CISPR 16-1-6

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

BASIC EMC PUBLICATION
PUBLICATION FONDAMENTALE EN CEM

AMENDMENT 2
AMENDEMENT 2

Specification for radio disturbance and immunity measuring apparatus and methods –
Part 1-6: Radio disturbance and immunity measuring apparatus – EMC antenna calibration

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

CISPR 16-1-6:2014-12/AMD2:2022-03 (en-fr)

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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

AMENDMENT 2

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Amendment 2 to CISPR 16-1-6:2014 has been prepared by subcommittee CISPR A: Radio-interference measurements and statistical methods, of IEC technical committee CISPR: International special committee on radio interference.

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

Draft	Report on voting
CIS/A/1362/FDIS	CIS/A/1365/RVD

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

The language used for the development of this Amendment is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications/.

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2 Normative references

Add to the existing list the following new references:

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*

3.1.2.5
magnetic field antenna factor

Replace the existing Note 1 to entry and Note 2 to entry as follows:

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($\Omega^{-1}\mathrm{m}^{-1}$).

Note 2 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.

Add Note 3 to entry:

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.

3.2 Abbreviations

Add to the existing list the following new abbreviations:

CPM	current probe method
SFM	standard field method

5.2.1 General

Replace the second and third paragraphs by the following five new paragraphs:

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 ± 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 ± 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.

Add, at the end of the existing 5.2.2.2, the following new subclauses:

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, $A_\mathrm{i}(i,j)$, between antenna i and antenna j is measured in a free-space environment [35], and is described by Equation (61).

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

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

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

where

f_{MHz}	is the frequency in MHz;
$A_{\mathrm{i}}(i,j)$	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).

$$A_{\mathrm{i}}(i,j) = -20\lg\left|S_{21}(i,j)\right| \text{ in dB;} \qquad (63)$$

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

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

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 $d\mathbf{s}_j$.

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:

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

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

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

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 (=2π/λ) 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.

$$\begin{aligned}
F_{\text{aH}}(1) &= \frac{1}{2}\left[A_{\text{i}}(1,2) + A_{\text{i}}(1,3) - A_{\text{i}}(2,3) - A_{\text{N}}(1,2) - A_{\text{N}}(1,3) + A_{\text{N}}(2,3)\right] \\
F_{\text{aH}}(2) &= \frac{1}{2}\left[A_{\text{i}}(1,2) - A_{\text{i}}(1,3) + A_{\text{i}}(2,3) - A_{\text{N}}(1,2) + A_{\text{N}}(1,3) - A_{\text{N}}(2,3)\right] \quad \text{in dB(S/m)} \\
F_{\text{aH}}(3) &= \frac{1}{2}\left[-A_{\text{i}}(1,2) + A_{\text{i}}(1,3) + A_{\text{i}}(2,3) + A_{\text{N}}(1,2) - A_{\text{N}}(1,3) - A_{\text{N}}(2,3)\right]
\end{aligned} \tag{67}$$

where

$A_{\text{i}}(i,j)$ 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).

$A_\mathrm{N}(i,j)$ 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.[1]

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

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

$r_{i,}r_j$ 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.

$$\Delta F_\mathrm{aH,G} = F_\mathrm{aH,G} - F_\mathrm{aH,num} \tag{69}$$

$$\Delta F_\mathrm{aH,I} = F_\mathrm{aH,I} - F_\mathrm{aH,num} \tag{70}$$

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

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

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

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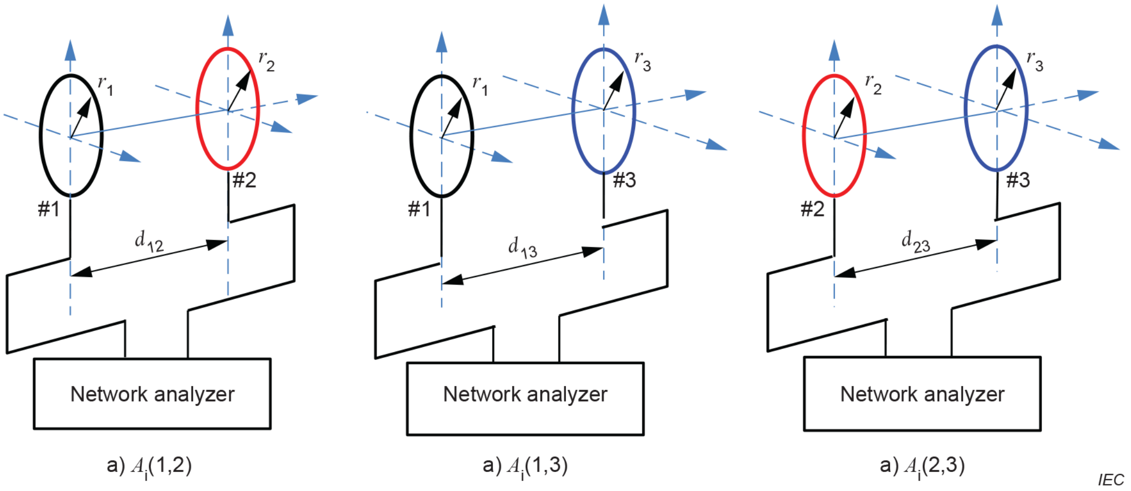
[1] As discussed in e.g. 10.6 of CIS/A/1240/RM, a project is ongoing for amending CISPR 16-1-4 to include site validation below 30 MHz; at the time of preparation of this FDIS the most recent documents for that project are CIS/A/1323/CDV and CIS/A/1288/CC.



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.

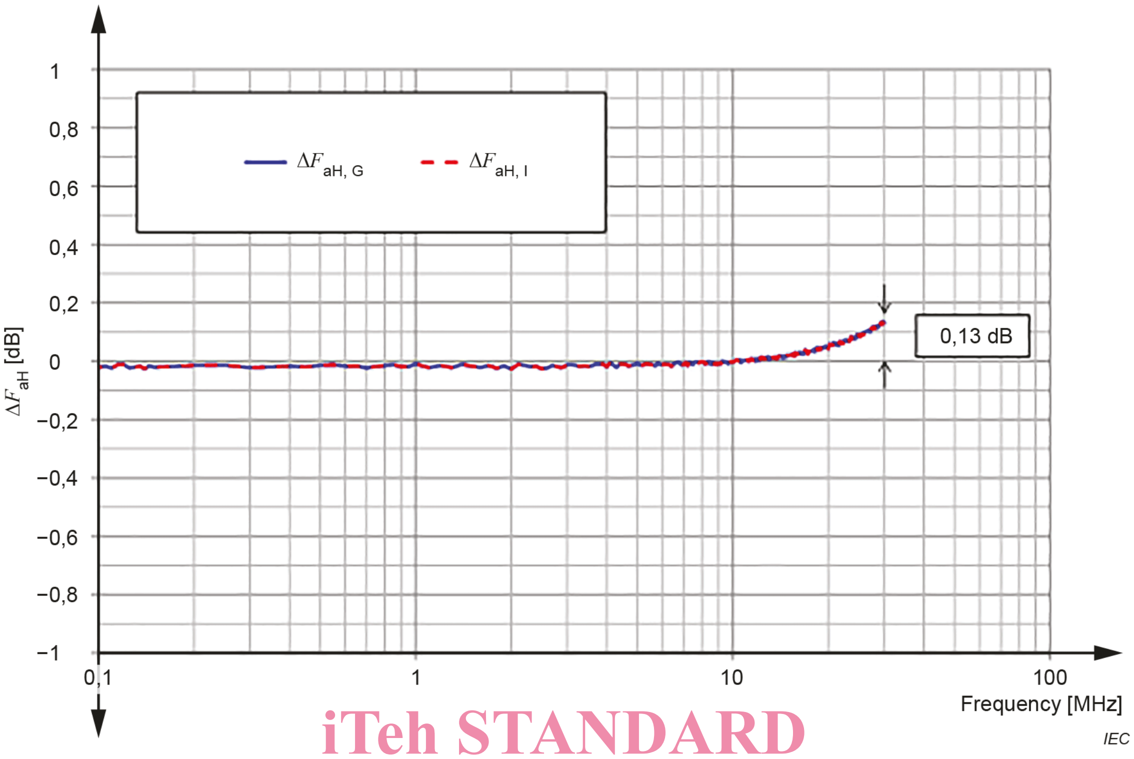
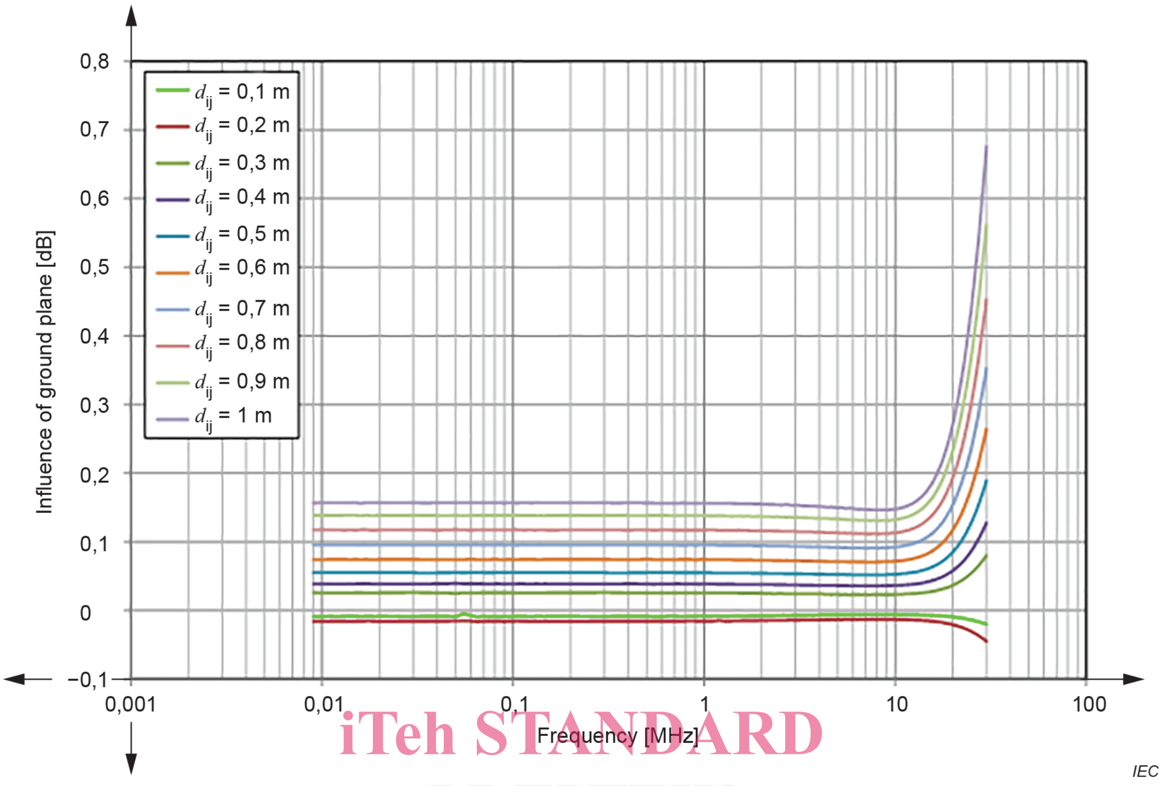
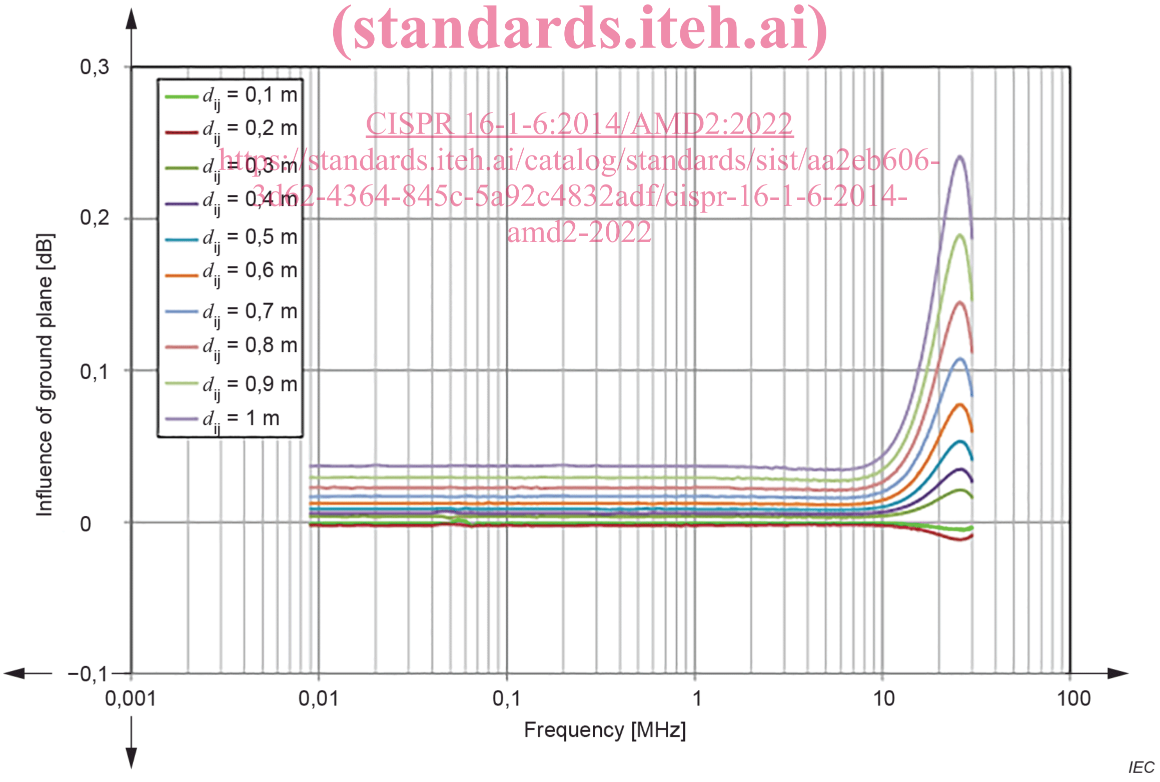


Figure 22 – Accuracy of Greene's formula and integral formula vs. frequency for r_i = 0,05 m, r_j = 0,3 m, and d = 0,39 m



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 $A_{\mathrm{i}}(i,j)$ 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).

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

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

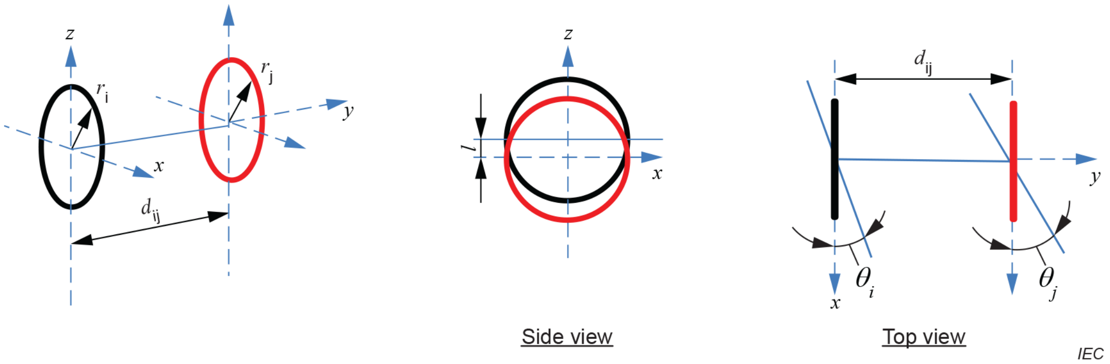
The measurement function for $A_{\mathrm{i}}(i,j)$ is given in Equation (72).

$$\delta A_{\mathrm{i}}(i,j)=\delta A_{\mathrm{LIN}}+\delta A_{\mathrm{M}}+\delta A_{\mathrm{L}}+\delta A_{\mathrm{SNR}}+\delta A_{\mathrm{BS}} \qquad (72)$$

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

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

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



Side view

Top view

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.						