See Table 16
Greene's formula	$K(1,2)$	0,8	Normal ($k = 2$)	1	1/2	0,2	$r_2 = 5$ cm $r_1 = 30$ cm $d_{12} = 31$ cm
Greene's formula	$K(1,3)$	0,8	Normal ($k = 2$)	1	1/2	0,2	$r_3 = 5$ cm $r_1 = 30$ cm $d_{13} = 31$ cm
Greene's formula	$K(2,3)$	1,3	Normal ($k = 2$)	1	-1/2	0,33	$r_2 = 5$ cm $r_3 = 5$ cm $d_{23} = 31$ cm
Combined standard uncertainty, u_c						0,46	
Expanded uncertainty, U ($k = 2$)						0,92	
NOTE The contributions from Greene's formula $K(2,3)$ are not equal to $K(1,2)$, $K(1,3)$, because the result depends on loop diameter and distance. The basis for the calculation is given in the Note column.							