# COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

# INTERNATIONAL ELECTROTECHNICAL COMMISSION

# CISPR 16-1-5

Première édition
First edition
2003-11

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

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

## Partie 1-5: Appareils de mesure des perturbations radioélectriques et de l'immunité aux perturbations radioélectriques – Emplacements d'essai pour l'étalonnage des antennes de 30 MHz à 1 000 MHz

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

## Part 1-5: Radio disturbance and immunity measuring apparatus – Antenna calibration test sites for 30 MHz to 1 000 MHz



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Commission Electrotechnique Internationale
International Electrotechnical Commission
Международная Электротехническая Комиссия

CODE PRIX
PRICE CODE XA

*Pour prix, voir catalogue en vigueur*
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INTERNATIONAL ELECTROTECHNICAL COMMISSION
INTERNATIONAL SPECIAL COMMITTEE ON RADIO INTERFERENCE

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

## Part 1-5: Radio disturbance and immunity measuring apparatus – Antenna calibration test sites for 30 MHz to 1 000 MHz

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International Standard CISPR 16-1-5 has been prepared by CISPR subcommittee A: Radio interference measurements and statistical methods.

This first edition of CISPR 16-1-5, together with CISPR 16-1-1, CISPR 16-1-2, CISPR 16-1-3 and CISPR 16-1-4, cancels and replaces the second edition of CISPR 16-1, published in 1999, amendment 1 (2002) and amendment 2 (2003). It contains the relevant clauses of CISPR 16-1 without technical changes.

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

The committee has decided that the contents of this publication will remain unchanged until 2005. At this date, the publication will be

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- withdrawn;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

# INTRODUCTION

CISPR 16-1, CISPR 16-2, CISPR 16-3 and CISPR 16-4 have been reorganised into 14 parts, to accommodate growth and easier maintenance. The new parts have also been renumbered. See the list given below.

**Old CISPR 16 publications**

| | |
|---|---|
| CISPR 16-1 | Radio disturbance and immunity measuring apparatus |
| CISPR 16-2 | Methods of measurement of disturbances and immunity |
| CISPR 16-3 | Reports and recommendations of CISPR |
| CISPR 16-4 | Uncertainty in EMC measurements |

**New CISPR 16 publications**

| | |
|---|---|
| CISPR 16-1-1 | Measuring apparatus |
| CISPR 16-1-2 | Ancillary equipment – Conducted disturbances |
| CISPR 16-1-3 | Ancillary equipment – Disturbance power |
| CISPR 16-1-4 | Ancillary equipment – Radiated disturbances |
| CISPR 16-1-5 | Antenna calibration test sites for 30 MHz to 1 000 MHz |
| CISPR 16-2-1 | Conducted disturbance measurements |
| CISPR 16-2-2 | Measurement of disturbance power |
| CISPR 16-2-3 | Radiated disturbance measurements |
| CISPR 16-2-4 | Immunity measurements |
| CISPR 16-3 | CISPR technical reports |
| CISPR 16-4-1 | Uncertainties in standardised EMC tests |
| CISPR 16-4-2 | Measurement instrumentation uncertainty |
| CISPR 16-4-3 | Statistical considerations in the determination of EMC compliance of mass-produced products |
| CISPR 16-4-4 | Statistics of complaints and a model for the calculation of limits |

More specific information on the relation between the 'old' CISPR 16-1 and the present 'new' CISPR 16-1-5 is given in the table after this introduction (TABLE RECAPITULATING CROSS REFERENCES).

Measurement instrumentation specifications are given in five new parts of CISPR 16-1, while the methods of measurement are covered now in four new parts of CISPR 16-2. Various reports with further information and background on CISPR and radio disturbances in general are given in CISPR 16-3. CISPR 16-4 contains information related to uncertainties, statistics and limit modelling.

CISPR 16-1 consists of the following parts, under the general title *Specification for radio disturbance and immunity measuring apparatus and methods – Radio disturbance and immunity measuring apparatus:*

- Part 1-1: Measuring apparatus,
- Part 1-2: Ancillary equipment – Conducted disturbances,
- Part 1-3: Ancillary equipment – Disturbance power,
- Part 1-4: Ancillary equipment – Radiated disturbances,
- Part 1-5: Antenna calibration test sites for 30 MHz to 1 000 MHz.

# TABLE RECAPITULATING CROSS REFERENCES

| Second edition of CISPR 16-1<br>Clauses, subclauses | First edition of CISPR 16-1-5<br>Clauses, subclauses |
|---|---|
| 1 | 1 |
| 2 | 2 |
| 3 | 3 |
| 5.13 | 4 |
| **Annexes** | **Annexes** |
| R | A |
| S | B |
| T | C |
| U | D |
| V | E |
| W | F |
| **Figures** | **Figures** |
| 55, 56, 57, 58, 59 | 1, 2, 3, 4, 5 |
| S.1, S.2, S.3, S.4 | B.1, B.2, B.3, B.4 |
| T.1, T.2, T.3 | C.1, C.2, C.3 |
| **Tables** | **Tables** |
| 19, 20 | 1, 2 |

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

## Part 1-5: Radio disturbance and immunity measuring apparatus – Antenna calibration test sites for 30 MHz to 1 000 MHz

## 1 Scope

This part of CISPR 16 is designated a basic standard which specifies the requirements for calibration test sites, used to perform antenna calibrations, as well as the test antenna characteristics, calibration site verification procedure and site compliance criteria. Further information on calibration site requirements, test antenna considerations and the theory of antennas and site attenuation is provided in informative annexes.

Measurement instrumentation specifications are given in CISPR 16-1-1 and CISPR 16-1-4. Further information and background on uncertainties in general is given in CISPR 16-4-1, which may be helpful in establishing uncertainty estimates for the calibration processes of antennas.

## 2 Normative references

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

CISPR 14-1:2000, *Electromagnetic compatibility – Requirements for household appliances, electric tools and similar apparatus – Part 1: Emission*

CISPR 16-1-1:2003, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-1: Radio disturbance and immunity measuring apparatus - Measuring apparatus*

CISPR 16-1-4:2003, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-4: Radio disturbance and immunity measuring apparatus – Ancillary equipment - Radiated disturbances*

CISPR 16-4-1:2003, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 4-1: Uncertainties, statistics and limit modelling - Uncertainties in standardised EMC tests*

CISPR 16-4-2:2003, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 4-2: Uncertainties, statistics and limit modelling – Measurement instrumentation uncertainties*

IEC 60050(161):1990, *International Electrotechnical Vocabulary (IEV) – Chapter 161: Electromagnetic compatibility*

*International Vocabulary of Basic and General Terms in Metrology,* International Organization for Standardization, Geneva, 2nd edition, 1993

## 3 Definitions

For the purpose of this section of CISPR 16, the following definitions apply. Also see IEC 60050(161).

**3.1**
**calibration test site (CALTS)**
open area test site with metallic ground plane and tightly specified site attenuation performance in horizontal and vertical electric field polarization

A CALTS is used for determining the free-space antenna factor of an antenna.

Site attenuation measurements of a CALTS are used for comparison to corresponding site attenuation measurements of a compliance test site, in order to evaluate the performance of the compliance test site

**3.2**
**compliance test site (COMTS)**
environment which assures valid, repeatable measurement results of disturbance field strength from equipment under test for comparison to a compliance limit

**3.3**
**antenna**
that part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic waves in a specified way

NOTE 1 In the context of this standard, the balun is a part of the antenna.

NOTE 2 See also the term "wire antenna".

**3.4**
**balun**
passive electrical network for the transformation from a balanced to an unbalanced transmission line or device or vice versa

**3.5**
**free-space-resonant dipole**
wire antenna consisting of two straight colinear conductors of equal length, placed end to end, separated by a small gap, with each conductor approximately a quarter-wavelength long such that at the specified frequency the input impedance of the wire antenna measured across the gap is pure real when the dipole is located in the free space

NOTE 1 In the context of this standard, this wire antenna connected to the balun is also called the "test antenna".

NOTE 2 This wire antenna is also referred to as "tuned dipole".

**3.6**
**site attenuation**
site attenuation between two specified positions on a test site is the insertion loss determined by a two-port measurement, when a direct electrical connection between the generator output and receiver input is replaced by transmitting and receiving antennae placed at the specified positions

**3.7**
**test antenna**
combination of the free-space-resonant dipole and the specified balun

NOTE For the purpose of this standard only.

**3.8**
**wire antenna**
a specified structure consisting of one or more metallic wires or rods for radiating or receiving electromagnetic waves

NOTE A wire antenna does not contain a balun.

# 4 Specifications and validation procedures for a test site to be used to calibrate antennas in the frequency range of 30 MHz to 1 000 MHz

Clause 5 of CISPR 16-1-4 specifies the requirements for a test site used to make radio disturbance field strength measurements in the frequency range of 30 MHz to 1 000 MHz. Such a test site may not be suitable for calibrating antennas. This clause specifies the requirements and validation procedure for a test site suitable for the calibration of antennas above a conducting, flat metal plane in the frequency range of 30 MHz to 1 000 MHz. A test site meeting these stringent requirements may also be used as a reference test site for comparison purposes in an alternative validation procedure to 5.6 of CISPR 16-1-4.

## 4.1 Introduction

A test site suitable for performing antenna calibration, referred to herein as CALTS, is intended to provide a suitable environment to calibrate an antenna for its free-space antenna factor. This calibration is performed most conveniently above a reflecting plane by using only horizontal polarization. Subclauses 4.3 through 4.6 specify the characteristics of a CALTS, the characteristics of a calculable test antenna and the CALTS verification (validation) procedure and performance criteria. The CALTS validation procedure given in 4.5 requires the use of a calculable dipole antenna as specified in 4.4, thus creating the possibility of comparing theoretically predicted site-attenuation to measured CALTS performance. Items to be reported in a CALTS validation report are summarized in 4.7. Annex A provides guidance for constructing a CALTS, which complies with validation criteria specified in 4.6.

In order for a CALTS to be used as a reference test site (REFSITE) for validating the performance of test sites according to clause 5 of CISPR 16-1-4, some additional requirements need to be specified. Subclause 4.7 specifies the additional characteristics and performance criteria. Test sites specified in clause 5 of CISPR 16-1-4, which are used for demonstrating compliance with radiated emission limits are referred to herein as a compliance test site (COMTS). Validation of a COMTS may be obtained by comparing it to the theoretical site attenuation given in clause 5 of CISPR 16-1-4 (which takes precedence) or by comparing site attenuation measurements of the REFSITE to corresponding site attenuation measurements of the COMTS, using the same measurement set-up and equipment (antennas, cables, generator, receiver, etc.).

The annexes to this standard contain informative specifications of a CALTS and of the calculable, free-space-resonant dipole (tuned dipole) to be used in the CALTS validation procedures. They also give a model for calculating theoretical site attenuation, numerical examples and a checklist for the validation procedure.

## 4.2 Antenna calibration test site (CALTS) specification

### 4.2.1 Introduction

The CALTS comprises the following main components:

- a good-conducting flat metal plane (the reflecting plane);
- an electromagnetically obstruction-free area surrounding the reflecting plane.

In addition, the following ancillary equipment is needed:

- two antenna masts carrying the antennas to be used in either the CALTS validation procedure or the antenna calibration procedure;
- the cables to be connected to these antennas; and
- electronic equipment, such as an RF generator and a measuring receiver.

The normative specification for a CALTS is given in 4.2.2, while annex A contains a number of informative specifications as a guidance to construct and place a CALTS in such a way that the validation criteria will normally be met.

### 4.2.2 Normative specification

For the calibration of antennas, the CALTS shall comply with the validation criteria given in 4.5.3, i.e.

a) site attenuation at fixed antenna heights, and

b) antenna heights for maximum site attenuation, or for maximum site attenuation, at all frequencies at which the antennas shall be calibrated.

NOTE 1 In the CALTS validation procedure, equipment is used which is also subject to normative specifications (see 4.3 and 4.4).

NOTE 2 The CALTS validation report (4.6) will contain information on how compliance with the requirements is maintained, so that the CALTS is deemed to comply with the requirements during its actual use.

## 4.3 Test antenna specification

### 4.3.1 Introduction

To allow (numerical) calculation of the theoretical site attenuation $SA_c$ needed in the validation procedure, antennas are needed which can be accurately modelled. Therefore, the test antenna shall be a free-space resonant dipole connected to a balun with specified properties. The normative test antenna specifications are given in 4.3.2. An example of the construction of a test antenna is given in annex B.

The test antenna consists of a balun and two colinear wire elements (conductors) each having a diameter $D_{we}$ and length $L_{we}$. These elements are connected to the two feed terminals (A and B in figure 1) at the balun. The gap between these feed terminals has a width $W_g$. The tip-to-tip length $L_a$ of the antenna is given by $L_a = 2L_{we} + W_g$. The centre of the test antenna is in the middle of the feed-terminal gap on the centre-line of the two colinear wire elements.

The balun has an unbalanced input/output (transmitting/receiving antenna) port and a balanced port at the two feed terminals A and B. As an example, in figure 1 the purpose of the balun is indicated schematically by the balance/unbalance transformer.

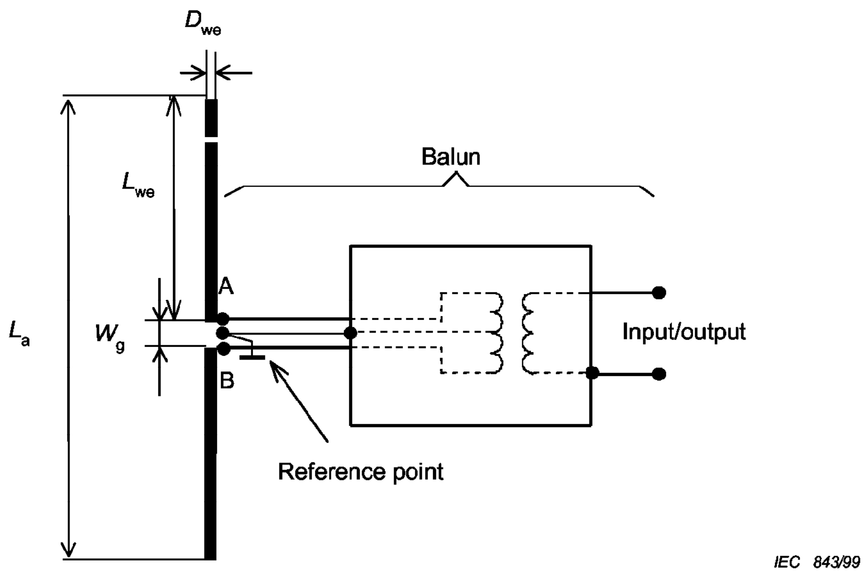
### 4.3.2 Normative specifications

**4.3.2.1** The test antenna shall have identical wire elements of length $L_{we}$ which can be disconnected from the balun to enable the balun parameters to be validated, and to allow the balun heads of the two antennas used in site attenuation measurements to be connected together.

**4.3.2.2** The tip-to-tip length $L_a(f, D_{we})$ of the approximately $\lambda/2$ wire antenna is determined by the condition that, at the specified frequency $f$ and in free space, the absolute value of the imaginary part of the input impedance at the feed terminals is smaller than 1 Ω.

NOTE 1 If the wire elements have a constant diameter and if $D_{we} << L_a$, then $L_a(f,D_{we})$ can be calculated from the equation (C.2) in subclause C.1.1. If the diameter is not a constant, e.g. when a telescopic antenna is used, $L_a(f)$ can only be calculated numerically, see C.2.2.

NOTE 2 When using a telescopic antenna, the telescopic elements should be tuned in such a way that the elements having the largest diameter are used first (see figure 2), and the numerical calculations should account for this approach.




NOTE – The centre of the test antenna is in the middle of the gap on the centre-line of the two wire elements.

**Figure 1 – Schematic diagram of the test antenna**

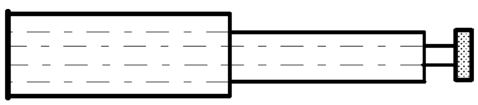



**Figure 2a – Correct**

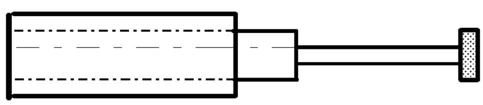



**Figure 2b – Incorrect**

**Figure 2 – Adjustment of a telescopic wire element to the length $L_{we}$**

Under consideration: At test frequencies between 30 MHz and 80 MHz, a fixed length dipole with $L_a = L_a$ (80 MHz) may be used.

**4.3.2.3** The feed-terminal gap shall be $W_g \leq 15$ mm or $W_g \leq 0{,}03\ \lambda_{min}$, whichever is the smaller,

where

$\lambda_{min} = c_0/f_{max}$,

$f_{max}$ is the highest test frequency at which the test antenna is used; and

$c_0$ is the velocity of the electromagnetic waves in vacuum.

**4.3.2.4** If the tip-to-tip length $L_a(f)$ of the actual wire antenna is within $\Delta L_a$ of the length $L_a(f)$ specified for that antenna (see table 2), that length is presumed to be validated when the width of the feed-terminal gap complies with 4.3.2.3.

**4.3.2.5** The balanced port of the balun shall have:

a) a specified impedance $Z_{AB}$ with a specified maximum VSWR, see table 2, when the unbalanced port is terminated in the impedance $Z_e$ presented to it by the external circuitry (the antenna feed cable);

b) an amplitude balance with respect to the balun reference point better than $\Delta A_b$ dB, see table 2, when both feed terminals are terminated in an impedance $Z_{AB}/2$ with respect to the balun reference point;

c) a phase balance of 180° ± $\Delta\phi_b$° (see table 2), when both feed terminals are terminated in an impedance $Z_{AB}/2$ with respect to the balun reference point.

NOTE 1 Connectors at the balun ports should enable RF measurements to be made at the three balun ports.

NOTE 2 The balanced port impedance $Z_{AB}$ is the impedance between the feed terminals A and B in figure 1. The preferred value of this impedance is $Z_{AB} = 100\ \Omega$ (real).

NOTE 3 The impedance $Z_e$ presented by the external circuitry is usually 50 Ω, being the preferred value.

NOTE 4 The amplitude and phase balance requirements ensure that the signals at the feed terminals A and B are sufficiently equal in amplitude and opposite in phase with respect to the balun reference point. When the balanced port meets these requirements, the isolation between the two feed terminals will be more than 26 dB when the unbalanced port is terminated in the impedance $Z_e$.

NOTE 5 As far as practical, the balun components should be oriented to present the minimum co-polarized reflecting surface to the wire antenna.

NOTE 6 The components of the balun are electrically screened, so that their (parasitic) properties cannot be influenced by the surroundings. The balun reference point and the ground terminal of the output/input port are connected to that screen.

**4.3.2.6** The balun properties required in 4.3.2.5 may be determined from S-parameter measurements and, partly, from injection measurements.

NOTE 1 The head-to-head connection of the baluns in 4.4.4.2 and 4.4.4.4 may be replaced by a cable-to-cable connection when the full set of balun S-parameters and the port impedances presented to the baluns by the generator and the receiver are known, provided the balun properties are incorporated in the $SA_c$ calculation.

NOTE 2 S-parameter and injection measurements are described in annex B.

**4.3.2.7** If, in the CALTS validation procedure, test antennas and/or test equipment is used with $Z_{AB}$ and/or $Z_e$ differing from the preferred values 100 Ω and 50 Ω, respectively, then this should be explicitly mentioned in the validation report (4.6).

### 4.4 Antenna calibration test site validation procedure

#### 4.4.1 Introduction

In the validation procedure, the measured site attenuation $SA_m$ is compared with the theoretically calculated site attenuation $SA_c$. The procedure thus verifies whether the CALTS sufficiently meets the properties assumed in the *SA* calculations, i.e.:

a) the plane is perfectly flat and infinitely large;

b) the absolute value of the reflection coefficient of that plane is r = 1; and

c) the phase difference of the incoming and reflected horizontally polarized EM waves at the plane is $\phi = \pi$ radians;

d) the influence of the ancillary equipment and surroundings of the plane is negligible.

To verify the properties, two sets of measurements are required:

1) the properties a), b) and d) are verified simultaneously in a *SA* measurement procedure using fixed antenna heights (see 4.4.4), after which the measured and calculated *SA* are compared;

2) the properties a), c) and d) are verified simultaneously in a procedure in which the height of one of the test antennas is scanned for maximum *SA* after which the measured and calculated height of that antenna corresponding with that maximum are compared (see 4.4.5).

Alternatively, the latter set of properties may also be verified simultaneously in a scanned frequency measurement procedure (see 4.4.6).

Below, a quantity ± ΔX represents the maximum tolerance of a parameter value X allowed in the validation procedure. The quantitative data for the tolerances are summarized in table 2.

#### 4.4.2 Test set-up

**4.4.2.1** The centres of the test antennas, the antenna masts and the antenna coaxial antenna cables are positioned in a plane perpendicular to the reflecting plane and centrally located on the reflecting plane.

NOTE The centre of the test antenna has been defined in 4.3.1

**4.4.2.2** The colinear wire elements are positioned parallel to the reflecting plane (antenna in horizontal polarization) throughout, and perpendicular to the (vertical) plane mentioned in 4.4.2.1.

NOTE At the lower end of the frequency range, e.g. 30 MHz to 40 MHz, the relatively long wire elements may droop, thus influencing the measuring results. This influence can be eliminated by physically propping up the wire elements, or can be accounted for in the calculation of the theoretical site attenuation (see also 4.4.4.3 and 4.5.3.1).

**4.4.2.3** The horizontal distance between the centres of the test antennas is

$$d = 10{,}00 \text{ m} \pm \Delta d \text{ m (see table 2).}$$

**4.4.2.4** The height of the centre of the transmitting antenna above the reflecting plane is

$$h_t = 2{,}00 \text{ m} \pm \Delta h_t \text{ m (see table 2).}$$

**4.4.2.5** The height of the centre of the receiving antenna above the reflecting plane shall be adjustable to the heights $h_r \pm \Delta h_r$, as specified in table 1 and table 2, and shall be scannable over the height range 1,0 m $\leq h_r \leq$ 4,0 m as required in 4.4.5.

**4.4.2.6** The coaxial cables connected to the baluns of the transmitting and receiving antennas run perpendicular to the wire elements and parallel to the reflecting plane over a distance of at least 1 m from the wire elements. After that, the cables may drop onto the reflecting plane and (preferably) continue to run underneath the reflecting plane or on top of that plane perpendicularly to the wire elements until they reach the edge of the plane. To avoid common mode coupling, ferrite loading of the coaxial cables connected to the baluns is advised.

NOTE 1 The cables should have a low transfer impedance to avoid influence on the measured results of the induced cable sheet currents through that impedance.

NOTE 2 When the cables run partly underneath the reflecting plane, the sheath of the cable should be bonded (360° around) to the reflecting plane when penetrating that plane.

**4.4.2.7** The RF generator and RF receiver shall not be elevated above the level of the reflecting plane if they are within 20 m from the plane.

**4.4.2.8** The RF generator shall have a good frequency and output level stability throughout the duration of the site-attenuation measurements. See also 4.4.4.5.

NOTE It might be necessary to include a warm-up time (normally indicated by the equipment manufacturer) of the RF generator and RF receiver in the measuring procedure, to assure a sufficient long-term stability of these equipments.

**4.4.2.9** The RF receiver shall have its linearity calibrated over a dynamic range of at least 50 dB. The uncertainty of the receiver linearity is denoted as ΔAr (see 4.5.2.2). A reasonable value for the receiver linearity uncertainty is 0,2 dB.

NOTE If the linear dynamic range is less than 50 dB a substitution method may be followed, using a calibrated precision attenuator as described in 4.4.4.7.

### 4.4.3 Test frequencies and receiving antenna heights

**4.4.3.1** With due observance to 4.2.2, the validation measurements described in 4.4.4 shall be carried out at least at the frequencies and the associated fixed heights of the centre of the receiving antenna $h_r$ (m) above the reflecting plane given in table 1.

NOTE 1 Information concerning the CALTS performance at the intermediate frequencies can be obtained by using swept-frequency measurements as described in A.2.2.

NOTE 2 Care shall be taken in case of high-Q responses, especially for frequencies above 300 MHz. In such a case a swept-frequency procedure should be carried out around the specified frequencies and at the associated heights.

**4.4.3.2** In addition to the validation measurements described in 4.4.4, either three receiving antenna height-scan measurements as described in 4.4.5 or three frequency-scan measurements as described in 4.4.6 shall be carried out.

a) When choosing to perform receiving-antenna, height-scan measurements, these shall be carried out at the frequencies $f_s$: 300 MHz, 600 MHz and 900 MHz, with the test antennas tuned to the associated frequency $f_s$.

b) When choosing to perform frequency-scan measurements, these shall be carried out with combinations $\{h_{rs}, f_s\}$: {2,65 m, 300 MHz}, {1,30 m, 600 MHz} and {1,70 m, 900 MHz} of the receiving antenna height $h_{rs}$ and the test antenna tuned frequency $f_s$.

**Table 1 – Frequency and fixed receiving antenna height data for *SA* measurements where $h_t$ = 2 m and *d* = 10 m (4.4.2.3 and 4.4.2.4)**

| **Frequency** MHz | $h_r$ m | **Frequency** MHz | $h_r$ m | **Frequency** MHz | $h_r$ m |
|---|---|---|---|---|---|
| 30 | 4,00 | 90 | 4,00 | 300 | 1,50 |
| 35 | 4,00 | 100 | 4,00 | 400 | 1,20 |
| 40 | 4,00 | 120 | 4,00 | 500 | 2,30 |
| 45 | 4,00 | 140 | 2,00 | 600 | 2,00 |
| 50 | 4,00 | 160 | 2,00 | 700 | 1,70 |
| 60 | 4,00 | 180 | 2,00 | 800 | 1,50 |
| 70 | 4,00 | 200 | 2,00 | 900 | 1,30 |
| 80 | 4,00 | 250 | 1,50 | 1 000 | 1,20 |

**4.4.3.3** If narrow-band noise, such as that originating from broadcast transmitters, hinders accurate measurement at a frequency specified in 4.4.3.1 and 4.4.3.2, a usable test frequency as close as possible to that specified frequency shall be chosen.

The rationale for a deviation from a specified frequency shall be recorded in the validation report (see 4.6).

**4.4.3.4** The frequency of the RF generator providing the signal for the transmitting antenna shall be adjusted to within $\Delta f$ (see table 2), of a test frequency specified in table 1 or in 4.4.3.2.

### 4.4.4 Site attenuation measurements

This subclause describes the three measurements needed to determine the measured site attenuation $SA_m$ (see 4.5.3.1), at the specified frequencies. The site attenuation being considered is the *SA* between the feed terminals of the transmitting antenna (A and B in figures 3 and 4) and those of the receiving antenna (C and D in figures 3 and 4).

NOTE Where a full set of balun S-parameters is available (see 4.3.2.6), it is also possible to consider the *SA* between the two cable/balun interfaces provided the balun properties are incorporated in the calculation of the theoretical *SA*. In the description given below, the latter possibility will be indicated by a note, where appropriate.

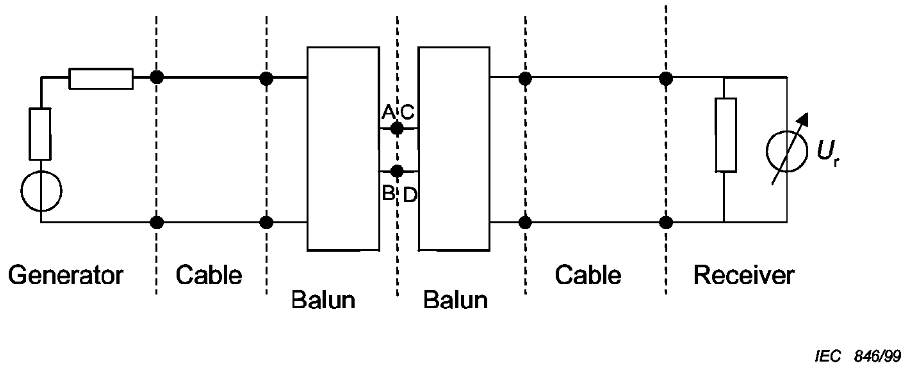



**Figure 3 – Determination $U_{r1}(f)$ or $U_{r2}(f)$**

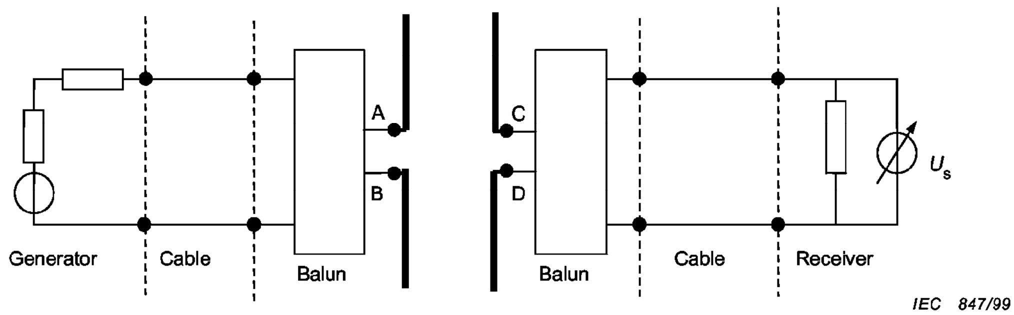



**Figure 4 – Determination $U_s(f)$ with the wire antennas in their specified position**

**4.4.4.1** Measurement 1: At a specified frequency *f*, the reference voltage $U_{r1}(f)$ is determined. This voltage makes it possible to account for the attenuation of the signal between the RF generator output port and the feed terminals of the transmitting wire antenna and, similarly, between the feed terminals of the receiving wire antenna and the receiver input port.

$U_{r1}(f)$ is determined as follows (see figure 3). The wire elements of the test antennas are disconnected from their balun and the two baluns are connected head-to-head (see also note 4 below) with a connection which is as short as possible, preferably < $\lambda_{min}/10$, where $\lambda_{min}$ has been defined in 4.3.2.3.

The level of the RF generator is set to give a receiver reading at least 60 dB above the noise level of the receiver (see note 2 below). The receiver reading is recorded as $U_{r1}(f)$.

NOTE 1 The level of the emitted field should not exceed the local transmission permitted levels.

NOTE 2 In this subclause it is presumed that the RF receiver complies with 4.4.2.9. Where the note to 4.4.2.9 applies, the method given in 4.4.4.7 should be applied.

NOTE 3 The noise level of the receiver can be reduced by reducing the receiver bandwidth. However, if the RF generator and RF receiver are not frequency-locked, as in the case of a tracking generator and spectrum analyser, the receiver bandwidth should be sufficiently wide that a possible drift of the frequency of the RF generator signal does not influence the measuring results.

NOTE 4 If the method given in the note to 4.4.4 is followed, the complete test antennas are disconnected and the two antenna cables are interconnected when determining $U_{r1}(f)$ and $U_{r2}(f)$ in 4.4.4.4.

**4.4.4.2** The amplitude setting of the RF generator used in 4.4.4.1 at a particular frequency remains unchanged throughout the measurements associated with 4.4.4.3 and 4.4.4.4.

**4.4.4.3** Measurement 2: The baluns are disconnected from each other, the wire elements connected to their balun (see figure 4), and are adjusted to the specified length $L_a(f)$. The test antennas are brought into position as specified in 4.4.2 and 4.4.3. All other elements in the test set-up are the same as in 4.4.4.1. See also the notes to 4.4.2.2 and 4.4.4.5.

At the specified test frequency $f$, and with the antennas in their specified position, the receiver reading is recorded as $U_s(f)$.

**4.4.4.4** Measurement 3: The measurement of the reference voltage (see 4.4.4.1), is repeated at the same specified frequency. The value is recorded as $U_{r2}(f)$.

**4.4.4.5** If $U_{r1}(f)$ and $U_{r2}(f)$, expressed in logarithmic units, differ by more than 0,2 dB, the stability of the test set-up shall be improved and the aforementioned measurements 1, 2 and 3 repeated.

NOTE A cause of instability effects may also be the temperature dependence of the coaxial cable attenuation, especially under direct sunlight exposure.

**4.4.4.6** The measured site attenuation $SA_m(f)$ is given by the following equation:

$$SA_m(f) = 20\log_{10}\left\{\frac{U_{ra}(f)}{U_s(f)}\right\} \quad \text{(dB)} \qquad (1)$$

where $U_{ra}(f)$ is the average of $U_{r1}(f)$ and $U_{r2}(f)$.

NOTE If no provisions have been taken to avoid the droop of the wire elements of both test antennas at the lower frequencies 30 MHz, 35 MHz and 40 MHz, it might be necessary to correct the measured site attenuation $SA_m$ (see 4.5.3.1).

**4.4.4.7** Where the dynamic range of the RF receiver does not comply with 4.4.2.9, the following substitution method may be used provided the full set of balun S-parameters is available and the balun properties are incorporated in the calculation of the theoretical *SA*.

a) Determine and record the receiver reading $U_s(f)$ as described in 4.4.4.3.

b) Replace the test antennas by a calibrated precision attenuator and connect both antenna cables to this attenuator. Adjust the insertion loss caused by the attenuator to a level $A_{i1}(f)$ such that the same receiver reading $U_s(f)$ as determined under a) is found. Record $A_{i1}(f)$ and its associated measurement uncertainty $\Delta A_i(f)$.

c) To demonstrate the stability of the test set-up mentioned in 4.4.2.8, repeat step b) to determine $A_{i2}(f)$ after a period of time approximating the total time between the reading of $U_s(f)$ in step a) and $A_{i1}(f)$ in step b). If $A_{i2}$(f) differs by more than 0,2 dB from $A_{i1}(f)$, the stability of the test set-up shall be improved and steps a), b) and c) repeated.

d) If the test set-up is sufficiently stable, the measured site attenuation is given by

$$SA_m(f) = 20\log_{10}\{A_{ia}\} \quad \text{(dB)} \qquad (2)$$

where $A_{ia}(f)$ is the average value of $A_{i1}(f)$ and $A_{i2}(f)$ in linear units.

### 4.4.5 Antenna-height scan measurements

This subclause describes the three antenna-height scan measurements needed to determine the receiving antenna height $h_{r,max}$ at which the measured site attenuation shows a sharp maximum (see 4.4.3.2a) and 4.5.3.2). The sharp maximum results from (near-total) cancellation of the direct wave arriving at the receiving antenna by the indirect wave, i.e. the wave reflected from the reflecting plane.

**4.4.5.1** At the frequencies $f_s$, specified in 4.4.3.2a) and in the test set-up as described in 4.4.2 the height of the receiving test antenna (tuned to the frequency $f_s$) is increased from a height $h_r$ = 1,0 m up to a height $h_{r,max}(f_s)$ corresponding with the first sharp maximum in the SA, i.e. the first sharp minimum in the receiver reading.

NOTE The value of the minimum in the receiver reading is not of interest. This reading is only an indicator to find $h_{r,max}(f_s)$.

**4.4.5.2** The height $h_{r,max}(f_s)$ is measured and recorded together with its associated measurement uncertainty $\Delta h_{r,max}(f_s)$.

NOTE The measured $h_{r,max}$(fs) may not be equal to $h_{rs}(f_s)$ as given in 4.4.3.2 b) because $h_{r,max}(f_s)$ depends on the properties of the actual test antennas as well.

### 4.4.6 Frequency scan measurements

This subclause describes the three swept frequency measurements needed to determine the frequency $f_{max}$ at which the measured site attenuation shows a sharp maximum, see 4.4.3.2b) and 4.5.3.3). The sharp maximum results from (near-total) cancellation of the direct wave arriving at the receiving antenna by the indirect wave, i.e. the wave reflected from the reflecting plane.

**4.4.6.1** At the fixed receiving test antenna heights, $h_{rs}(f_s)$ specified in 4.4.3.2 b) and in the test set-up with the test antennas tuned to the associated frequency $f_s$ as given in 4.4.3.2 b), the frequency of the RF generator is scanned from a frequency well below $f_s$, say 100 MHz lower than $f_s$, up to a value $f_{max}(h_{rs})$ corresponding with a full sharp maximum in the *SA*, i.e. minimum in the receiver reading.

NOTE The value of the minimum in the receiver reading is not of interest. This reading is only an indicator to find $f_{max}(h_{rs})$.

**4.4.6.2** The frequency $f_{max}(h_{rs})$ is recorded together with its associated measuring uncertainty, $\Delta f_{max}(h_{rs})$.

NOTE The measured $f_{max}(h_{rs})$ need not be equal to $f_s(h_{rs})$ as given in 4.4.3.2 a) because $f_{max}(h_{rs})$ depends on the properties of the actual test antennas as well.

## 4.5 Antenna calibration test site compliance criteria

### 4.5.1 Introduction

The CALTS is deemed to be satisfactory when, at all frequencies at which antenna calibrations requiring a CALTS are to be performed, the measured site attenuation (4.4.3.1) and the measured antenna heights or the measured frequency (4.4.3.2) are within a certain margin of the calculated theoretical values (4.5.3). Apart from the uncertainties in the various measurement data, this margin also takes into account the tolerances allowed in the measurement set-up.

As explained in 4.5.2, the uncertainty margin consists of a part which shall be calculated using the theoretical model and a part which is directly coupled to the uncertainty in the voltage measurements from which the measured site attenuation is determined, and to uncertainties in the scanned height or swept frequency measurements.

### 4.5.2 Tolerances and measurement uncertainties

**4.5.2.1** The maximum tolerances for the various parameters are listed in table 2.

**Table 2 – Maximum tolerances for *d* = 10 m**

| Variable | Maximum tolerance | Subclause |
|---|---|---|
| $L_a$ | $\pm 0{,}0025\ L_a$ or<br>$\pm 0{,}001$ (m) if $L_a < 0{,}400$ (m) | 4.3.2.4 |
| $Z_{AB}$ | VSWR $\leq 1{,}10$ | 4.3.2.5 a) |
| $A_b$ | ±0,4 dB | 4.3.2.5 b) |
| $\phi_b$ | ±2° | 4.3.2.5 c) |
| $d$ | ±0,04 m | 4.4.2.3 |
| $h_t$ | ±0,01 m | 4.4.2.4 |
| $h_r$ | ±0,01 m | 4.4.2.5 |
| $f$ | $\pm 0{,}001f$ | 4.4.3.4 |
| NOTE The need to take into account the tolerance $\Delta D_{we}$ in the radius of a wire element and the uncertainties associated with the alignment of the wire antennas, is under consideration. | | |

**4.5.2.2** The measurement uncertainty $\Delta SA_m$ in the measured site attenuation $SA_m$ as defined in equation (1) in 4.4.4.6 is given by

$$\Delta SA_m(\text{dB}) = \sqrt{\{\Delta SA_r(\text{dB})\}^2 + \{\Delta SA_t(\text{dB})\}^2} \tag{3}$$

where $\Delta SA_r$ is given by $\Delta A_r$ in 4.4.2.9, or by $\Delta A_i(f)$ in 4.4.4.7, whichever subclause is applicable. $\Delta SA_t$ accounts for the sensitivity of the site attenuation to the parameter tolerances (maximum values as given in table 2). The 95 % confidence level values of $\Delta SA_r$ and $\Delta SA_t$ shall be used in equation (3).

NOTE $\Delta SA_t$ (95 %) may be calculated using the model given in annex C.

**4.5.2.3** If the tolerances of the parameters comply with those given in table 2, $\Delta SA_t$ (95 %) = 0,2 dB may be used for the whole frequency range from 30 MHz to 1 000 MHz. In that case, it is not needed to perform $\Delta SA_t$ calculations nor to report the results of the calculations in the CALTS validation report.

NOTE A rationale for $\Delta SA_t$ (95 %) = 0,2 dB is given in C.1.3.2.

**4.5.2.4** The measurement uncertainty $\Delta h_{rm}$ in the measured height of the receiving antenna $h_{r,max}$ as defined in 4.4.5, is given by

$$\Delta h_{rm}(\text{m}) = \sqrt{\{\Delta h_{r,max}(\text{m})\}^2 + \{\Delta h_{rt}(\text{m})\}^2} \tag{4}$$

where $\Delta h_{r,max}$ is defined in 4.4.5.2, and $\Delta h_{rt}$ accounts for the sensitivity of $h_{r,max}$ to the parameter tolerances (maximum values as given in table 2).

NOTE $\Delta h_{rt}$ can be calculated using the model given in C.1.3.3.

**4.5.2.5** If the tolerances of the parameters comply with those given in table 2, $\Delta h_{rt}$ (95 %) = 0,025 m may be used at the three specified frequencies. In that case, it is not needed to perform $\Delta h_{rt}$ calculations nor to report the results of the calculations in the CALTS validation report.

NOTE A rationale for $\Delta h_{rt}$ (95 %)= 0,025 m is given in C.1.3.3.

**4.5.2.6** The measurement uncertainty $\Delta f_m$ at the measured frequency $f_{max}$ as defined in 4.4.6, is given by

$$\Delta f_m (\text{MHz}) = \sqrt{\{\Delta f_{max} (\text{MHz})\}^2 + \{\Delta f_t (\text{MHz})\}^2} \qquad (5)$$

where

$\Delta f_{max}$ is defined in 4.4.6.2; and

$\Delta f_t$ accounts for the sensitivity of $f_{max}$ to the parameter tolerances (maximum values as given in table 2).

NOTE $\Delta f_t$ can be calculated using the model given in C.1.3.4.

**4.5.2.7** If the tolerances of the parameters comply with those given in table 2, $\Delta f_t$ (95 %)/$f_c$ = 0,015 may be used at the three specified receiving antenna heights. In that case, it is not needed to perform $\Delta f_t$ calculations nor to report the results of the calculations in the CALTS validation report.

NOTE A rationale for $\Delta f_t$ (95 %)/$f_c$ = 0,015 is given in C.1.3.4.

### 4.5.3 Compliance criteria

In this subclause, the parameter values to be used in the calculations are the actual values realized in a measurement. The actual parameter values are assumed to be determined with a sufficiently small measurement uncertainty so that the conclusion that a parameter value is within the maximum tolerance range as given in table 2 is justifiable.

EXAMPLE – If the specified distance between the antenna centres $d$ = 10,00 m (4.4.2.3) and during the actual *SA* measurements that distance equals $d_a$ = 10,01 m, the latter value is used in the calculations. However ($d - d_a$) shall always be smaller than 0,04 m (see table 2), while $d_a$ has been determined with such a small measurement uncertainty that $|d - d_a| < 0{,}04$ m is justifiable.

**4.5.3.1** The CALTS complies with the site attenuation validation criterion if, at all frequencies used for antenna calibration (figure 5)

$$\left|SA_c(\text{dB}) - SA_m(\text{dB})\right| < T_{SA}(\text{dB}) - \Delta SA_m(\text{dB}) \qquad (6)$$

where

$SA_c(f)$ is the theoretical *SA* at the specified frequency, calculated as depicted in annex C, using the test antenna data following after the application of 4.3.2.6 and using the actual geometrical parameter values $L_a$, $d$, $h_t$ and $h_r$;

$SA_m(f)$ is the measured *SA* following from equation (1) or equation (2) (see also the note);

$\Delta SA_m(f)$ is the *SA* measurement uncertainty (95 % confidence level) as derived in 4.5.2.2;

$T_{SA}(f)$ is the allowed tolerance in *SA*.

Unless stated otherwise in the antenna calibration standard requiring the use of a CALTS, the allowed tolerance is $T_{SA}(f)$ = 1,0 dB over the whole frequency range 30 MHz to 1 000 MHz.

As a minimum, it shall be demonstrated that the CALTS complies with the *SA* criterion at the frequencies listed in table 1.

NOTE 1 At the frequencies 30 MHz to 40 MHz, the value of $SA_m$ needs to be corrected when there is a significant droop at the tip of the wire antenna.

a) At 30 MHz a 4,8 m long dipole droops by 16 cm at the tips. $SA_m$ should be increased by 0,27 dB, 0,13 dB and 0,08 dB when the dipole is at heights of 1 m, 2 m and 4 m respectively, in order to properly compare $SA_m$ with $SA_c$.

b) If the droop at the tip is larger than 20 cm, the increase of $SA_m(f)$ should be calculated numerically (see clause C.2).

NOTE 2 EXAMPLE

If $\Delta SA_t$ (95 %)= 0,2 dB (application of 4.5.2.3) and $\Delta SA_r$ (95 %) = 0,2 dB, then $\Delta SA_m$ (95 %) = 0,3 dB. Consequently, 0,7 dB is the maximum acceptable difference between calculated and measured site attenuation. The maximum acceptable difference can be increased by using a receiver with a lower value of $\Delta SA_r$ (95 %), by decreasing the tolerances of the various parameters and by considering the actual value of $\Delta SA_t$ (95 %).

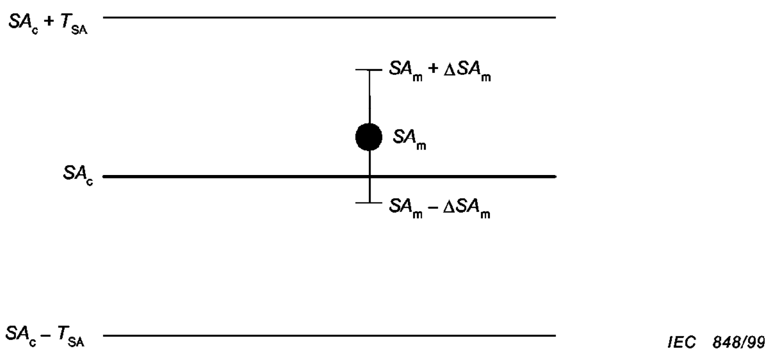



**Figure 5 – Relation between the quantities used in the *SA* compliance criterion**

**4.5.3.2** The CALTS complies with the receiving antenna height criterion for a maximum in the *SA* if at the frequencies $f_s$ given in 4.4.3.2a):

$$\left| h_{rc}\,(\mathrm{m}) - h_{r,\max}(\mathrm{m}) \right| < T_{hr}(\mathrm{m}) - \Delta h_{rm}(\mathrm{m}) \tag{7}$$

where

$h_{rc}$(m) is the theoretical height of the receiving antenna at which the maximum in the *SA* occurs, i.e. the minimum in the signal transfer, calculated as depicted in annex C, using the test antenna data after the application of 4.3.2.7 and using the actual geometrical parameters $L_a$, $d$, $h_t$, and the actual frequency $f_s$;

$h_{r,max}$(m) is the measured receiving antenna height following the procedure outlined in 4.4.5;

$\Delta h_{rm}$(m) is the receiving antenna height measurement uncertainty (95 % confidence level) as derived in 4.5.2.4;

$T_{hr}$(m) is the allowed tolerance of $h_{r,max}$.

Unless stated otherwise in the antenna calibration standard requiring the use of a CALTS, the allowed tolerance is $T_{hr}$ = 0,05 m.

NOTE Either 4.5.3.2 or 4.5.3.3 is applicable; see also 4.4.3.2.

**4.5.3.3** The CALTS complies with the frequency criterion for a maximum in the *SA* if, at the receiving antenna heights $h_{rs}$, with the antennas tuned to the associated frequencies $f_s$ listed in 4.4.3.2 b)

$$\left|f_c(\text{MHz}) - f_{max}(\text{MHz})\right| < T_f - \Delta f_m(\text{MHz}) \tag{8}$$

where

$f_c$(MHz) is the theoretical frequency at which the maximum in the *SA* occurs, i.e. the minimum in the signal transfer, calculated as depicted in annex C, using the test antenna data following after the application of 4.3.2.7 and using the actual geometrical parameters $L_a$, $d$, $h_t$ and $h_{rs}$;

$f_{max}$(MHz) is the measured frequency following the procedure outlined in 4.4.6;

$\Delta f_m$(MHz) is the frequency measurement uncertainty (95 % confidence level) as derived in 4.5.2.6;

$T_f$ is the allowed tolerance of $f_{max}$.

Unless stated otherwise in the antenna calibration standard requiring the use of a CALTS, the allowed tolerance $T_f$ = 0,03 $f_c$.

NOTE Either 4.5.3.2 or 4.5.3.3 is applicable; see also 4.4.3.2.

## 4.6 The validation report

### 4.6.1 Introduction

This standard specifies the requirements, the validation procedure and the compliance criteria for a CALTS. This validation process is finalized by the editing and approval of a so-called "CALTS validation report".

This validation report is a means to trace and guarantee the compliance with the CALTS requirements set in this standard.

Either the CALTS owner or other parties may be responsible for the actual demonstration of the validity of the CALTS.

The CALTS validation report shall comply with the requirements given in 4.6.2.

### 4.6.2 Validation report requirements

The CALTS validation report shall address a number of items, each of them dealing with a validation aspect of the CALTS. Each item and the justification for inclusion in the validation report are described below. A summarizing checklist for the items to be addressed is given in annex F.

a) **General information**

General information such as the CALTS location, responsible owner, etc. shall be given.

If the site validation is carried out by other parties/organizations, then these parties/ organizations shall be indicated.

The CALTS configuration shall be described, as well as its ancillary components using drawings, photographs, part numbers, etc.

In addition, the date(s) of the validation actions and the issue date of the validation report shall be given. The names of the responsible persons for the editing and authorization of the validation report shall be visible on a cover page, including their signatures.

b) **Assessment of the validity period and limiting conditions**

It is stated that the validity shall be demonstrated prior to the calibration of the antennas (see 4.2.2 a).

Therefore, it is important to indicate the period of anticipated validity of the CALTS under consideration. As the CALTS may be either an indoor or outdoor facility, the anticipated validity of the CALTS may differ and may be affected by different factors such as environmental changes, ageing of cables or ageing of the absorber. It is the responsibility of the facility owner to assess and declare the period of validity of the CALTS validation.

In relation to this validity assessment, items or aspects shall be identified which may be subject to change during the course of use of the facility: for example for outdoor ranges the environment, trees, snow, ground humidity, etc. In general, the performance stability of cabling, equipment, antennas and antenna masts is of importance. Also environmental conditions, ageing of instruments or absorber and validity of calibration of equipment may determine the period of validity of the CALTS.

Quick measurement aids or visual inspection procedures may be incorporated to assess continuously the validity/similarity of the CALTS performance.

Specific environmental or configuration conditions or limitations shall be stated explicitly.

c) **Test antenna description and validation**

This item of the validation report deals with the demonstration of compliance with the antenna requirements.

The test antennas (elements and baluns) shall comply with the normative specifications given in 4.3.2. and the applicable values given in table 2.

Each of the normative specification items shall be checked against compliance either by inspection or measurement. The compliance verification results shall be available in an annex or in a separate document (photographs, measurement results, calibration results, supplier statements, etc.).

d) **The test set-up**

This item of the validation report deals with the evidence on the test set-up. The test set-up shall comply with the normative specifications given in 4.4.2 and the applicable values given in table 2.

Each of the normative specifications shall be checked for compliance either by inspection or measurement. The compliance verification results shall be available in an annex or in a separate document.

e) **Validation measurements**

The results of the site attenuation validation measurements carried out in accordance with the procedure given in 4.4.4 and at the test frequencies and antenna heights given in table 1 shall be described in this section of the validation report. In addition, the results of either the antenna height scan measurements (4.4.5) or the frequency scan measurements (4.4.6) shall be reported in this item.

f) **Calculation site antenna attenuation and tolerances**

This item in the validation report shall indicate whether the antenna length is calculated using the procedures from annex C or using different numerical procedures. The results of the site attenuation calculations and the results of the total measurement uncertainty calculations shall be presented in this item using default values or calculated values in case of deviations with the tolerances in table 2.

g) **Compliance criteria calculations**

In this item of the validation report, the results of the calculated and measured values of the *SA*, and the corresponding allowed tolerances and uncertainties will be used in equation (6) to determine compliance as a function of frequency. Similarly, compliance with either the height criterion (equation (7)) or the frequency-scan criterion (equation (8)) will be determined.

h) **Final statement of compliance**

Provided the measured site attenuation complies with equation (6) at all frequencies and either the height or the frequency scan criteria conditions are met, then the CALTS under consideration can be declared compliant with the CALTS requirements taking into account the period of validity and the stated limiting conditions and configurations given in item b).

## 4.7 Validation of the CALTS for vertical polarization

Under consideration.

### 4.7.1 Introduction

### 4.7.2 Site specification

### 4.7.3 Validation procedure

### 4.7.4 Compliance criteria

### 4.7.5 Validation report

# Annex A
(informative)

# CALTS requirements

## A.1 Introduction

The normative specifications mean that, in general, a CALTS will also be an open area test-site (OATS). However, normative specifications do not require that a CALTS shall always be an OATS. Consequently, a CALTS may be weather protected, located in a large salt mine, etc., as long as all normative specifications are met.

Test-site details may be found in clause 5 of CISPR 16-1-4, while additional information is given below. Particular care has been taken to supply the user of this standard with a reference list (see clause A.4).

## A.2 The reflecting plane

### A.2.1 Reflecting plane construction

The plane material can be a solid sheet or a wire mesh. The sheet or the mesh should preferably be continuously welded at the seams, or at distances along the seams < $\lambda_{min}/10$, where $\lambda_{min}$ is the wavelength associated with the largest frequency to be considered. If a wire mesh is chosen, care must be taken that the crossing wires make good conductive contact with each other. The mesh width should be < $\lambda_{min}/10$.

The thickness of the material is determined by mechanical strength and stability requirements. A conductivity equal to or better than that of iron is sufficiently high. The shape of the plane is not very critical as long as the plane is not elliptical (see A.2.2). The reflecting plane should not be covered by a protective layer of significant thickness, as this layer may alter the phase of the reflected wave, i.e. it causes $\phi$ in 4.4.1 to differ from $\pi$ radians [A.4]*. For information about the flatness and roughness of the plane, see clause 5 of CISPR 16-1-4 and [A.3]. A flatness of ±10 mm will normally suffice for measurements up to 1 000 MHz.

The horizontal dimensions of the plane have to be large enough that the influence of the finite plane dimensions on the uncertainty margin associated with the antenna calibration is sufficiently low. Unfortunately, as yet no theoretical models are available which relate the minimum horizontal plane dimensions to a specified maximum uncertainty margin as a result of an antenna calibration. A possible criterion is that the first Fresnel zone should be incorporated in the reflecting plane ([A.1], [A.2] and [A.3]). This leads to a plane with minimum dimensions of 20 m (length) by 15 m (width), but a smaller plane might also meet the CALTS requirements. At the lowest frequency (30 MHz) the length $L_a$ of the test antenna is about 5 m. So, in the case of a 20 m by 15 m plane, the distance between the projection of the validation set-up on the plane and a plane edge is at least $L_a$ at all frequencies in the range 30 MHz to 1 000 MHz.

* References in square brackets refer to the reference documents found under clause A.4.

### A.2.2 Plane-edge effects and plane surroundings

When limiting the dimensions of the reflecting plane, the edge of that plane automatically presents a transition to a medium with different reflecting properties, so that the EM waves may be scattered at that edge and cause an unwanted influence on the measuring results. Edge diffraction is usually noticed for vertically polarized results, but is negligible for horizontally polarized results [A.7].

Among other things, the amount of scattering depends on whether the reflecting plane is in the same plane as the surrounding soil (wet or dry soil may already introduce a difference [A.5]) or the reflecting plane is elevated, e.g. it is located on a roof top. Results of investigations can be found in [A.6], where it is also demonstrated that the reflecting plane should never have the shape of the first Fresnel ellipse, as in that case the uncertainties introduced by the scattering at the edge may accumulate.

The edge of the reflecting plane may be multi-point earthed to the surrounding soil and if the soil has good conductivity, e.g. when wet, it forms a good extension to the metal reflecting plane [A.7].

If potentially reflective obstacles are within a distance of, say, 40 m from the boundaries of the reflecting plane, it should be verified that the influence of these obstacles can be ignored. This verification might be performed by means of swept-frequency measurements using fixed length dipoles. Such measurements are comparable to those described in 4.4.6. A possible choice of fixed length antenna (tuned to the frequency $f_r$), associated swept-frequency range and fixed height $h_r$ of the receiving antenna in the case of a transmitting antenna at $h_t$ = 2 m is given in table A.1. The broadband approach is calculable using numerical techniques such as the NEC (see clause C.3) [C.5]).

**Table A.1 – Combinations of fixed-length dipole antenna, swept-frequency range and receiving antenna height**

| $f_r$<br>MHz | $B_s$<br>MHz | $h_r$<br>m |
|---|---|---|
| 60 | 30 to 100 | 4,0 |
| 180 | 100 to 300 | 1,8 |
| 400 | 300 to 600 | 1,2 |
| 700 | 600 to 1 000 | 1,4 |

In the absence of anomalies, the response will vary in a smooth way. In the presence of anomalies, relatively narrow-band resonances will be superimposed on this response. These resonances identify exact frequencies where the reflections from obstacles are worse. The location of a suspected obstacle can be verified at these frequencies by exaggerating its effect by placing a large metal plate in front of it, oriented at an angle that gives maximum effect.

## A.3 Ancillary equipment

Care should be taken that antenna mast material, adaptors, rope, effects of wetness of masts and ropes, guiding of the cables, connectors, possible presence of a turntable if the CALTS is also used as a COMTS do not influence the measurement results. Also, in these cases, swept frequency measurements as mentioned in A.2 may reveal possible problems.

## A.4 Reference documents

[A.1] ANSI Standard C63.4, 1992, *Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the range of 9 kHz to 40 GHz*, 1992.

[A.2] *Microwave Antenna Measurements*, Hollis, J.S., Lion T.J. and Clayton L. (Editors), Scientific Atlanta Inc., Atlanta, GA, U.S.A., 1986.

[A.3] *Transmission and Propagation of Electromagnetic Waves*, Sander K.F. and Reed G.A.L., Cambridge University Press, Cambridge, UK, 1987.

[A.4] *Note on the Open-Field Site Characterization*, Livshits B. and Harpell K., IEEE EMC Symposium, Denver, pp 352-355, 1992.

[A.5] *Site Attenuation for Various Ground Conditions*, Sugiura A., Shimizu Y. and Yamanaka Y., Trans. IEICE, E73, 9, pp 1517-1523, September 1990.

[A.6] *Ground-Plane Size and Shape experiments for Radiated Electromagnetic Emission Measurements*, Berquist A.P. and Bennett W.S., EMC/ESD Symposium, Denver, U.S.A. pp 211-217, 1992.

[A.7] *EMC Antenna Calibration and the Design of an Open-Field Site*, Salter M.J. and Alexander M.J., Meas. Sci. Technol., 2, pp 510-519, 1991.

[A.8] *Calibration of Antennas used for Radiated Emission Measurements in Electromagnetic Interference (EMI) Control*, ANSI Standard C63.5, 1988.

# Annex B
# (informative)

## Test antenna considerations

An example of a test antenna is presented in clause B.1, while clause B.2 discusses the determination of the balun properties from S-parameter measurements, and/or from injection measurements, as mentioned in 4.3.2.6.

## B.1 Example of a test antenna

An example of a test antenna, based on [B.1]*, is shown in figure B.1. The balun of the antenna consists of the following:

a) a 180° 3 dB hybrid coupler of which the sum port (Σ) is always terminated in the characteristic load impedance (assumed to be 50 Ω), and the difference port (Δ) is the input/ output port of the test antenna;

b) semi-rigid coaxial cables connected to the balanced ports A and B of the hybrid coupler via high quality connectors, e.g. SMA connectors. The cables have a length of approximately 1 m, where this length is also used to distance the wire antenna from mast and coupler reflections;

c) ferrite beads (F) around the semi-rigid cables to limit the induction of common-mode currents on the balun and the connected antenna cable;

d) 3 dB attenuators at the output end of the semi-rigid cables acting as impedance stabilizing or matching pads (M), to which the wire elements are attached via SMA connectors. These connectors form the A and B ports (or C and D ports) mentioned in 4.4.4 and annex C. The external conductors of these connectors are in electrical contact near the wire antenna. This contact point is the reference point of the balun when performing S-parameter measurements.

It should be noted that the aforementioned balun is just an example of a useful balun. Other types of balun may be used as well. In fact every type is allowed, provided the requirements set out in 4.3.2 are met.

The wire elements should have a length such that after attachment the test antenna meets the $L_a(f)$ requirement as set out in 4.3.2.2 (see C.1.1 for the calculation of $L_a(f)$). In table C.1 it has been assumed that if $f$ < 180 MHz the diameter of the wire elements is 10 mm, thus giving the relatively long wire antennas a good mechanical strength. In table C.1 it has also been assumed that at frequencies $f \geq 180$ MHz an element diameter of 3 mm is sufficient. At frequencies $f$ < 60 MHz, the elements might be telescopic, or use might be made of a fixed length dipole antenna (see annex D).

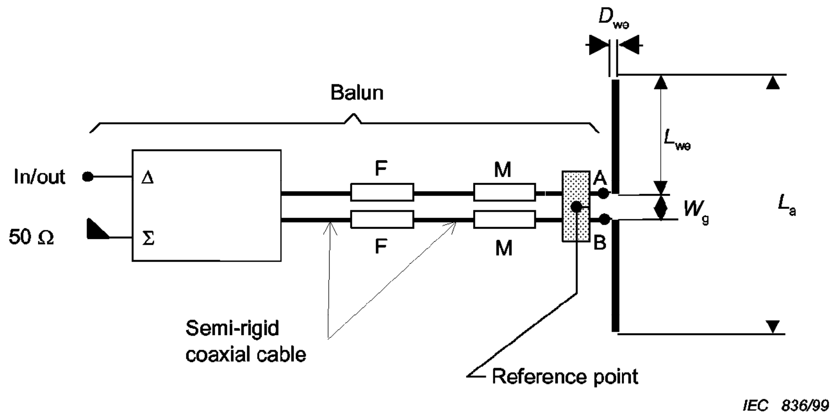
## B.2 Determination balun properties

### B.2.1 The ideal, loss-less balun

The ideal, loss-less balun is characterized by having signals at the A and B ports that are exactly equal in amplitude and exactly 180° out of phase, provided all three ports (see

* References in square brackets refer to the reference documents given in clause B.3.

figure B.2) are terminated in their characteristic impedance. Under the same condition, none of the ports will reflect an incoming signal and an incoming signal at port 2 is not transferred to port 3 (and vice versa).




F = ferrite bead

M = matching pad

NOTE The balun uses a coaxial hybrid junction.

**Figure B.1 – Example of a test antenna**

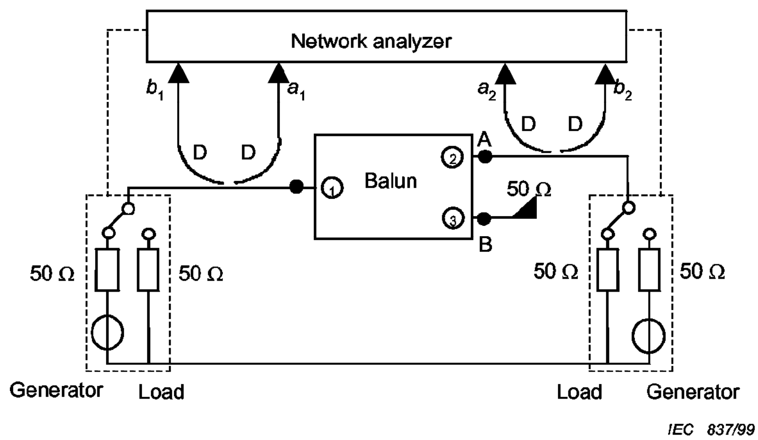



**Figure B.2 – Diagram of the measurement of $S_{11}$ and $S_{12}$ and of $S_{22}$ and $S_{21}$ when generator and load are interchanged (in this figure by putting both switches in their alternative position)**

The basic set-up to measure S-parameters is given in figure B.2. The unbalanced input/output port of the balun is numbered "1", and the balanced ports are numbered "2" and "3".

It is assumed that the characteristic impedance of each these three ports equals 50 Ω (see 4.3.2.5). Compared to figure B.1, the complete balun (coupler, cables, etc.) is represented in figure B.2 by the single box labelled "Balun". The Σ-port of the hybrid coupler in figure B.1 is always terminated in its characteristic impedance and, hence, does not play a part.

S-parameters give the relation between the incoming waves represented in figure B.2 by $a_1$ or $a_2$ and the scattered waves represented by $b_1$ and $b_2$. The incoming and scattered signals are measured by the analyser via directional couplers (D). The parameters $S_{11} = b_1/a_1$ and $S_{21} = b_2/a_1$ (under the condition $a_2 = 0$) are measured with port 3 terminated in 50 Ω. Interchanging the generator and load (by changing the position of both switches) results in the measurement of $S_{22} = b_2/a_2$ and $S_{12} = b_1/a_2$ (under the condition $a_1 = 0$). Similarly, terminating port 2 with the 50 Ω load and measuring between ports 1 and 3, yields $S_{11}$, and $S_{13}$, $S_{31}$ and $S_{33}$. Finally, terminating port 1 with the 50 Ω load and measuring between ports 2 and 3, yields (again) $S_{22}$ and $S_{33}$, and $S_{23}$ and $S_{32}$.

The S-parameter matrix for the ideal, loss-less balun is given by the following equation:

$$\begin{pmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & -1 \\ 1 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix} \tag{B.1}$$

In this S-matrix, $S_{11} = S_{22} = S_{33} = 0$ since there is no reflection at the ports. $S_{12} = S_{21} = 1$ and $S_{13} = S_{31} = -1$ as the balance is perfect (equal absolute values equal to 1 as this balun is loss-less) and the phase shift equals exactly 180° (indicated by the minus sign). Finally, $S_{23} = S_{32} = 0$ as the isolation between port 2 and port 3 is perfect.

### B.2.2 Relations between balun properties and S-parameters

The S-matrix can be transformed into an impedance matrix, which relates the input and output currents and voltages of the balun. Terminating port 1 in the characteristic impedance and considering ports 2 and 3 only, it can be shown that (see [B.2]):

$$\begin{pmatrix} Z_{22} & Z_{23} \\ Z_{32} & Z_{33} \end{pmatrix} = \frac{50}{(1-S_{22})(1-S_{33})-S_{23}\,S_{32}} \cdot \begin{pmatrix} [(1+S_{22})(1-S_{33})+S_{23}S_{32}] & 2S_{32} \\ 2S_{23} & [(1-S_{22})(1+S_{33})+S_{23}S_{32}] \end{pmatrix} \tag{B.2}$$

so that the impedance $Z_{AB}$ (see 4.3.2.5 a)) is given by the following equation:

$$Z_{AB} = \frac{1 - S_{22}S_{33} + S_{23}S_{32} - S_{23} - S_{32}}{(1 - S_{22})(1 - S_{33}) - S_{23}S_{32}} 100 = R_{AB} + j\,X_{AB} \qquad \text{(B.3)}$$

The measured value of $Z_{AB}$ is needed in the calculation of $SA_c$ (see annex C). The impedance $Z_{CD}$ for the other balun needed in that calculation is determined similarly.

The associated VSWR complies with 4.3.2.5 a) and table 2 if

$$\frac{1 + |\Gamma|}{1 - |\Gamma|} < 1{,}10, \text{ where } \Gamma = \frac{Z_{AB} - 100}{Z_{AB} + 100} \qquad \text{(B.4)}$$

NOTE If the hybrid coupler itself does not comply with the requirement formulated in equation (B.4), the VSWR can be lowered by using matched attenuators (M in figure B.1) with very low VSWR.

The balance and phase shift of an actual balun is verified by considering

$$\frac{S_{12}}{S_{13}} = \frac{S_{21}}{S_{31}} = r_b\,e^{j\phi_b} \qquad \text{(B.5)}$$

The amplitude balance complies with 4.3.2.5 b) and table 2 if

$$0{,}95 < r_b < 1{,}05 \qquad \text{(B.6)}$$

and the phase balance complies with 4.3.2.5 c) and table 2 if

$$178^\circ < \left|\frac{180\,\phi_b}{\pi}\right| < 182^\circ \qquad \text{(B.7)}$$

The isolation of an actual balun is verified by considering the actual value of $S_{23}$ and $S_{32}$. It complies with 4.3.2.5, note 4 if

$$|S_{23}| = |S_{32}| < 0{,}05 \qquad \text{(B.8)}$$

The possible loss in the actual balun is accounted for during measurement of the reference voltage $U_r$ in the CALTS validation procedure. For the balun used in the example and depicted in figure B.1, an important contribution to the loss stems from the 3 dB matching pads.

### B.2.3 Insertion loss measurements

It is also possible to verify the balun specifications set in 4.3.2.5 b) and 4.3.2.5 c) by performing the insertion loss measurements depicted in figures B.3 and B.4. From the results, the so-called balun unbalance rejection (*BUR*) can be determined.

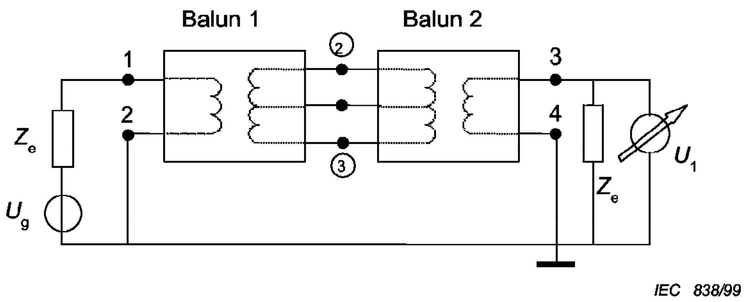



**Figure B.3 – Schematic diagram of the determination of the insertion loss $A_1(f)$**

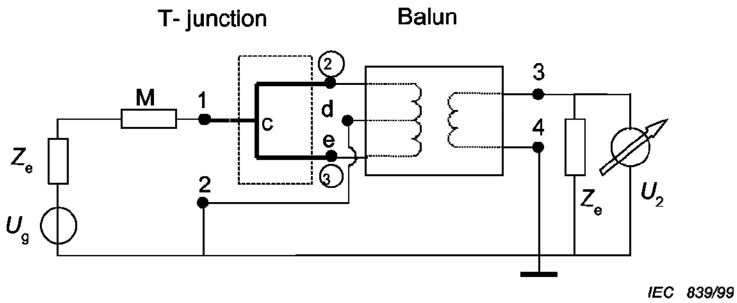



**Figure B.4 – Schematic diagram of the determination of the insertion loss $A_2(f)$**

The measurements comprise the determination of the insertion loss $A_1(f)$ of two identical baluns connected head-to-head as in 4.4.4.1, and the determination of the insertion loss $A_2(f)$ for a single balun when the balanced ports 2 and 3 (see also figure B.4) are connected in parallel. Assuming that $A_1$ stems from equal contributions of the two baluns, the balun unbalance rejection, also referred to as the common-mode rejection, expressed in decibels is given by the following equation:

$$BUR(f) = A_2(f) - \frac{A_1(f)}{2} \text{ (dB)} \tag{B.9}$$

It can be shown that the balun complies with the aforementioned clauses and the associated numerical values of the tolerances as given in table 2 when $BUR$ > 28 dB.

In the first insertion loss measurement, firstly the reference voltage $U_{r1}(f)$ is determined as a function of frequency over the frequency band specified for the balun. The measuring circuit is that of figure B.3 in the absence of the two baluns but with a short circuit between the connection points 1 and 3 and 2 and 4. Next, the voltage $U_1(f)$ is measured after insertion of the two baluns connected head-to-head (see figure B.3). Then $A_1(f)$ expressed in decibels is given by the following equation:

$$A_1(f) = 20\log_{10}\left(\frac{U_r1(f)}{U_1(f)}\right) \text{ (dB)} \tag{B.10}$$

In the second insertion loss measurement, firstly the reference voltage $U_{r2}(f)$ is determined as a function of frequency over the frequency band specified for the balun. The measuring circuit is that of figure B.4 in the absence of the T-junction and the balun but with a short circuit between the connection points 1 and 3 and 2 and 4. Next, the voltage $U_{2a}(f)$ is measured after insertion of the T-junction and the balun to be verified (see figure B.4). In this measurement the ports 2 and 3 (see also figure B.2) are connected in parallel via a coaxial symmetrical T-junction constructed of semi-rigid cables and having the same electrical length of the parts c-d and c-e of the T (full mechanical symmetry). In this measurement d is connected to port 2 and e to port 3. The 6 dB matched attenuator pad, indicated in figure B.4 by M, has been added to avoid standing wave effects.

To avoid errors caused by parasitic effects, the latter measurement is repeated after reversing the connection between the balun and T-junction, i.e. d is connected to port 3 and e to port 2. This measurement yields the voltage $U_{2b}(f)$. Then $A_2(f)$ expressed in decibels is given by the following equation:

$$A_2(f) = 20\log_{10}\left(\frac{U_{r2}}{\max\{U_{2a}(f), U_{2b}(f)\}}\right) \tag{B.11}$$

For the ideal balun $A_2(f) = \infty$ dB, at all frequencies.

NOTE Instead of this T-junction plus 6 dB attenuator, a calibrated 6 dB power divider may be used. In this case, the attenuation caused by the power divider should be taken into account in the calculation of the *BUR*.

## B.3 Reference documents

[B.1] *Standard Linear Antennas, 30-1 000 MHz*, FitzGerell R.G., IEEE Trans. on Antennas and Propagation, **AP-34**, 12, pp 1425-1429, December 1986.

[B.2] *Microwave Impedance Measurement,* Somlo P.I., Hunter J.D., published by Peter Peregrinus Ltd., London, UK, 1985.

[B.3] *Low Measurement Uncertainties in the Frequency Range 30 MHz to 1 GHz using Calculable Standard Dipole Antenna and National Reference Ground Plane,* Alexander M.J. and Salter M.J., IEE Proc. Sci. Meas. Technol., Vol. 143, no. 4, pp 221 – 228, July 1996.

# Annex C
(informative)

# Antenna and site attenuation theory

## C.1 Analytical relations

This clause gives an analytical approach to the calculation of the total length $L_a(f)$ of the wire antenna (C.1.1) and the site attenuation $SA_c$ (C.1.2). The model takes into account the mutual coupling between the transmitting antenna, the receiving antenna and their images in the reflecting plane. It also accounts for the actual field distribution along the receiving antenna, i.e. it is not assumed that the field arriving at the receiving antenna is a plane wave. The only assumption made in this approach is that the current distribution over the wire antenna is sinusoidal.

A value of $SA_c$ calculated from the analytical relations is within ± 0,01 dB of the value of $SA_c$ obtained from exact numerical calculations provided the value of $L_a$ of a sufficiently thin wire antenna is used in the analytical approach. In the context of this standard, sufficiently thin means that the radius $R_{we}$ of the wire antenna satisfies the following condition [C.1]*:

$$\alpha = 2\ln\left(\frac{L_a}{R_{we}}\right) \text{ with } \alpha \geq 30$$

For a half-wavelength dipole antenna ($L_a = \lambda_0/2$) this condition is given by the following equation:

$$R_{we} = \frac{\lambda_0}{2\sqrt{e^{\alpha}}} \text{ with } \alpha \geq 30 \qquad \text{(C.1)}$$

A complete numerical example, including measurement uncertainty considerations is given in C.1.3. Annex E gives an example of a computer program to calculate the various quantities.

### C.1.1 Total length of the test antenna

By definition, the total length $L_a(f)$ of the test antenna, i.e. the free-space resonant dipole at the frequency $f$ follows when solving the following equation:

$$X_a(f, R_{we}) = 0 \qquad \text{(C.2)}$$

where

$X_a(f,R_{we})$ is the imaginary part of the impedance of that dipole radiating into an unbounded medium, i.e. in free space;

$R_{we}$ is the radius of a wire element, assumed to be a constant along its length (non-telescopic elements) and to be much smaller than $L_a$.

* References in square brackets refer to the reference documents given in clause C.3.

The feed-point gap $W_g$ is assumed to be infinitely small. $X_a$ is given by the following equation (see [C.2]):

$$X_a = \frac{\eta}{4\pi} \times \left[ 2\,Si(kL_a) + \cos(kL_a) \times \{ 2Si(kL_a) - Si(2kL_a) \} - \sin(kL_a)\{ 2\,Ci(kL_a) - Ci(kL_a) - Ci(2kR_{we}^2/L_a) \} \right] \times \sin^{-2}(kL_a/2) \tag{C.3}$$

where

$\eta$ = 377 Ω;

$k = 2\pi/\lambda_0$; and

$\lambda_0$ the wavelength in vacuum.

$Si(x)$ and $Ci(x)$ are given by the following equations:

$$Si(x) = \int_0^x \frac{\sin(\tau)}{\tau} d\tau \tag{C.4a}$$

$$Ci(x) = \int_\infty^x \frac{\cos(\tau)}{\tau} d\tau \tag{C.4b}$$

$$Si(x) = \frac{\pi}{2} - f(x)\cos x - g(x)\sin x \quad (x \geq 1)$$

$$Si(x) = \sum_{n=0}^{\infty} \frac{(-1)^n x^{2n+1}}{(2n+1)(2n+1)!} \quad (x < 1) \tag{C.5a}$$

and can be calculated sufficiently accurately from [C.3]

$$Ci(x) = f(x)\sin x - g(x)\cos x \quad (x \geq 1)$$

$$Ci(x) = \gamma + \ln x + \sum_{n=1}^{\infty} \frac{(-1)^n x^{2n}}{2n\,(2n)!} \quad (x < 1) \tag{C.5b}$$

$$f(x) = \frac{1}{x}\left( \frac{x^4 + a_1 x^2 + a_2}{x^4 + b_1 x^2 + b_2} \right), g(x) = \frac{1}{x^2}\left( \frac{x^4 + c_1 x^2 + c_2}{x^4 + d_1 x^2 + d_2} \right) \tag{C.5c}$$

with $a_1$ = 7,241163 $b_1$ = 9,068580 $c_1$ = 7,547478 $d_1$ = 12,723684

$a_2$ = 2,463936 $b_2$ = 7,157433 $c_2$ = 1,564072 $d_2$ = 15,723606

The $L_a(f)$ data in table C.1 have been derived from equation (C.2), using equations (C.3) to (C.5).

### C.1.2 Theoretical site attenuation

The site attenuation (*SA*) is calculated by using a network model [C.4] (see figure C.1). The RF generator supplies a signal to the feed terminals A and B at the balun of the transmitting antenna. The signal arriving at the feed terminals C and D of the receiving antenna is measured across the receiver impedance $Z_r$. The cables and baluns are represented by the T-networks.

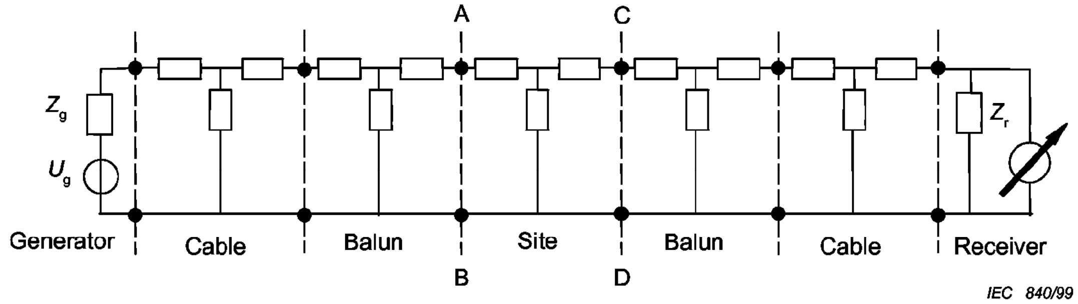



**Figure C.1 – Network model for *SA* calculations**

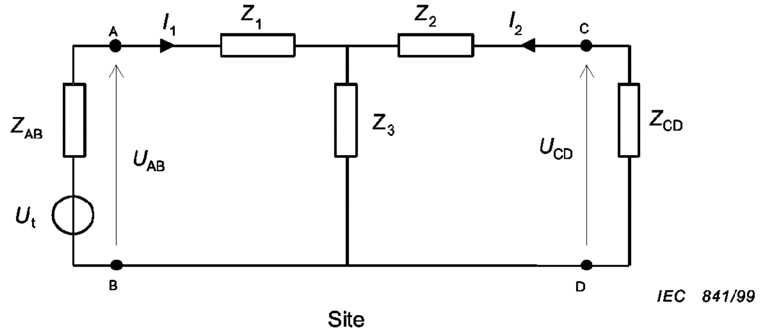



**Figure C.2 – Equivalent circuit to the network in figure C.1**

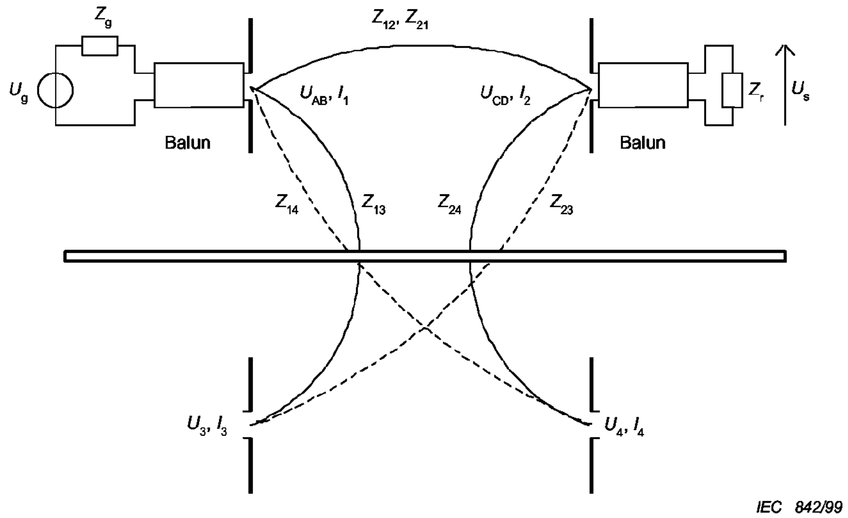



**Figure C.3 – Definition of the mutual couplings, feed-terminal voltages and antenna currents of the antennas above the reflecting plane and their images**

When the reference voltages $U_{r1}(f)$ and $U_{r2}(f)$ (see 4.4.4.1 and 4.4.4.4) are measured, the feed terminals A and C are interconnected by a short conductor having a negligible impedance. Similarly, B and D are interconnected. When measuring $U_s(f)$ (see 4.4.4.3), with the wire antennas connected to the feed terminals and the test antennas in their specified positions, the influence of the site on the signal transfer is represented by a T-network with ports AB and CD as shown in figure C.1.

The circuit of figure C.1 can be simplified to that of figure C.2, in which $Z_{AB}$ and $Z_{CD}$ are the measured balanced-port impedances (see annex B). From the circuit in figure C.2 it follows that when measuring the reference voltage $U_r$ (so that $Z_1 = Z_2 = 0$ and $Z_3 = \infty$):

$$U_{CD} = U_{CD,r} = \frac{Z_{CD}}{Z_{AB} + Z_{CD}} U_t \tag{C.6}$$

It also follows that when measuring $U_s$

$$U_{CD} = U_{CD,s} = \frac{Z_{CD} Z_3}{(Z_{AB} + Z_1 + Z_3)(Z_{CD} + Z_2 + Z_3) - Z_3^2} U_t \tag{C.7}$$

so that the calculated site attenuation $SA_c$ is given by

$$SA_c = \frac{U_{CD,r}}{U_{CD,s}} = \frac{(Z_{AB} + Z_1 + Z_3)(Z_{CD} + Z_2 + Z_3) - Z_3^2}{Z_3 (Z_{AB} + Z_{CD})} \tag{C.8}$$

The next step is to relate the impedances $Z_1$, $Z_2$ and $Z_3$ to the actual situation as depicted in figure C.3, i.e. to the two test antennas above the reflecting plane.

The signal transfer between the transmitting port 1 (feed terminals A and B) and the receiving port 2 (feed terminals C and D) is influenced by the various couplings between the antennas and their images. In figure C.3 this is indicated by the transfer impedances $Z_{nm}$ (n,m: 1 to 4, n ≠ m).

The terminal voltages $U_{AB}$ and $U_{CD}$ are formally related to the antenna currents $I_1$ through $I_4$ of the four antennas in figure C.3 via

$$\begin{aligned} U_{AB} &= Z_{11} I_1 + Z_{12} I_2 + Z_{13} I_3 + Z_{14} I_4 \\ U_{CD} &= Z_{21} I_1 + Z_{22} I_2 + Z_{23} I_3 + Z_{24} I_4 \end{aligned} \tag{C.9}$$

For the theoretical reflecting plane and in the case of horizontally polarized antennas which are aligned parallel to each other $I_3 = \rho I_1$ and $I_4 = \rho I_2$, where $\rho = re^{j\phi}$ is the complex reflection coefficient of the conducting plane. In the ideal case, $\rho = -1$ in the present configuration. Moreover, because of reciprocity $Z_{12} = Z_{21}$ and $Z_{23} = Z_{14}$. So equation (C.9) reduces to the following:

$$\begin{aligned} U_{AB} &= (Z_{11} + \rho Z_{13}) I_1 + (Z_{12} + \rho Z_{14}) I_2 \\ U_{CD} &= (Z_{12} + \rho Z_{14}) I_1 + (Z_{22} + \rho Z_{24}) I_2 \end{aligned} \tag{C.10}$$

From the circuit in figure C.2 it follows that

$$\begin{aligned} U_{AB} &= (Z_1 + Z_3) I_1 + Z_3 I_2 \\ U_{CD} &= Z_3 I_1 + (Z_2 + Z_3) I_2 \end{aligned} \qquad \text{(C.11)}$$

and comparison with equation (C.10) yields

$$Z_1 + Z_3 = Z_{11} + \rho Z_{13}, \qquad Z_2 + Z_3 = Z_{22} + \rho Z_{24} \qquad \text{and } Z_3 = Z_{12} + \rho Z_{14}$$

so that equation (C.8) can be rewritten as

$$\mathrm{SA_c} = \frac{(Z_{AB} + Z_{11} + \rho Z_{13})(Z_{CD} + Z_{22} + \rho Z_{24}) - (Z_{12} + \rho Z_{14})^2}{(Z_{12} + \rho Z_{14})(Z_{AB} + Z_{CD})} \qquad \text{(C.12)}$$

From equation (C.9) it follows that $Z_{11}$ and $Z_{22}$ are the input impedance of the wire antenna radiating into free space, thus in absence of the reflecting plane. The imaginary part of these impedances can be calculated from $X_{11} = X_{22} = X_a$ as given by equation (C.3), the real part $R_{11} = R_{22} = R_a$ from the following:

$$\begin{aligned} R_a = \frac{\eta}{2\pi} \Big\{ & \gamma + \ln(kL_a) - Ci(kL_a) \\ & + \frac{1}{2}\sin(kL_a) \times [Si(2kL_a) - 2\,Si(kL_a)] \\ & + \frac{1}{2}\cos(kL_a) \times [\gamma + \ln(kL_a/2) + Ci(2kL_a) - 2\,Ci(kL_a)] \Big\} \times \sin^{-2}(kL_a/2) \end{aligned} \qquad \text{C.13)}$$

The mutual impedances $Z_{12}$, $Z_{13}$, $Z_{14}$ and $Z_{24}$ can be calculated with the aid of the Lorentz reciprocity theorem [C.1, C.2]. In this calculation the actual field along the wire antenna is taken into account, thus eliminating the need to assume a plane wave arriving at the receiving antenna. The only assumption made is that the current distribution on the wire antennas is sinusoidal, which is allowed if $L_a(f) \approx \lambda_0/2$ and if $R_{we}$ satisfies the condition given in equation (C.1).

If $Z_{nm} = R_{nm} + jX_{nm}$ (n = 1,..,4, m = 1,..,4, n ≠ m) the real part is given by the following [C.1]:

$$\begin{aligned} R_{nm} = \frac{\eta}{4\pi} \times \Big\{ & 2[2\,Ci(kr_{nm}) - Ci(ks_3) - Ci(ks_4)] \\ & + \cos(kL_a) \times [2\,Ci(kr_{nm}) + Ci(ks_1) + Ci(ks_2) - Ci(ks_3) - 2\,Ci(ks_4)] + \sin(kL_a) \\ & + \sin(kL_a) \times [Si(ks_1) - Si(ks_2) - 2\,Si(ks_3) + 2\,Si(ks_4)] \Big\} \times \sin^{-2}(kL_a/2) \end{aligned} \qquad \text{(C.14)}$$

and the imaginary part by the following:

$$\begin{aligned} X_{nm} = \frac{-\eta}{4\pi} \times \Big\{ & 2[2\,Si(kr_{nm}) - Si(ks_3) - Si(ks_4)] \\ & + \cos(kL_a) \times [2\,Si(kr_{nm}) + Si(ks_1) + Si(ks_2) - 2\,Si(ks_3) - 2\,Si(ks_4)] \\ & - \sin(kL_a) \times [Si(ks_1) - Ci(ks_2) - 2\,Ci(ks_3) + 2\,Ci(ks_4)] \Big\} \times \sin^{-2}(kL_a/2) \end{aligned} \qquad \text{(C.15)}$$

where $r_{nm}$ is the distance between the centres of the antennas n and m, and

$$s_1 = \sqrt{r_{nm}^2 + L_a^2} + L_a$$

$$s_2 = \sqrt{r_{nm}^2 + L_a^2} - L_a \qquad \text{(C.16)}$$

$$s_3 = \sqrt{r_{nm}^2 + (L_a / 2)^2} + L_a / 2$$

$$s_4 = \sqrt{r_{nm}^2 + (L_a / 2)^2} - L_a / 2$$

Now $SA_c$, as needed in 4.5.3.1, can be calculated from equation (C.12) as all impedances in that equation are known: $Z_{AB}$ and $Z_{CD}$ from experimental data (see annex B), and the other impedances as calculated from equations (C.3) and (C.13) to (C.16). The same equations can be used to calculate $SA_c(h_r)$ at a given frequency, so as to determine $h_{r,max}(f_s)$ as needed in 4.5.3.2, and to calculate the measurement uncertainties $\Delta SA_t$ and $\Delta h_{r,max}$ needed in 4.5.2.2 and 4.5.3.2.

### C.1.3 Numerical example

Results of a numerical example are given in table C.1: $L_a$ and $SA_c$ calculations; Table C.2: $\Delta SA_t$ calculations; table C.3: $h_{rc}$ and $\Delta h_{rt}$ calculations; and table C.4: $f_c$ and $\Delta f_t$ calculations. An example of a computer program to calculate these data is given in annex E.

In all calculations the height of the receiving antenna and that of the transmitting antenna, the horizontal distance between the centres of the antennas, and the frequencies have the values specified in 4.4. When performing measurement uncertainty calculations, the tolerances given in 4.5.2.1 have been used.

In the range 30 MHz $\leq f <$ 180 MHz it has been assumed that the radius of the wire antenna $R_{we}$ = 5,0 mm, and that $R_{we}$ = 1,5 mm if 180 MHz $\leq f \leq$ 1 000 MHz.

#### C.1.3.1 $L_a$ and $SA_c$ calculations (table C.1)

The antenna length $L_a(f)$ has been calculated from equation (C.2). The value of $SA_c(f)$ has been calculated from equations (C.13) to (C.16), assuming ideal baluns with balanced port impedances having the preferred value of (100 + $j$0) Ω, and assuming an ideal reflecting plane, i.e. $\rho = -1$.

#### C.1.3.2 $\Delta SA_t$ calculations (table C.2)

The measurement uncertainty $\Delta SA_t$ (4.5.2.2) with 95 % confidence level can be calculated from the following (see [C.6])

$$\Delta SA_t = \frac{2}{\sqrt{3}} \sqrt{\sum_{i=1}^{9} \Delta SA_c^2(i)} \qquad \text{(C.17)}$$

assuming a rectangular probability distribution of the variables $\Delta SA_c$(i) and accounting for the uncertainties in the $p$ = 9 variables: $h_r$, $h_t$, $d$, $f$, $Z_{AB}$, $Z_{CD}$, $L_a$, $A_b$ and $\phi_b$ (see also table 2).

For the first six variables, $\Delta SA_c$ can be calculated from

$$SA_c\,(\mathrm{i}) = \mathrm{Max}\ [Abs\{SA_c - SA\,(p_i \pm \Delta p_i)\}] \quad (i = 1, 2, ...., 6) \tag{C.18}$$

where

$SA_c$ is the nominal value of the site attenuation as calculated in C.1.3.1;

$SA(p_i + \Delta p_i)$ and $SA(p_i - \Delta p_i)$ are the calculated site attenuation for the variable $p$ plus the tolerance $\Delta p$ and $p$ minus that tolerance.

Results of $\Delta SA_c$ caused by $\Delta h_r$, $\Delta h_t$, $\Delta d$ and $\Delta f$ specified in table 2 are given in columns 3 to 6 of table C.2.

NOTE When calculating the effect of $\Delta f$, the antenna length $L_a$ remains a constant equal to $L_a$ at the nominal frequency. In the "procedure *SA*" in the computer program given in annex E, the variable "*f*0" keeps $L_a$ constant when varying the variable "*f*" representing the frequency.

**Table C.1 – Numerical example, calculation of $L_a$, $SA_c$ (see C.1.3.1)**

| $f$ MHz | $h_r$ m | $R_{we}$ mm | $L_a$ m | $SA_c$ dB | $f$ MHz | $h_r$ m | $R_{we}$ mm | $L_a$ m | $SA_c$ dB |
|---|---|---|---|---|---|---|---|---|---|
| 30 | 4,00 | 5,00 | 4,803 | 21,03 | 160 | 2,00 | 5,00 | 0,885 | 26,44 |
| 35 | 4,00 | 5,00 | 4,112 | 20,95 | 180 | 2,00 | 1,50 | 0,797 | 27,52 |
| 40 | 4,00 | 5,00 | 3,594 | 20,60 | 200 | 2,00 | 1,50 | 0,716 | 29,37 |
| 45 | 4,00 | 5,00 | 3,192 | 20,70 | 250 | 1,50 | 1,50 | 0,572 | 30,43 |
| 50 | 4,00 | 5,00 | 2,870 | 21,12 | 300 | 1,50 | 1,50 | 0,476 | 32,47 |
| 60 | 4,00 | 5,00 | 2,388 | 22,13 | 400 | 1,20 | 1,50 | 0,355 | 34,90 |
| 70 | 4,00 | 5,00 | 2,043 | 21,76 | 500 | 2,30 | 1,50 | 0,283 | 37,02 |
| 80 | 4,00 | 5,00 | 1,785 | 20,93 | 600 | 2,00 | 1,50 | 0,236 | 38,35 |
| 90 | 4,00 | 5,00 | 1,585 | 21,49 | 700 | 1,70 | 1,50 | 0,201 | 39,59 |
| 100 | 4,00 | 5,00 | 1,425 | 22,97 | 800 | 1,50 | 1,50 | 0,176 | 40,91 |
| 120 | 4,00 | 5,00 | 1,185 | 25,16 | 900 | 1,30 | 1,50 | 0,156 | 41,84 |
| 140 | 2,00 | 5,00 | 1,013 | 27,20 | 1 000 | 1,20 | 1,50 | 0,140 | 42,71 |

For the impedances $Z_{AB}$ and $Z_{CD}$, table 2 specifies a maximum VSWR of 1,10. In the present numerical example this means that both impedances have a circle (centre at $p$ = 100 + $j$0 Ω, radius $\Delta p$ = 9,5 Ω) as a boundary in the impedance plane. Investigations show that it is sufficient to only perform the calculations for $p = (100 \pm \Delta p + j0)$ and $p = (100 \pm j\Delta p)$. Results of calculations are given in columns 7 and 8. Note that the $\Delta SA_c$ values given in table C.2 columns 7 and 8 are equal only when $h_r = h_t$.

$\Delta SA_c$ associated with $L_a$, $A_b$ and $\phi_b$ can only be estimated via numerical techniques, such as discussed in clause C.2. Using these techniques it is found that $\Delta SA_c(L_a)$ < 0,03 dB and that $\Delta SA_c(A_b,\phi_b)$ < 0,03 dB.

Table C.2 column 9 gives the root-sum-square (RSS) value $\Delta SA_\Sigma = \sqrt{[\Sigma\{\Delta SA(i)\}]}$ of the six values $\Delta SA_c$ in the preceding columns. The 95 % confidence level values in column 10 follow 10 from multiplying the column 9 data by $2/\sqrt{3}$ (see equation (C.17)). The 95 % confidence level values of $\Delta SA_t$ follow from:

$$\Delta SA_t(\mathrm{CL} = 95\,\%) = \frac{2}{\sqrt{3}}\sqrt{\left\{\sum_{i=1}^{6}\Delta SA_c^2(i)\right\} + \Delta SA_c^2(L_a) + \Delta SA_c^2(A_b, \phi_b)} \qquad \text{(C.19)}$$

Assuming $\Delta SA_c(L_a)$ = 0,03 dB and $\Delta SA_c(A_b,\phi_b)$ = 0,03 dB, the $\Delta SA_t$ values given in column 11 follow. In this example, the maximum value equals $\Delta SA_t$ = 0,19 dB (at 80 MHz). This is why a value of $\Delta SA_t$ = 0,20 dB is mentioned in 4.5.3.1.

**Table C.2 – Numerical example, calculation of $\Delta SA_t$ (see C.1.3.2)**

| Frequency<br>MHz | $SA_C$<br>dB | $\Delta h_r$<br>$\Delta SA_c$<br>dB | $\Delta h_t$<br>$\Delta SA_c$<br>dB | $\Delta d$<br>$\Delta SA_c$<br>dB | $\Delta f$<br>$\Delta SA_c$<br>dB | $\Delta Z_{AB}$<br>$\Delta SA_c$<br>dB | $\Delta Z_{CD}$<br>$\Delta SA_C$<br>dB | RSS<br>$\Delta SA_\Sigma$<br>dB | 95 %<br>$\Delta SA_\Sigma$<br>dB | 95 %<br>$\Delta SA_t$<br>dB |
|---|---|---|---|---|---|---|---|---|---|---|
| 30 | 21,03 | 0,023 | 0,018 | 0,056 | 0,031 | 0,110 | 0,026 | 0,13 | 0,15 | 0,16 |
| 35 | 20,95 | 0,028 | 0,020 | 0,051 | 0,007 | 0,080 | 0,057 | 0,12 | 0,13 | 0,14 |
| 40 | 20,60 | 0,025 | 0,024 | 0,054 | 0,005 | 0,059 | 0,105 | 0,14 | 0,16 | 0,16 |
| 45 | 20,70 | 0,013 | 0,028 | 0,055 | 0,013 | 0,036 | 0,121 | 0,14 | 0,16 | 0,17 |
| 50 | 21,12 | 0,001 | 0,033 | 0,048 | 0,016 | 0,010 | 0,106 | 0,12 | 0,14 | 0,15 |
| 60 | 22,13 | 0,002 | 0,044 | 0,051 | 0,005 | 0,027 | 0,049 | 0,09 | 0,10 | 0,11 |
| 70 | 21,76 | 0,019 | 0,050 | 0,050 | 0,038 | 0,061 | 0,058 | 0,12 | 0,14 | 0,14 |
| 80 | 20,93 | 0,014 | 0,041 | 0,038 | 0,039 | 0,104 | 0,098 | 0,16 | 0,18 | 0,19 |
| 90 | 21,49 | 0,011 | 0,012 | 0,035 | 0,011 | 0,121 | 0,084 | 0,15 | 0,18 | 0,18 |
| 100 | 22,97 | 0,007 | 0,021 | 0,036 | 0,027 | 0,106 | 0,056 | 0,13 | 0,15 | 0,15 |
| 120 | 25,16 | 0,008 | 0,039 | 0,012 | 0,018 | 0,051 | 0,092 | 0,12 | 0,13 | 0,14 |
| 140 | 27,20 | 0,043 | 0,043 | 0,047 | 0,029 | 0,055 | 0,055 | 0,11 | 0,13 | 0,14 |
| 160 | 26,44 | 0,030 | 0,032 | 0,046 | 0,023 | 0,097 | 0,097 | 0,15 | 0,18 | 0,18 |
| 180 | 27,52 | 0,021 | 0,021 | 0,039 | 0,029 | 0,086 | 0,086 | 0,13 | 0,16 | 0,16 |
| 200 | 29,37 | 0,015 | 0,015 | 0,029 | 0,017 | 0,057 | 0,057 | 0,09 | 0,10 | 0,11 |
| 250 | 30,43 | 0,035 | 0,019 | 0,038 | 0,027 | 0,089 | 0,072 | 0,13 | 0,15 | 0,15 |
| 300 | 32,47 | 0,010 | 0,008 | 0,016 | 0,020 | 0,075 | 0,076 | 0,11 | 0,13 | 0,13 |
| 400 | 34,90 | 0,042 | 0,054 | 0,008 | 0,016 | 0,084 | 0,092 | 0,14 | 0,16 | 0,17 |
| 500 | 37,02 | 0,005 | 0,006 | 0,047 | 0,009 | 0,068 | 0,069 | 0,11 | 0,12 | 0,13 |
| 600 | 38,35 | 0,000 | 0,004 | 0,013 | 0,012 | 0,075 | 0,075 | 0,11 | 0,12 | 0,13 |
| 700 | 39,59 | 0,002 | 0,046 | 0,017 | 0,008 | 0,080 | 0,072 | 0,12 | 0,14 | 0,14 |
| 800 | 40,91 | 0,004 | 0,051 | 0,008 | 0,009 | 0,071 | 0,075 | 0,12 | 0,13 | 0,14 |
| 900 | 41,84 | 0,005 | 0,018 | 0,025 | 0,009 | 0,075 | 0,068 | 0,11 | 0,12 | 0,13 |
| 1 000 | 42,71 | 0,011 | 0,062 | 0,004 | 0,010 | 0,079 | 0,075 | 0,13 | 0,15 | 0,15 |
| $\Delta SA$ (dB) maximal | | 0,043 | 0,062 | 0,056 | 0,039 | 0,121 | 0,121 | 0,16 | 0,18 | 0,19 |

NOTE The bottom line in this table gives the maximum value in each column. Three digits behind the comma in columns 3 to 8 have no practical meaning, and are only given for the comparison of calculated results.

### C.1.3.3 $h_{rc}$ and $\Delta h_{rt}$ calculations (table C.3)

This subclause considers $h_{r,max}(f_s)$ as specified in 4.4.3.2 a) and 4.4.5. The value can be found by a procedure which searches for the first sharp maximum in *SA* for $h_r$ > 1 m. Care should be taken that a sharp maximum is found, i.e. a maximum associated with a cancelling of the direct and indirect waves at the receiving antenna. Results of $h_{rc}$ (see 4.5.3.2) at the frequencies $f_s$ specified in 4.4.3.2 a) are given in table C.3.

Also given in table C.3 are the results of measurement uncertainty calculations, yielding $\Delta h_{r,max}$, similar to those given in C.1.3.2, using the tolerances given in table 2. In the case of

$h_{r,max}$ only the tolerances $\Delta h_t$, $\Delta d$ and $\Delta f$ play a noticeable part. The maximum value of $\Delta h_{rt}$ (CL = 95 %) found is 0,02 m. This is why a value of 0,025 m is mentioned in 4.5.2.5.

**Table C.3 – Numerical example, calculation of $h_{rc}$ and $\Delta h_{rt}$ (see C.1.3.3)**

| Frequency<br>MHz<br>4.4.3.2 a) | $h_{rc}$<br><br>m | $\Delta h_t$<br>$\Delta h_{rc}$<br>m | $\Delta d$<br>$\Delta h_{rc}$<br>m | $\Delta f$<br>$\Delta h_{rc}$<br>m | RSS<br>$\Delta h_{rc\Sigma}$<br>m | 95 %<br>$\Delta h_{r,t}$<br>m |
|---|---|---|---|---|---|---|
| 300 | 2,630 | 0,014 | 0,010 | 0,004 | 0,017 | 0,020 |
| 600 | 1,284 | 0,006 | 0,005 | 0,005 | 0,010 | 0,011 |
| 900 | 1,723 | 0,008 | 0,009 | 0,002 | 0,013 | 0,015 |
| Maximum | – | 0,014 | 0,010 | 0,005 | 0,017 | 0,020 |

### C.1.3.4 $f_c$ and $\Delta f_t$ calculations (table C.4)

This subclause considers $f_{max}(h_r,f_s)$ as specified in 4.4.3.2 b) and 4.4.6. The value can be found by a procedure which searches for the maximum in *SA* for the specified combinations $\{h_r,f_s\}$. Care should be taken that a sharp maximum is found, i.e. a maximum associated with a cancelling of the direct and indirect waves at the receiving antenna. Results of $f_c$ (see 4.5.3.3) at the combinations specified in 4.4.3.2 b) are given in table C.4.

**Table C.4 – Numerical example, calculation of $f_c$ and $\Delta f_t$ (see C.1.3.4)**

| **Frequency/ height**<br>MHz/m<br>**4.4.3.2 b)** | $f_c$<br>MHz | $\Delta h_r$<br>$\Delta f_c/f_c$ | $\Delta h_t$<br>$\Delta f_c/f_c$ | $\Delta d$<br>$\Delta f_c/f_c$ | RSS<br>$\Delta f_{c\Sigma}/f_c$ | 95 %<br>$\Delta f_t/f_c$ |
|---|---|---|---|---|---|---|
| 300/2,65 | 297,4 | 0,004 | 0,006 | 0,005 | 0,009 | 0,010 |
| 600/1,30 | 592,6 | 0,008 | 0,005 | 0,004 | 0,010 | 0,012 |
| 900/1,70 | 912,1 | 0,006 | 0,005 | 0,004 | 0,009 | 0,010 |
| Maximum | – | 0,008 | 0,006 | 0,005 | 0,010 | 0,012 |

Also given i table C.4 are the results of measurement uncertainty calculations, yielding $\Delta f_t/f_c$, similar to those given in C.1.3.2, using the tolerances given in table 2. In the case of $f_{max}$ only the tolerances $\Delta h_r$, $\Delta h_t$ and $\Delta d$ play a noticeable part. The maximum value of $\Delta f_t$ (CL = 95 %) found is 0,012 $f_c$. This is why a value of 0,015 $f_c$ is mentioned in 4.5.2.7.

## C.2 Numerical calculations

This subclause gives an alternative approach to the calculation of antenna impedance, total antenna length and minimum site attenuation. This approach uses a commercially available computer program based on the method of moments which can be operated on a PC. An example of such a program is MININEC [C.6, C.7]. The method does not assume a sinusoidal current distribution on the wire antennas.

In the program, the antennas are represented by straight wires which are divided up into segments for the purpose of analysis. In order to achieve accurate results it is important that the segments are neither too long nor too short compared to the wavelength and also that the length of the segment is greater than the diameter of the segment. About 30 segments per half wavelength give good results.

To check that the chosen segmentation is appropriate, one can investigate the convergence of the calculated impedance and current as the number of segments is increased. The program allows an infinite, perfectly conducting ground plane to be included in the model. The program also allows a voltage to be applied at a point on a wire and a lumped load impedance to be connected at a point on a wire.

### C.2.1 Antenna input impedance

Antenna input impedance, $Z_a$, at the feed point can be read from the program output.

### C.2.2 Total length of the test antenna

The length of the antenna is chosen so that the antenna is resonant (i.e. has zero input reactance) in free space. The length is chosen iteratively. Starting with the antenna length equal to a half wavelength, the program is run to determine the input reactance. If the input reactance is positive, then the length of the antenna is decreased whilst if it is negative the length of the antenna is increased. The program is run again with the new antenna length to determine the new antenna input reactance.

This process of changing the antenna length and calculating the resulting antenna input reactance is repeated until the modulus of the input reactance is less than 1 Ω. At this stage the antenna is of the correct length.

### C.2.3 Theoretical site attenuation

The geometry that is entered into the method of moments program consists of two wires above an infinite, perfectly conducting ground plane. The two wires have the correct heights and separation. The wire representing the transmitting antenna is fed with a voltage of $U_f$ = $1 + j0$ V at its centre and the wire representing the receiving antenna is loaded with an impedance equal to $Z_{CD}$ (the input impedance of the cascade combination of the balun and cable of the receiving antenna and the receiver, see figure C.2). The parameters of interest in the program output are the input impedance of the transmitting antenna and the amplitude of the load current.

The site attenuation is now given by the following equation:

$$SA_c = 20\log_{10}\left\{\frac{U_f}{|I_2|}\left|\frac{Z_a + Z_{AB}}{Z_a(Z_{AB} + Z_{CD})}\right|\right\} \quad \text{(C.20)}$$

where

$I_2$ is the load current (see figure C.2);

$Z_a$ is the input impedance of the transmitting antenna (see C.2.1);

$Z_{AB}$ is the input impedance of the cascade combination of the balun and cable of the transmitting antenna and the generator; and

$Z_{CD}$ is the input impedance of the cascade combination of the balun and cable of the receiving antenna and the receiver (see figure C.2).

The above formula gives the minimum site attenuation which is appropriate if the balun heads are connected together. If, instead, the cables from the generator and receiver are connected together, then the measured balun S-parameters also enter into the calculation of the site attenuation.

## C.3 Reference documents

[C.1] *High-Frequency Models in Antenna Investigations*, Brown & King, Proc. IRE, vol. 22, No.4, pp 457-480, April 1934.

[C.2] *Antenna Theory, Analysis and Design*, Balanis C.A., Harper & Row, Section 7.3.2., New York, 1982. (Other text books on antenna theory may provide an expression for the antenna impedance as well.)

[C.3] *Handbook of Mathematical Functions*, Abramowitz M. and Stegun I.A., Dover, Section 5.2., New York, 1972.

[C.4] *Formulation of Normalized Site Attenuation in terms of Antenna Impedances*, Sigiura A., Trans. IEEE on EMC, EMC-32, 4, pp 257-263, 1990.

[C.5] NIST Technical Note 1297, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, 1994 Edition.

[C.6] *The MININEC system: Microcomputer Analysis of Wire Antennas*, Rockway J.W., Logan J.C., Daniel W.S.T. and Li S.T., Artech House, London, 1988.

[C.7] *Low Measurement Uncertainties in the Frequency Range 30 MHz to 1 GHz Using a Calculable Standard Dipole Antenna and a National Reference Ground Plane,* Alexander M.J. and Salter M.J., IEE Proc. Sci. Meas. Technol., vol 143, No.4, July 1996.

# Annex D
(informative)

## Application of a fixed length dipole (30 MHz ≤ $f$ ≤ 80 MHz)

Under consideration (see also 4.3.2.2).

# Annex E
(informative)

## Pascal Program used in C.1.3

The purpose of this annex is to make the needed calculations easily accessible. The following Pascal Program (Turbo Pascal 7.0) was used to calculate the results given in C.1.3. No attempts have been made to optimize this program.

The programming follows closely the equations given in clause C.1, so that easy checks are possible. The *{comment}*-part at the end of a PROCEDURE refers to the corresponding equation(s). The "actual program", after *{Calculations}*, consists only of two lines in which $L_a$ and $SA_c$ are calculated. That part is preceded by a part *{Input Data}* and succeeded by a part *{Output Data}*. The latter two parts can easily be adapted to the actual calculations to be carried out.

```
PROGRAM analytical_calculation_SA_OATS;
USES crt,dos;
LABEL impedance, calculate;
VAR  f,f0,laf,la0,wr,ht,hr,d,rab,xab,rcd,xcd,saf,arc,fir: real;
     yn                                          : char;

PROCEDURE cprod(r1,i1,r2,i2:real; var rz,iz:real);
begin
 rz:= r1*r2-i1*i2; iz:= i1*r2+r1*i2;
end; {cprod, complex product}

PROCEDURE fsc(x:real; var fx: real);
var a1,a2,b1,b2,nom,denom:real;
begin
 a1:= 7.241163; a2:= 2.463936;
 b1:= 9.068580; b2:= 7.157433;
 nom:= x*x*x*x+a1*x*x+a2;
 denom:= x*x*x*x+b1*x*x+b2;
 fx:= nom/denom/x;
end; {fsc, equation (C.5c)}

PROCEDURE gsc(x:real; var gx: real);
var c1,c2,d1,d2,nom,denom:real;
begin
 c1:= 7.547478; c2:= 1.564072;
 d1:=12.723684; d2:=15.723606;
 nom:= x*x*x*x+c1*x*x+c2;
 denom:= x*x*x*x+d1*x*x+d2;
 gx:= nom/denom/x/x;
end; {gsc, equation (C.5c)}

PROCEDURE Si(x:real; var six:real);
var fx,gx:real;
begin
 if x>=1 then
 begin
  fsc(x,fx); gsc(x,gx); six:= Pi/2-fx*cos(x)-gx*sin(x);
 end;
 if x<1 then
 six:= x-x*x*x/18+x*x*x*x*x/600-x*x*x*x*x*x*x/35280;
end; {Si, equation (C.5a)}
```

```
PROCEDURE Ci(x:real; var cix:real);
var fx,gx,sum: real;
begin
 if x>=1 then
 begin
  fsc(x,fx); gsc(x,gx); cix:= fx*sin(x)-gx*cos(x);
 end;
 if x<1 then
 cix:= 0.577+ln(x)-x*x/4+x*x*x*x/96-x*x*x*x*x*x/4320+x*x*x*x*x*x*x*x/322560;
end; {Ci, equation (C.5b)}


PROCEDURE Ra(f,laf:real; var raf:real);
var kx0,g,k,x,cix,ci2x,six,si2x,ssi,sci:real;
begin
 kx0:= 377/2/Pi; g:= 0.577; k:= 2*Pi*f/3E8;
 Si(k*laf,six);  Ci(k*laf,cix);
 Si(2*k*laf,si2x); Ci(2*k*laf,ci2x);
 ssi:= si2x-2*six; sci:= g+ln(k*laf/2)+ci2x-2*cix;
 x:= k*laf;
 raf:= kx0*(g+ln(x)-cix+sin(x)*ssi/2+cos(x)*sci/2)/sin(x/2)/sin(x/2);
end; {Ra, free space, equation (C.13)}


PROCEDURE Xa(f,laf,wr:real; var xaf:real);
var kx0,k,x,cix,ci2x,cixa,six,si2x,ssi,sci:real;
begin
 kx0:= 377/4/Pi;  k:= 2*Pi*f/3E8;
 Si(k*laf,six );  Ci(k*laf,cix );
 Si(2*k*laf,si2x); Ci(2*k*laf,ci2x);
 Ci(2*k*wr*wr/laf,cixa);
 ssi:= 2*six+cos(k*laf)*(2*six-si2x);
 sci:= sin(k*laf)*(2*cix-ci2x-cixa);
 x:= k*laf/2;
 xaf:= kx0*(ssi-sci)/sin(x)/sin(x);
end; {Xa, equation (C.3)}


PROCEDURE la(f,wr:real; var laf:real);
label again;
var del,lat,lao,xat:real;
begin
 del:= 0.1; lat:= 3E8/f/2; lao:= lat;
again:
 Xa(f,lat,wr,xat);
 lat:= lat-del*lat;
 if xat>0 then begin lao:= lat; goto again; end;
 lat:= lao+1.1*del*lao;
 Xa(f,lat,wr,xat);
 if abs(xat)>0.00001 then begin del:= del/10; goto again; end;
 laf:= lat;
end; {la, length antenna (f), equation (C.2)}
```

```
PROCEDURE Rm(r,f,laf,s1,s2,s3,s4:real; var rmf:real);
var k,fac,kcr,kc1,kc2,kc3,kc4,ks1,ks2,ks3,ks4,t1,t2,t3:real;
begin
 k:= 2*Pi*f/3E8; fac:= 377/4/Pi/sin(k*laf/2)/sin(k*laf/2);
 Ci(k*r,kcr);
 Ci(k*s1,kc1); Ci(k*s2,kc2); Ci(k*s3,kc3); Ci(k*s4,kc4);
 Si(k*s1,ks1); Si(k*s2,ks2); Si(k*s3,ks3); Si(k*s4,ks4);
 t1:= 2*(2*kcr-kc3-kc4);
 t2:= cos(k*laf)*(2*kcr+kc1+kc2-2*kc3-2*kc4);
 t3:= sin(k*laf)*(ks1-ks2-2*ks3+2*ks4);
 rmf:= fac*(t1+t2+t3);
end; {R-mutual, equation (C.14)}

PROCEDURE Xm(r,f,laf,s1,s2,s3,s4:real; var xmf:real);
var k,fac,ksr,kc1,kc2,kc3,kc4,ks1,ks2,ks3,ks4,t1,t2,t3:real;
begin
 k:= 2*Pi*f/3E8; fac:= 377/4/Pi/sin(k*laf/2)/sin(k*laf/2);
 Si(k*r,ksr);
 Si(k*s1,ks1); Si(k*s2,ks2); Si(k*s3,ks3); Si(k*s4,ks4);
 Ci(k*s1,kc1); Ci(k*s2,kc2); Ci(k*s3,kc3); Ci(k*s4,kc4);
 t1:= 2*(2*ksr-ks3-ks4);
 t2:= cos(k*laf)*(2*ksr+ks1+ks2-2*ks3-2*ks4);
 t3:= sin(k*laf)*(kc1-kc2-2*kc3+2*kc4);
 xmf:= -fac*(t1+t2-t3);
end; {X-mutual, equation (C.15)}

PROCEDURE Dist(r,laf:real; var s1,s2,s3,s4:real);
var sqr1,sqr2:real;
begin
 sqr1:= sqrt(r*r+laf*laf); sqr2:= sqrt(r*r+laf*laf/4);
 s1:= sqr1+laf;  s2:= sqr1-laf;
 s3:= sqr2+laf/2; s4:= sqr2-laf/2;
end; {Distances, equation (C.16)}

PROCEDURE SA(f,f0,d,ht,hr,arc,fir,rab,xab,rcd,xcd:real; var saf:real);
var r,r11,x11,r12,x12,r13,x13,r14,x14,r22,x22,r24,x24,rrc,irc,
  rd,xd,rna,xna,rnb,xnb,rn,xn,s1,s2,s3,s4,wr0,la0,alpha  :real;
begin
 rrc:= arc*cos(fir); irc:= arc*sin(fir); alpha:= 40;
 wr0:= 1.5E8/f0/sqrt(exp(alpha)); la(f0,wr0,la0);
 Ra(f,la0,r11); Xa(f,la0,wr0,x11); r22:= r11; x22:= x11;
 r:= sqrt(d*d+(ht-hr)*(ht-hr)); Dist(r,la0,s1,s2,s3,s4);
 Rm(r,f,la0,s1,s2,s3,s4,r12); Xm(r,f,la0,s1,s2,s3,s4,x12);
 r:= 2*ht; Dist(r,la0,s1,s2,s3,s4);
 Rm(r,f,la0,s1,s2,s3,s4,rd); Xm(r,f,la0,s1,s2,s3,s4,xd);
 cprod(rrc,irc,rd,xd,r13,x13);
 r:= sqrt(d*d+(ht+hr)*(ht+hr)); Dist(r,la0,s1,s2,s3,s4);
 Rm(r,f,la0,s1,s2,s3,s4,rd); Xm(r,f,la0,s1,s2,s3,s4,xd);
 cprod(rrc,irc,rd,xd,r14,x14);
 r:= 2*hr; Dist(r,la0,s1,s2,s3,s4);
 Rm(r,f,la0,s1,s2,s3,s4,rd); Xm(r,f,la0,s1,s2,s3,s4,xd);
 cprod(rrc,irc,rd,xd,r24,x24);
 cprod(r12+r14,x12+x14,rab+rcd,xab+xcd,rd,xd);
 cprod(rab+r11+r13,xab+x11+x13,rcd+r22+r24,xcd+x22+x24,rna,xna);
 cprod(r12+r14,x12+x14,r12+r14,x12+x14,rnb,xnb);
 rn:= rna-rnb; xn:= xna-xnb;
 saf:= sqrt((rn*rn+xn*xn)/(rd*rd+xd*xd));
 saf:= 20*ln(saf)/ln(10);
end; {SA, Eqs.(C.6) and (C.12)}
```

```
PROCEDURE YesNo(var rk: char);
begin
 repeat
  rk:= readkey; rk:= upcase(rk);
 until (rk= 'Y') or (rk= 'N');
 writeln(rk);
end; {Yes/No}

BEGIN
 {Input Data}
 clrscr;
 write('Frequency         (MHz)= '); read(f ); f:= f*1E6;
 write('Radius Wire Antenna    (mm)= '); read(wr ); wr:= wr*1E-3;
 write('Height Transmitting Antenna (m)= '); read(ht );
 write('Height Receiving Antenna  (m)= '); read(hr );
 write('Horizontal Antenna Distance (m)= '); read(d );
 write('Ideal Plane Reflection?  (Y/N)= '); YesNo(yn); if yn='Y' then
 begin arc:=1; fir:= Pi; goto impedance; end;
 write('Modulus Reflection Coefficient = '); read(arc);
 write('Phase  Refl. Coef.  (Degrees)= '); read(fir); fir:= fir*Pi/180;
impedance:
 write('Ideal Antenna Impedance  (Y/N)= '); YesNo(yn); if yn='Y' then
 begin rab:= 100; xab:= 0; rcd:= 100; xcd:= 0; goto calculate; end;
 write('R-AB (transmit)    (Ohm)= '); read(rab);
 write('X-AB (transmit)    (Ohm)= '); read(xab);
 write('R-CD (receive)     (Ohm)= '); read(rcd);
 write('X-CD (receive)     (Ohm)= '); read(xcd);

 {Calculations}
calculate:
 f0:=f
 la(f0,wr,laf);
 SA(f,f0,d,ht,hr,arc,fir,rab,xab,rcd,xcd,saf);

 {Output Data}
 writeln;
 writeln('f(MHz)= ',f/1E6:3:0,' La(m)= ',laf:3:3,' SAc(dB)= ',saf:3:3);
 writeln;
END.
```

# Annex F
(informative)

## Checklist validation procedure

**Table F.1 – Items to be addressed in the CALTS validation report**

| Reference 4.6.2 | Item | Remarks |
|---|---|---|
| **a** | **General information** | |
| a1 | Address, CALTS location | |
| a2 | Address, tel/fax number CALTS owner | |
| a3 | Address, tel/fax number of the person/organization responsible for the CALTS validation report | Might be the same as under a2. |
| a4 | Address, tel/fax number of the person/organization who carried out the CALTS validation. | Might be the same as under a2 and/or a3. |
| a5 | Signatures of the persons/organizations mentioned under a2, a3 and a4. | |
| a6 | General description of the CALTS configuration and ancillary components as used during the CALTS validation. | The use of photographs, drawings and part numbers may facilitate the description. |
| a7 | Date of the completion CALTS validation and issue date of the validation report. | |
| **b** | **Validity assessment** | |
| b1 | Results validity assessment. | |
| b2 | Determination period of validity of the present CALTS validation. | |
| b3 | Identification limiting conditions and configurations. | |
| **c** | **Test antennas** | |
| c1 | Identification of calculable antennas. | Type, part number. |
| c2 | Check compliance with the applicable normative specifications. | Reference 4.3.2 and the values in table 2. |
| c3 | Identify characteristic impedance used. | See 4.3.2.7. |
| **d** | **Test set-up** | |
| d1 | Detailed description of test set-up. | |
| d2 | Check compliance with the applicable normative specifications. | Reference 4.4.2 and the values in table 2. |
| **e** | **Measurements** | |
| e1 | If applicable give rationale for deviation from specified frequencies. | See 4.4.3.3. |
| e2 | Results *SA* measurement i.a.w. 4.4.4 and table 1 and determination *SA* uncertainty. | See 4.4.3.1 and 4.4.4. |
| e3 | Results of either antenna height-scan measurements or frequency-scan measurements and the uncertainty. | See 4.4.3.2 and either 4.4.5 or 4.4.6. |

| Reference 4.6.2 | Item | Remarks |
|---|---|---|
| **f** | **Calculation site attenuation and tolerances** | **See 4.5.2.** |
| f1 | Description used calculation methods for *SA* and either height or frequency criterion for maximum *SA*. | Reference: annex C or numerical procedures. |
| f2 | Determine theoretical *SA* and either height or frequency criterion. | |
| f2 | Determine total measurement uncertainties using default values or calculated values in case of deviations in table 2. | Equations (3) and (4) or (5). |
| **g** | **Compliance criteria calculations** | **See 4.5.3.** |
| g1 | Determine absolute values of calculated and measured values of *SA* and either the antenna height or frequency. | |
| g2 | Determine difference between allowed tolerance and measurement uncertainties of *SA* and either the antenna height or frequency. | |
| g3 | Check compliance using the equations (6) and (7) or (8). | |
| **h** | **Final statement of compliance** | |
| h1 | Summarize results, declare compliance taking into account period of validity and the stated limiting conditions and configurations. | Reference b |