

American National Standard for Electromagnetic Compatibility— Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration and Qualification of Antennas (9 kHz to 40 GHz)

C63[®]

Accredited Standards Committee C63[®]—Electromagnetic Compatibility

Accredited by the
American National Standards Institute

IEEE
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New York, NY 10016-5997
USA

ANSI C63.5-2017
(Revision of
ANSI C63.5-2006)

American National Standard for Electromagnetic Compatibility— Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration and Qualification of Antennas (9 kHz to 40 GHz)

Accredited Standards Committee C63®—Electromagnetic Compatibility

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American National Standards Institute

Secretariat

Institute of Electrical and Electronics Engineers, Inc.

Approved 31 January 2017

American National Standards Institute

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Abstract: Methods for determining antenna factors of antennas used for radiated emission measurements in electromagnetic interference (EMI) control from 9 kHz to 40 GHz are provided. Antennas included are linearly polarized antennas such as loops, rods (monopoles), tuned dipoles, biconical dipoles, log-periodic dipole arrays, biconical and log-periodic dipole array hybrids, broadband horns, etc., that are used in measurements prescribed by ANSI C63.4 and ANSI C63.10. The antenna calibration methods include standard site method (i.e., three-antenna method), reference antenna method, equivalent capacitance substitution method, standard transmit loop method, standard antenna method, and standard field method.

Keywords: ANSI C63.5, antenna factors, equivalent capacitance substitution, linearly polarized antennas, near-free space, reference antenna method, standard antenna method, standard site method, standard transmit loop method

The Institute of Electrical and Electronics Engineers, Inc.
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PDF: ISBN 978-1-5044-3576-5 STD22323
Print: ISBN 978-1-5044-3577-2 STDPD22323

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* Also served as working group chair during the development project.

Introduction

This introduction is not part of ANSI C63.5-2017, ANSI Standard for Electromagnetic Compatibility—Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration and Qualification of Antennas (9 kHz to 40 GHz).

ANSI C63.5, American National Standard for Electromagnetic Compatibility—Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration and Qualification of Antennas (9 kHz to 40 GHz), traces its history to the original C63 standard, i.e., American Standards Association (ASA) C63.1-1946, American War Standard—Method of Measuring Radio Interference of Electrical Components and Completed Assemblies of Electrical Equipment for the Armed Forces from 150 Kilocycles to 20 Megacycles. ASA C63.1-1946 was based primarily on Joint Army-Navy (JAN) Specification JAN-I-225, released in 1945.

In 1951, ASA Sectional Committee C63, through its Subcommittee No. 1 on Techniques and Developments, started work on improving and extending measurement methods mentioned in a 1940 report produced by the Edison Electric Institute-National Electrical Manufacturers Association-Radio Manufacturers Association (EEI-NEMA-RMA) Joint Co-ordination Committee on Radio Reception, and those in military specifications at the time.¹ In the course of this work, Subcommittee No. 1 developed American Standard ASA C63.4-1963, American Standard Methods of Measurement of Radio-Noise Voltage and Radio-Noise Field Strength, 0.015 to 25 Megacycles/Second, Low-Voltage Electric Equipment, and Nonelectric Equipment. ASA C63.4-1963 was reaffirmed in 1969, and was revised and improved with a new version released in 1981.

Subcommittee 1 continued to improve the ASA C63.4 standard and concentrated on improving the reproducibility of measuring radiated emissions from one test site to another test site. Evidence showed that the variability was due, in part, to inadequate: a) control of site ground plane conductivity, flatness, site enclosures, effects of surrounding objects, and certain other site construction features; b) accounting for antenna factors (AFs), associated cabling, and balun and equipment under test (EUT) characteristics; and c) consideration of mutual coupling effects between the EUT and the receiving antennas and their images in the ground plane. Accordingly, ANSI C63.4 was republished in 1988. Also, ANSI C63.5, ANSI C63.6, and ANSI C63.7 were all published in 1988 to provide additional information. Thus, the first edition of ANSI C63.5 was published in 1988, American National Standard for Calibration of Antennas Used for Radiated Emission Measurements in Electromagnetic Interference (EMI) Control.

In 1993 a concerted effort was begun to bring the Standard Site Method of ANSI C63.5 into CISPR as the method of antenna calibration to be used in CISPR Publication 16.² During the ensuing discussions, it became apparent that several features of ANSI C63.5 were not acceptable to the international community. In particular, antenna calibration measurements at 3 m were deemed unacceptable. Furthermore, while ANSI C63.5-1988 recommended that only horizontal polarization be used for antenna calibration, it also included information on calibration using vertical polarization; this was considered ambiguous and unacceptable by CISPR Subcommittee A. During the use of ANSI C63.5 in the early and mid-1990s a number of errors were discovered that needed correction. ANSI C63.2 and ANSI C63.4 specify antennas from 9 kHz to 30 MHz and from 1000 MHz to 40 GHz for which no calibration procedure was available in ANSI C63.5. Accordingly, the ANSI C63.5-1998 edition eliminated those features that the international community found objectionable, and thus provided harmonization with international standards while still

¹ C. V. Aggers, D. E. Foster, and C. S. Young, "Instruments and Methods of Measuring Radio Noise," *Electrical Engineering*, Transactions Section, American Institute of Electrical Engineers, Mar. 1940, vol. 59, pp. 178-192. "Synopsis: This paper embodies the relevant agreed recommendations of the Joint Co-ordination Committee on Radio Reception of EEI, NEMA, and RMA, as to the nature, essential characteristics, and performance of an instrument for the measurement of radio-noise voltages. It further gives detailed descriptions of the recommended practices for measuring radio noise directly from low- and high-voltage apparatus, for making noise measurements along overhead lines, for determining broadcast field-strength levels, and methods of collecting data for the establishment of radio-noise standards."

² CISPR is the Comité International Spécial des Perturbations Radioélectriques, or in English the International Special Committee on Radio Interference, and is a part of the International Electrotechnical Commission (IEC) standards development organization.

allowing a US national deviation from those standards. The 1998 edition of ANSI C63.5 corrected errors that use of the standard had shown, and extended it to cover all of the antennas specified in ANSI C63.2 and ANSI C63.4 from 9 kHz to 40 GHz.

In 1999 a collaborative effort was organized in Subcommittee 1 of the Accredited Standards Committee C63® to determine how the ANSI C63.5 technique could be further improved. Evidence showed that significant errors are introduced into normalized site attenuation (NSA) results when free-space antenna factors (FSAF) of biconical dipole antennas are used without corrections for NSA measurements. These errors are due, in part, to mutual coupling effects between the antennas and between the receive antenna and the image of the transmit antenna in the ground plane. Corrections for this situation were included in the ANSI C63.5-2004 edition for use with biconical dipoles. An alternative measurement technique was also provided for other types of antennas. Minor editorial corrections were also made for the ANSI C63.5-2004 edition.

In 2005, ASC C63® received a request for an interpretation of 5.1 of ANSI C63.5-2004 and an apparent conflict with the associated flowchart in Annex G (i.e., Figure G.2) therein. The issue revolved around the apparent confusion of the process for AF calibration for product measurements versus the calibration process when making NSA measurements and how it was shown in Figure G.2. The clarification and correct application of the calibration is contained in the revised 5.1 and the revised Figure G.2 of ANSI C63.5-2006.

In 2008, a working group was formed to address several issues identified since the preceding revision. Along with several text corrections, a new subclause was needed to provide free-space correction terms for tuned dipole antennas, and another new subclause for requirements of frequency spacing. These were added along with a subclause and an annex on the use of time-gating to determine FSAFs above 1 GHz. Other items that were changed are additional details for horn antenna calibration requirements, addition of an equation and associated details for vertical $E_d^{\max}$ in Annex A, clarifications/updates to the symmetry measurement for antennas used from 30 MHz to 300 MHz, an expansion of allowable reference antennas, and expanded information about estimating measurement uncertainties. Furthermore, selected portions of IEEE Std 291™-1991 for loop antenna calibration measurements are provided in a new annex, ACS requirements were expanded and placed in a separate annex, and an annex was added for measurement uncertainty of the reference antenna method (RAM).³ This work led to the present edition of the standard, ANSI C63.5-2017.

³ Information on references can be found in Clause 2.

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American National Standard for Electromagnetic Compatibility— Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration and Qualification of Antennas (9 kHz to 40 GHz)

1. Overview and scope

This standard provides methods for determining antenna factors (AFs) and associated parameters of antennas used to perform radiated emission measurements in electromagnetic interference (EMI) control from 9 kHz to 40 GHz. Antennas covered by this standard are linearly polarized antennas, such as loops, rods (monopoles), tuned dipoles, biconical dipoles, log-periodic dipole arrays, hybrids (i.e., combination broadband dipole and log-periodic dipole array antennas), broadband horns, etc., that are used in measurements defined by various ASC C63[®] emission measurements standards (e.g., ANSI C63.4 and ANSI C63.10).⁴ The associated compliance measurement requirements are provided within other ASC C63[®] standards. The methods used for antenna calibration measurements include the standard site method (SSM), the reference antenna method (RAM), the equivalent capacitance substitution method (ECSM), the standard transmit loop method (STLM), the standard antenna method (SAM), and the standard field method (SFM). In 4.1, the latter three methods are included in this document by reference.

Harmonization with international standards (Goedbloed [B22], CISPR 16-2-3 [B11]) is obtained as much as possible primarily by requiring that a single measured AF be used at each frequency and that it be a free-space or near-free-space antenna factor.⁵ For 30 MHz to 1000 MHz, antennas are measured using a test site with a ground plane and a measurement geometry that yields near-free-space AFs; above 1 GHz, a free-space environment is used. The free-space condition is obtained when the site reflections are removed by applying RF absorber to the ground plane, by increasing the antenna heights, or by time-domain gating of the data.

Measurement conditions are described and acceptable measurement methods are listed in Clause 4. The SSM is explained in Clause 5, and the RAM in Clause 6. For monopoles, the ECSM is described in Clause 7. Normative annexes cover monopole characteristics (Annex E), free-space correction factors for tuned dipole antennas (Annex F) and biconical dipole antennas (Annex G), measurement procedure for geometry-specific correction factors (GSCF) (Annex I), requirements for antenna calibration sites (ACS) (Annex J), and guidelines for using time-domain gating (Annex K).

⁴ Information on references can be found in Clause 2.

⁵ The numbers in brackets correspond to those of the bibliography in Annex O.

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ANSI C63.4, American National Standard for Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz.⁶

ANSI C63.7, American National Standard Guide for Construction of Test Sites for Performing Radiated Emission Measurements.

ANSI C63.10, American National Standard of Procedures for Compliance Testing of Unlicensed Wireless Devices.

ANSI C63.14, American National Standard Dictionary of Electromagnetic Compatibility (EMC) including Electromagnetic Environmental Effects (E3).

ANSI/NCSL Z540.3-2006 (R2013), American National Standard for Requirements for the Calibration of Measuring and Test Equipment.

CISPR 16-1-4:2010-04, Specification for radio disturbance and immunity measuring apparatus and methods—Part 1-4: Radio disturbance and immunity measuring apparatus—Antennas and test sites for radiated disturbance measurements.⁷

IEEE Std 149™-1979 (Reaff 2008), IEEE Standard Test Procedures for Antennas.^{8, 9}

IEEE Std 291™-1991, IEEE Standard Methods for Measuring Electromagnetic Field Strength of Sinusoidal Continuous Waves, 30 Hz to 30 GHz.¹⁰

ISO/IEC 17025:2005, General requirements for the competence of testing and calibration laboratories.¹¹

⁶ C63® publications are available from the Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>) and the American National Standards Institute (<http://www.ansi.org/>).

⁷ CISPR documents are available from the International Electrotechnical Commission (<http://www.iec.ch/>) and the American National Standards Institute (<http://www.ansi.org/>).

⁸ IEEE publications are available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

⁹ The IEEE standards or products referred to in Clause 2 are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.

¹⁰ IEEE Std 291-1991 has been withdrawn; however, copies can be obtained from the Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

¹¹ ISO publications are available from the International Organization for Standardization (<http://www.iso.org/>) and the American National Standards Institute (<http://www.ansi.org/>). IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch/>) and the American National Standards Institute (<http://www.ansi.org/>).

3. Definitions, acronyms, and abbreviations

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* and ANSI C63.14 should be consulted for terms not defined in this clause.¹²

3.1 Definitions

ambient level: The magnitude of radiated and conducted signals and noise existing at a specific test location in the absence of signals from a test sample.

antenna: Transducer that converts the guided electromagnetic energy of the feed line into a radiated wave in space and vice versa. (CISPR 16-1-6:2014)

NOTE 1—See CISPR 16-1-6:2014 [B10].¹³

NOTE 2—In this document, for antennas for which a balun is intrinsic to the functioning of the **antenna**, the term *antenna* includes the balun.

antenna calibration site (ACS): A site used to calibrate antennas. The site requirements are divided into two frequency ranges, i.e., 30 MHz to 1000 MHz and 1 GHz to 40 GHz.

NOTE—The test site shall meet the requirements listed in Annex J for the frequency range of interest.

antenna factor (AF): Ratio of the electric field strength (E) in the polarization direction of the antenna to the voltage (V_o) induced across the load connected to the antenna and expressed in decibel form $[20 \log (E/V_o)]$. The AF has units of dB(1/m) in logarithmic units and 1/m in linear units. *See also:* **free-space antenna factor; near-free-space antenna factor.**

balun: A device for transforming an unbalanced voltage to a balanced voltage or vice versa. (ANSI C63.14)

biconical dipole antenna: symmetric antenna formed by two conical radiating elements having a common axis, and adjacent vertices at which they are fed. (CISPR 16-1-6:2014, MOD) *Syn:* **biconical antenna.**

NOTE—See CISPR 16-1-6:2014 [B10].

broadband antenna: An antenna that has a relatively constant gain, and that functions satisfactorily, over a wide range of frequencies (bandwidth of 2:1 or larger), for example a log-periodic dipole array antenna or a double-ridged waveguide horn antenna. (ANSI C63.14-2014, 4.51 MOD)

calculable antenna: Antenna for which the antenna factor (AF) of a single antenna, and the relative insertion loss between a pair of antennas, can be calculated using either analytical or numerical (method of moments) techniques based on the dimensions, load impedance and geometrical parameters, and for which the AF and relative insertion loss results can be verified by measurement. (CISPR 16-1-6:2014, MOD)

NOTE—See CISPR 16-1-6:2014 [B10].

dipole antenna: Antenna consisting of two straight collinear conductors of equal length, placed end to end, separated by a small gap constituting a balanced feed, with each conductor approximately a quarter-wavelength long such that at the specified frequency the input impedance of the antenna measured across the gap has zero reactance when the dipole is located in free space. (CISPR 16-1-6:2014) *Syn:* **resonant dipole antenna; tuned dipole antenna.**

¹²*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>.

¹³Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

NOTE 1—See CISPR 16-1-6:2014 [B10].

NOTE 2—The term *Roberts dipole* refers to a tuned half-wavelength-resonant dipole with a series-parallel coaxial stub balun, with design as described in Annex C and Annex D.

free-space antenna factor (FSAF): Antenna factor measured in a free-space environment, for a plane wave incident from the direction corresponding to the mechanical boresight (i.e., the main axis of the antenna). *See also:* **antenna factor; near-free-space antenna factor.**

NOTE—For biconical antennas, the FSAF is calculated by application of the ΔAF correction factor (see Annex G).

geometry-specific correction factor (GSCF): Correction factor (in dB) that is calculated or measured for each frequency in a specific measurement geometry. GSCFs are subtracted from the site attenuation (SA) calculated using the theoretical model that employs near-free-space or free-space antenna factors. GSCFs include the effects of the $1/r^2$ and $1/r^3$ radiation terms (r is the distance between the antennas), non-uniform illumination of the receive antenna, mutual coupling between the transmit antenna and the receive antenna, and mutual coupling between the antennas and the ground plane. *See also:* **measurement geometry; near-free-space geometry.**

ground plane: (A) A conducting surface used as a common reference point for circuit returns and electric or signal potentials. **(B)** A conducting or reflecting plane functioning to image a radiating structure.

hybrid antenna: Antenna constructed as a combination of both broadband dipole (e.g., biconical, bow-tie) elements and log-periodic dipole array (LPDA) elements. *Syn:* **bicon-log hybrid antenna.**

ideal site: A test site with a flat, level, reflective surface that has infinite conductivity and size.

measurement geometry: A specified polarization, separation distance, transmit antenna height, and receive antenna height(s) for a pair of antennas during their antenna factor (AF) measurement. *See also:* **near-free-space geometry.**

near-free-space antenna factor (NFSAF): Antenna factor (AF) that is minimally affected by the test environment. This value will represent the free-space antenna factor (FSAF) usually within an error smaller than the measurement uncertainty. This error is relatively small compared to other contributions to measurement uncertainty of the results when these AFs are used for product emission measurements. *See also:* **antenna factor; free-space antenna factor.**

near-free-space geometry (NFSG): Measurement geometry to obtain near-free-space antenna factors (NFSAFs). The measurement setup for this condition using the standard site method (SSM) is horizontal polarization, $R = 10$ m, $h_1 = 2$ m, and $h_2 = 1$ m to 4 m scanned.

normalized site attenuation (NSA): Site attenuation (SA) divided by the free-space antenna factors (all in linear units) of the transmit antenna and the receive antenna, and corrected by the geometry-specific correction factors (GSCF) if available. Results can be stated in decibel units.

site attenuation (SA): The minimum relative insertion loss measured between two polarization-matched antennas located on a test site when one antenna is moved vertically over a specified height range.

test site: (A) A location meeting appropriate validation criteria, if identified, to perform electromagnetic compatibility (EMC) measurements on equipment under test (EUT). This may also include in situ locations or areas where the EUT is installed or operated. (ANSI C63.7-2015) **(B) (radiated emissions test site)** A site with specified requirements (see ANSI C63.4) suitable for measuring electromagnetic fields emanating from a device, equipment, or system under test. *Syn:* **radiated emission test site.**

3.2 Acronyms and abbreviations

ACS	antenna calibration site
AF	antenna factor
AUC	antenna under calibration
dB	decibel
ECSM	equivalent capacitance substitution method
EMI	electromagnetic interference
EUT	equipment under test
FSAF	free-space antenna factor
GSCF	geometry-specific correction factor
LPDA	log-periodic dipole array
NFSAF	near-free-space antenna factor
NFSG	near-free-space geometry
NSA	normalized site attenuation
OATS	open-area test site
RAM	reference antenna method
RF	radio frequency
SA	site attenuation
SAM	standard antenna method
SFM	standard field method
SSM	standard site method
STLM	standard transmit loop method
SUT	site-under-test
S_{VSWR}	site voltage standing wave ratio
VNA	vector network analyzer
VSWR	voltage standing wave ratio

4. General measurement considerations

4.1 General

This standard provides procedures for the determination of antenna factors (AFs) for antennas used in radiated emission measurements as described in ASC C63[®] measurements documents. These AFs shall be used for either vertically polarized or horizontally polarized measurements at distances from the EUT of 3 m or more. The general measurement conditions and parameters for antenna calibration and characterization are described in 4.2 through 4.4. Table 1 gives a summary of antenna types and the calibration methods used for product measurement and normalized site attenuation (NSA) measurement purposes. AFs may be determined in several ways; the decision as to which approach is best in a particular case shall be based upon the allocated time, instrumentation, facilities, and personnel

(see e.g., CISPR 16-1-6:2014 [B10]). The following three commonly used antenna calibration methods are described in Clause 5, Clause 6, and Clause 7, respectively:

- Standard site method (SSM) (Smith [B40])
- Reference antenna method (RAM)
- Equivalent capacitance substitution method (ECSM)

Measurement uncertainties of results obtained with these methods may be estimated using the guidance provided in Annex L and Annex M; see also 4.5. In addition, the estimated uncertainty will depend on: 1) the quality of the calibration site when using the SSM site, 2) the accuracy of the calibration of the reference antenna when using the RAM, and 3) the accuracy of the simulated capacitance when using the ECSM.

The ECSM may be used for the calibration of monopole antennas from 9 kHz to 30 MHz for use in measurements in accordance with ANSI C63.4.

Free-space antenna factors (FSAFs) may be developed for biconical dipole antennas, with either a 50 Ω or a 200 Ω balun, using Clause 5 and Annex G (see Table 1). Using the methods in Clause 5 and Annex G will provide more accurate results for biconical dipole antennas when used in NSA measurements compared to the use of Clause 5 alone. See 4.4.2 and Annex H for additional information and rationale about geometry-specific correction factors (GSCFs) for biconical dipole antennas.

Near-free-space antenna factors (NFSAFs) may be determined for broadband antennas (including hybrid antennas) using the methods specified in Table 1. Annex I provides a measurement procedure to determine GSCFs for biconical dipole, log-periodic dipole array (LPDA), and hybrid antennas. Annex J provides the site requirements for an ACS that is used to calibrate antennas and to measure GSCF.

For above 1 GHz to 40 GHz, AF results for horn antennas are measured using the methods of 5.1.3, and shall be deemed valid over the distances as described in 5.1.3. Antennas used in site voltage standing wave ratio (S_{VSWR}) measurements shall meet the requirements of 8.3.3.1 of CISPR 16-1-4:2010, with AF results measured using the methods of 5.1.3.

Three additional antenna calibration methods are the following:

- Standard field method (SFM) (IEEE Std 291-1991)
- Standard antenna method (SAM) (Fitzgerrel [B18], Taggart and Workman [B42], IEEE Std 149-1979)
- Standard transmit loop method (STLM) (a specialized version of the standard antenna method; IEEE Std 291-1991)

The latter three additional methods are included in this standard by reference. For convenience, selected portions of IEEE Std 291-1991 for loop antenna calibration measurements are repeated in Annex N.

Table 1—Calibration methods of antennas for use with ASC C63® measurement methods

Antenna type	Antennas for product measurements				Antennas for NSA measurements		
	Clause 5	Clause 6	Clause 7	Annex (if applicable)	Clause 5	Clause 6	Annex (if applicable)
Monopole			X				
Tunable dipole	X	X		Annex F	X	X	Annex F
Biconical dipole	X	X		Annex G	X	X	Annex G, Annex I
LPDA	X				X		Annex I
Hybrid (bicon-log)	X						
Horn	X						

4.2 Calibration measurement geometry

Accurate antenna calibrations require restrictions on measurement geometry. The antenna separation distance R shall be large enough to reduce the near-field effects and antenna-to-antenna mutual coupling effects. Antenna heights (h_1 , h_2) shall be large enough to reduce antenna-to-ground plane mutual coupling effects.

The separation distance, R , between antennas shall be measured between points projected vertically from the antenna to the ground plane. This is equivalent to the horizontal distance between antennas when the antennas are at the same height. For dipole and biconical dipole antennas, R shall be measured from the midpoint of the dipole elements. For LPDA antennas and hybrid antennas, R shall be measured to the midpoint of the elements along the longitudinal axis of each antenna. For horn antennas, R shall be measured from the aperture plane of the antenna. Figure 1 shows the effective reference plane position for these antenna types.

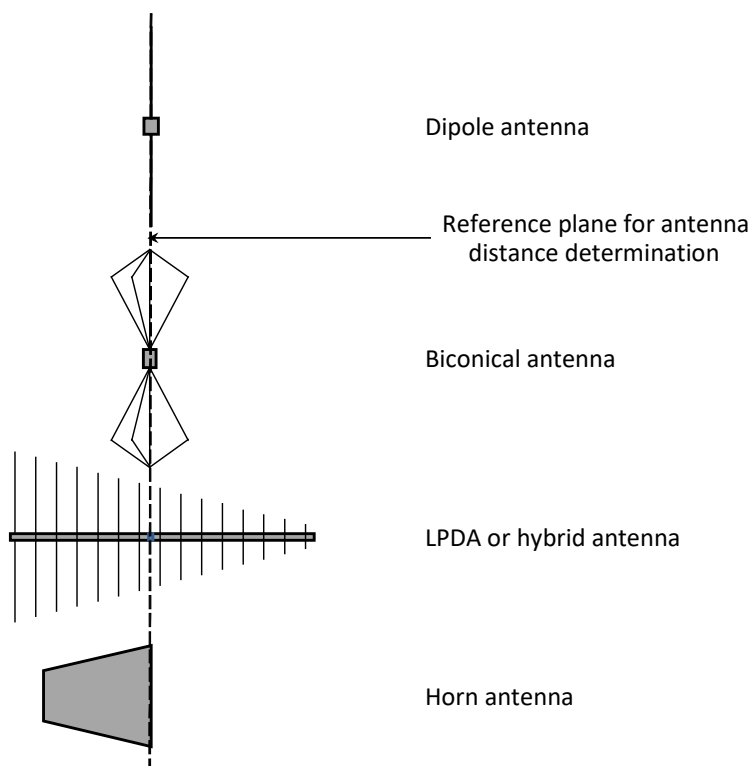


Figure 1—Reference plane for separation distance measurements

4.3 Test site and measurement instrumentation

- a) An ACS used to measure AF and GSCF shall meet the requirements in Annex J.
- b) All measurement instrumentation (including signal generators, spectrum analyzers, receivers, etc.) shall have a nominal impedance of 50 Ω .
- c) Attenuators shall be used whenever the voltage standing wave ratio (VSWR) of the antenna exceeds 2:1, if the VSWR is not otherwise corrected for in the measurement.
- d) Lossy ferrite material shall be applied to at least the first 1 m of both the transmit antenna cable and the receive antenna cable whenever dipole, biconical dipole, or hybrid antennas are calibrated, to serve as a common-mode choke that reduces the induced currents on the cable shield due to coupling with the radiating elements.
- e) The signal sources shall provide sufficient power to produce a signal at the receiver input of at least 16 dB above the noise level at the receiver input. Reducing the IF bandwidth, using averaging, or adding an amplifier at the transmit antenna, or a low-noise pre-amplifier at the receive antenna, may be used to improve the signal-to-noise ratio. See L.3.4.2 for further information on this error term.
- f) The source amplifier power requirements will depend upon receiver sensitivity, preamplifier sensitivity and gain, AFs, cable losses, ambient signal level, and measurement distance *R*. Care shall be taken to avoid overloading preamplifiers or receivers with signals that are close to or higher than their defined compression levels. Band-pass filters may be used to prevent out-of-band signals from saturating a preamplifier or receiver.
- g) It is preferable to use preamplifiers at the receiver input rather than power amplifiers at the source output when calibrations are performed at a (non-shielded) ACS. This will improve the signal-to-noise ratio at the receiver, while minimizing the potential for interference with susceptible equipment or licensed radio services in the vicinity of the test site.
- h) Measurement equipment such as signal sources, antennas, and receiving equipment (receivers and preamplifiers), etc., shall be calibrated at regular intervals in a traceable manner.
 - 1) Traceability shall be maintained to a national metrology institute.
 - 2) Effects of drift, especially during the measurement time, shall be compensated or corrected.
 - 3) An example of an acceptable program for calibration of instrumentation can be found in ANSI/NCSL Z540.3-2006, along with ISO/IEC 17025:2005.

4.4 Antenna calibration and characterization parameters

4.4.1 Antenna factors

The antenna calibration procedures in this standard are capable of producing FSAFs or NFSAFs with relatively low uncertainties for various types of antennas. AFs shall be measured for a particular antenna type as stated in Table 1 of 4.1. AFs usually account for balun impedance and losses in the balun, if used. If a balun external to the antenna is used, its effects shall be measured or otherwise accounted for and included with the data.¹⁴ If the measured AFs are adjusted to correct for fixed-length cable losses, this shall be clearly stated in the antenna calibration report.

¹⁴ Typical antennas intended within the scope of this document have the balun and antenna element(s) portions combined such that the entire assembly is calibrated. Regardless, one example where balun characteristics are measured separately from the antenna elements is indicated in Figure D.10 of Annex D.

4.4.2 Geometry-specific correction factors (GSCF), 30 MHz to 1000 MHz

Measurement of NSA at a radiated emission test site requires the use of correction factors that depend upon the setup geometries used (see Annex H for rationale and details). GSCFs, for a typical biconical antenna with dimensions shown in Figure G.1, are provided in Table G.2 and Table G.3 of Annex G. For LPDA antennas, hybrid antennas, and other biconical antennas, Annex I provides the measurement method to obtain GSCF for these antennas. Figure G.3 summarizes the process of adjusting NSA measurement results using the GSCFs of Annex G or Annex I.

Antennas that are to be used for NSA measurements shall be calibrated together in pairs (i.e., two biconical antennas, or two LPDA antennas) using the *standard site method* (see Clause 5) when determining their respective AFs. The GSCFs determined using the tables in Annex G or using the measurement procedure specified in Annex I (as applicable) shall be used during the calculation of NSA.

4.4.3 Antenna symmetry measurement, 30 MHz to 300 MHz

Antenna symmetry measurements are intended to determine whether received signals on both element sides are similar across the usable frequency range of the antenna.¹⁵ This measurement is used to detect mechanical or electrical differences that can affect the AF values (Adhyapak and Chen [B1]).

- a) The antenna symmetry shall be checked for biconical and hybrid antennas.¹⁶
- b) Antenna separation distance R shall be 10 m.
- c) Frequency step size shall be selected as defined in Table 2 of 4.4.4.
- d) Cabling shall be configured as used for antenna calibrations.
- e) The receive antenna [antenna under calibration (AUC)] shall be placed at 1 m height above the ground plane. This height is to maximize the coupling effects.
- f) A linearly polarized antenna shall be used for the transmit antenna. This antenna shall be designed for use in the measured frequency range. The transmit antenna shall be scanned in height as described in step g1).
- g) Connect the pair of antennas to measurement instrumentation conforming to 4.3. The symmetry measurement is performed as follows:
 - 1) With both antennas vertically polarized, the transmit antenna shall be raised from 1 m to 4 m with a step size of 0.05 m; or alternatively the height shall be changed continuously such that a 5 cm height change is completed within one complete scan of the measuring instrument over the frequency range of interest. The maximum transmission response, A_{0° , between the two antennas for each frequency shall be recorded.
 - 2) Keeping the measurement setup constant, the receive antenna shall be rotated by 180° , then the maximum transmission response, A_{180° , for the transmit antenna height scan as described in step g1) shall be recorded.
 - 3) At all measured frequencies, the signal level A_{180° in dB shall be within ± 1.0 dB of the signal level A_{0° in dB; i.e., $|A_{180^\circ} - A_{0^\circ}| < 1.0$ dB.

¹⁵ Symmetry measurement results provide qualitative information about the relative levels of differential-mode (wanted) and common-mode (unwanted) voltages and currents in a balun-fed antenna (see also, e.g., CISPR 16-1-4:2010; ITU-T Rec. K.10 [B28]), conventionally also known as *balun unbalance* or *imbalance*.

¹⁶ Per 4.5.4.1 of CISPR 16-1-4:2010-04, a symmetry (or imbalance) check is applied also for dipole antennas.

4.4.4 Frequency step size for swept-frequency measurements

When antenna factors or antenna symmetry are measured for a broadband antenna (i.e., per 5.3.3 and 4.4.3, respectively), frequency step sizes are defined to improve accurate characterization of the AUC and to reduce error due to interpolation of AF data. Broadband antennas shall be measured using the frequency step size(s) specified in Table 2, or smaller step sizes.

Table 2—Frequency step size

Start frequency (MHz)	Stop frequency (MHz)	Step size (MHz)
30	200	1
200	1 000	5
1 000	10 000	50
10 000	18 000	100
18 000	40 000	250

4.5 Measurement uncertainty

4.5.1 General

Antenna calibration reports should reference the measurement uncertainty considerations described in Annex L (SSM) or Annex M (RAM) of this document, as applicable, or as described in CISPR 16-1-6:2014 [B10]. Annex L of this document and CISPR 16-1-6:2014 [B10] give only general guidance on uncertainty components and uncertainty estimation methods; actual measurement uncertainty budgets and selection of the uncertainty estimation methods used are the responsibility of each individual antenna calibration laboratory. For subsequent emission field strength measurements using methods from ASC C63[®] standards,¹⁷ the measured AFs shall be used for determining the field strength results, and the measurement uncertainty of the AF shall be included in the uncertainty estimation of the radiated emission measurement results; see, e.g., 5.4.2 and Table 10 in 5.7 of ANSI C63.23-2012 [B2]. Hence, both the AF measurement results and the estimated measurement uncertainty shall be provided in an antenna calibration measurement report or certificate.

NOTE—Other approaches or methods may be used where more viable for a particular laboratory and that provide rigor similar as the three measurement uncertainty estimation methods noted in this subclause.

4.5.2 Measurement uncertainty for ECSM antenna factors

Measurement uncertainty for results from the ECSM may be determined by using 5.1.2.5 of CISPR 16-1-6:2014 [B10]. Both the AF measurement results and the estimated measurement uncertainty shall be provided in an antenna calibration measurement report or certificate.

¹⁷ ANSI C63.4 and ANSI C63.10, for example, require antenna factor measurement uncertainty to be given in the calibration certificates of antennas used for emission measurements; the relevant provisions in each of those documents are: 1) ANSI C63.4-2014, 4.7.3 and footnote a to Table 2 in 4.5.1; 2) ANSI C63.10-2013, 4.4.3 and footnote a to Table 1 in 4.3.1.

5. Standard site method (30 MHz to 40 GHz)

5.1 General considerations

5.1.1 Basic parameters for SSM antenna calibrations

The standard site method (SSM) (Smith [B40]) applies to AF measurements from 30 MHz to 40 GHz. Figure 2 identifies the required site attenuation (SA) measurement geometry. As indicated in Clause 1, consistent with international standards such as CISPR 16-2-3:2010 [B10], the FSAF shall be used for radiated emission measurements. For the purposes of measuring to ASC C63[®] standards, FSAF shall be used for biconical antennas (obtained by applying the correction factors in Annex G), and NFSAF shall be used for LPDA and hybrid antennas. In the following subclauses, descriptions of the SSM parameters are given for two frequency ranges: a) frequencies from 30 MHz to 1 GHz for measurements over a ground plane (see 5.1.2), and b) frequencies from 1 GHz to 40 GHz for measurements in a free-space environment (see 5.1.3).

- a) An ACS appropriate for the AUC frequency range shall be used for SSM.
- b) The test site and measurement instrumentation requirements in 4.3 shall be met.
- c) Horizontal polarization is required for antenna calibration up to 1 GHz, based on the following rationale:
 - 1) Mutual coupling between the antenna and the orthogonal cable is negligible,
 - 2) Scattering from the cable is negligible,
 - 3) The horizontally polarized ground plane reflection is less sensitive to differences in the ground plane conductivity and permittivity than the vertically polarized reflections,
 - 4) Ground plane edge reflections are smaller for horizontal polarization.
- b) AF measurement errors caused by site anomalies may be evaluated using the procedure in L.4.7 (see also J.3).
- c) Signal cables shall be routed straight back from the antenna connector at least 1 m before being routed down vertically to the ground plane.
- d) Signal cables that are routed orthogonal to the antenna elements will have minimal coupling to the antenna field, but the cable shields can carry external currents caused by balun imperfections; see also 4.3 item d). Also, portions of the cables that are not straight down or straight back will couple to the antenna fields; see, e.g., DeMarinis [B13] and [B12] for further discussion of the preceding effects.
- e) 10 dB attenuators, with a return loss of greater than 15 dB, shall be connected to the transmit antenna and receive antenna, for matching purposes between each antenna and cable.

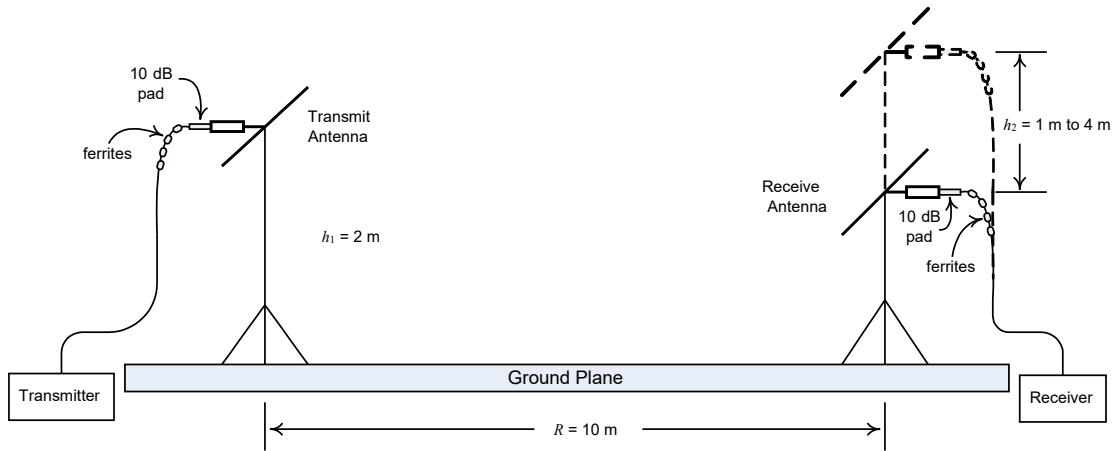


Figure 2—SSM SA measurement geometry

5.1.2 SSM measurement general requirements for frequencies of 30 MHz to 1 GHz

- a) Antenna calibrations using SSM for frequencies of 30 MHz to 1 GHz shall use the following measurement geometry:
 - 1) Separation distance R is 10 m
 - 2) Transmit antenna height h_1 is 2 m
 - 3) Receive antenna height h_2 is scanned from 1 m to 4 m
- b) Table 3 provides values for $E_D^{\max}$ and NSA that are used along with the equations in 5.2.1 to determine the AFs for the measurement geometry of 5.1.2 item a).
- c) The measurement geometry of 5.1.2 item a) and the procedures of 5.2 and 5.3 provide near-free-space antenna factors (NFSAFs) for the antenna types listed in Table 1.
 - 1) NFSAFs obtained for tuned dipole antennas with the SSM, when applicable, which are used for either product radiated emission measurements or 10 m NSA measurements, shall be corrected to free-space values using the correction factors provided in Annex F. NSA measurements at 3 m using tuned dipoles with NFSAFs shall also apply the mutual coupling correction factors given in ANSI C63.4.
 - 2) NFSAFs obtained for biconical dipole antennas with the SSM, when applicable, which are used for either product radiated emission measurements or NSA measurements, shall be corrected to free-space values using the correction factors provided in Annex G.
 - 3) The NFSAFs for the other antennas listed in Table 1 shall be used without further corrections for product radiated emission measurements in accordance with the relevant ASC C63® documents.

**Table 3—Tabulation of $E_D^{\max}$ and NSA for horizontal polarization,
 $h_1 = 2$ m, $h_2 = 1$ m to 4 m scan, $R = 10$ m**

Frequency [MHz]	$E_D^{\max}$ [dB(μ V/m)]	NSA [dB(1/m ²)]
30.0	−4.76	24.1
35.0	−3.56	21.6
40.0	−2.55	19.4
45.0	−1.69	17.5
50.0	−0.95	15.9
60.0	0.24	13.1
70.0	1.09	10.9
80.0	1.69	9.2
90.0	2.05	7.8
100.0	2.21	6.7
120.0	2.39	5.0
140.0	2.49	3.5
160.0	2.56	2.3
180.0	2.60	1.2
200.0	2.63	0.3
250.0	2.68	−1.7
300.0	2.71	−3.3
400.0	2.71	−5.8
500.0	2.57	−7.6
600.0	2.63	−9.3
700.0	2.67	−10.7
800.0	2.69	−11.8
900.0	2.71	−12.9
1000.0	2.72	−13.8

NOTE 1—The values of $E_D^{\max}$ were calculated for a metal ground plane assuming $K = 1$, $\sigma = \infty$ (perfectly conducting) per the formulas in A.2. Additional values may be determined from the equations in Annex A.

NOTE 2—NSA values are listed for convenience, but are not used for determining AFs.

5.1.3 SSM measurement general requirements for frequencies above 1 GHz to 40 GHz

5.1.3.1 Basic requirements

The antenna calibration measurements shall be performed in a free-space test environment and at a fixed height, as described in this subclause. The swept-frequency measurement method of 5.3.3 shall be used.

- a) Antenna calibrations for horn antennas and LPDA antennas using SSM for frequencies above 1 GHz shall use the following setup configuration.
 - 1) Calibration measurement antenna separation distance R :
 - i) No calibrations shall be performed at distances with $R < 0.62 \sqrt{D^3 / \lambda}$.
 - ii) AFs measured at distances with $0.62 \sqrt{D^3 / \lambda} \leq R < 2D^2 / \lambda$ shall be deemed acceptable at the calibrated distance.
 - iii) AFs measured at distances with $R \geq 2D^2 / \lambda$ shall be deemed acceptable at the calibrated distance and greater.

- iv) In the preceding items, R is the separation distance, D is the largest linear dimension (e.g., width or height) of the aperture of the antenna (per IEEE Std 149-1979, Annex A), and λ is the wavelength at the frequency being considered, all in meters.
- 2) The transmit antenna height shall be 1.5 m or greater.
- 3) The receive antenna height shall be fixed at the same height as the transmit antenna ($h_1 = h_2$).
- b) Table 4 lists a single value for $E_D^{\max}$, which is valid only for the specified measurement geometry, i.e., $R = 3$ m in a free-space environment, and that is used along with the equations in 5.2.1 to determine the AFs. For other distances, $E_D^{\max}$ shall be calculated using Equation (A.4) of A.4.

**Table 4— $E_D^{\max}$ for frequencies above 1 GHz (no ground reflections),
example geometry: $R = 3$ m, $h_1 = h_2$, (h_1 and h_2) ≥ 1.5 m**

Frequency (GHz)	$E_D^{\max}$ [dB(μ V/m)]
1 to 40	7.36
NOTE— $E_D^{\max}$ is specified in A.4.	

- c) Free-space test environment requirements:
 - 1) The validity of the free-space test environment at the selected antenna height shall be verified by measuring the site insertion loss in both horizontal polarization and vertical polarization. The difference between the two measurement results shall be less than 1 dB.
 - 2) If the requirement of 5.1.3 item c1) is not met, then raise the height of both antennas, or add RF absorber material on the ground plane between the antennas, until the requirement is met.
 - 3) Time gating of the data may also be used to meet the requirement of 5.1.3 item c1) and to obtain free-space AFs (FSAFs) (i.e., see Camell et al. [B4] and Annex K), as outlined in 5.1.3.2.
- d) Standard gain horn antennas are pyramidal horn antennas designed to have the gain (or AF) established by their physical dimensions, the frequency of interest, and the distance to the measurement point (see 12.3.1 of IEEE Std 149-1979). While reasonable gain values can be calculated using the physical dimensions and analytical formulas, a calibration measurement provides AFs specific to a particular antenna along with the associated traceability. For the purposes of this standard, it is acceptable to determine AF for a standard gain horn by calculation from the physical dimensions, or using individual antenna calibration measurements in accordance with this subclause. Either method of determination of AF will have its own stated measurement uncertainty.

5.1.3.2 Time gating to determine FSAFs above 1 GHz to 40 GHz

Time-domain processing techniques may be used to remove unwanted signals from antenna calibration measurement results to emulate a free-space environment response. By applying proper gating techniques to site insertion loss data in the time domain, a free-space environment can be mathematically simulated. This method may be accomplished by using internal functions of a typical vector network analyzer (VNA), or by post-processing of transmission measurement results. See Camell et al. [B4] and Annex K for guidance and details about appropriate gating procedures. Time gating may be applied to determine FSAF along with the other basic conditions of 5.1.1 and 5.1.3.

5.2 Calculation of antenna factors from SSM measurement results

5.2.1 Calculations

The SSM requires three SA measurements with the setup of Figure 2 under identical geometries (h_1 , h_2 , R) using three antennas taken in pairs, as shown in Figure 3.

NOTE—It is recommended that three antennas of the same type be used, to minimize measurement uncertainties.

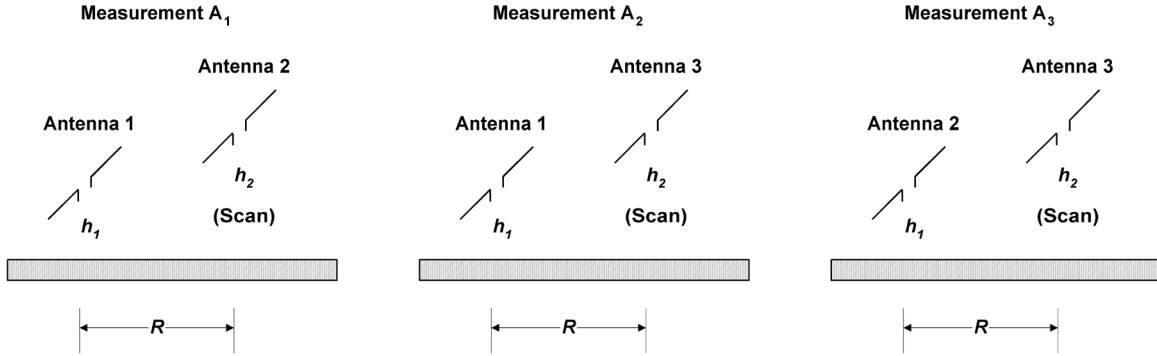


**Figure 3—Three site-attenuation measurements using
three different antennas in pairs**

The three SA measurements are associated with Equation (1), Equation (2), and Equation (3) (all quantities are in dB).

$$AF_1 + AF_2 = A_1 + 20 \log f_M - 48.92 + E_D^{\max} \quad (1)$$

$$AF_1 + AF_3 = A_2 + 20 \log f_M - 48.92 + E_D^{\max} \quad (2)$$

$$AF_2 + AF_3 = A_3 + 20 \log f_M - 48.92 + E_D^{\max} \quad (3)$$

where

$E_D^{\max}$ is the maximum received field at separation distance R from the transmit antenna, shown in Table 3 and Table 4, in dB(μ V/m) (see Smith [B40] and Annex A)
 AF_1, AF_2, AF_3 are the AFs in dB(1/m)
 A_1, A_2, A_3 are the measured SA values in dB (see Figure 2 and 5.3)
 f_M is the frequency in MHz

Solving Equation (1), Equation (2), and Equation (3) simultaneously gives the desired expressions for the AFs in terms of the maximum total field strength term, $E_D^{\max}$, and the measured SA, A_n ($n = 1, 2, 3$). The AFs are obtained using Equation (4), Equation (5), and Equation (6); see also Table 1 of 4.1 and 4.4.2 for GSCF requirements.

$$AF_1 = 10 \log f_M - 24.46 + (E_D^{\max} + A_1 + A_2 - A_3) / 2 \quad (4)$$

$$AF_2 = 10 \log f_M - 24.46 + (E_D^{\max} + A_1 - A_2 + A_3)/2 \quad (5)$$

$$AF_3 = 10 \log f_M - 24.46 + (E_D^{\max} - A_1 + A_2 + A_3)/2 \quad (6)$$

If two identical antennas are to be calibrated, the AF, AF [dB(1/m)], may be obtained from a single SA measurement, A (dB), using Equation (7):

$$AF = 10 \log f_M - 24.46 + (E_D^{\max} + A)/2 \quad (7)$$

In practice, two antennas are never identical, and the AF that is calculated by Equation (7) is the geometric mean (in linear units) of the individual factor for each of the two antennas. Certain antennas can be constructed to be nearly identical. In this case their individual AFs differ by less than the measurement uncertainty.

If two antennas are to be calibrated and the AFs of one are known, use Equation (8) to determine the AF of the unknown antenna.

$$AF_1 = A_1 + 20 \log f_M - 48.92 + E_D^{\max} - AF_2 \quad (8)$$

where AF_2 is the known AF.

NOTE—The accuracy of AFs determined by Equation (4) through Equation (8) is dependent upon the complexity of the model used for computing SA. Corrections to the model have been derived for use with biconical dipole antennas (see Annex G and Annex H for details). NFSAFs for other antenna types are obtained when the measurement geometry is $R = 10$ m, $h_1 = 2$ m, $h_2 = 1$ m to 4 m scan, and horizontal polarization.

5.2.2 Basic considerations

SA measurement errors in Equations (4) through Equation (8) can be reduced by judicious selection of the measurement method since SA is determined by measuring of the ratio V_{direct} to V_{site} , where V_{direct} is the receiver input voltage when the measurement equipment (signal generator, receiver, etc.) is connected directly together through the cables and attenuators, and V_{site} is the receiver input voltage when the measurement equipment is connected via the same cables and attenuators from the transmit antenna and the receive antenna.

The recommended methods for discrete-frequency SA measurements and swept-frequency SA measurements, given in 5.3.2 and 5.3.3, respectively, are identical to the methods for NSA measurements given in ANSI C63.4, except that AFs are not subtracted to determine the measured NSA. Instead, the theoretical SA, along with the applicable correction factor (e.g., as given in Annex G for biconical antennas), is used to determine the AFs; see Table 1 of 4.1 and 4.4.2.

Scanning of the receive antenna height h_2 , as specified in 5.1.2 for 30 MHz to 1 GHz measurements, is used to eliminate the sensitivity of measurement to nulls, because the large spatial rate of change of the field in the region of a null can result in large measurement errors from small errors in antenna positioning. Height scanning is not used in a free-space environment above 1 GHz.

A separation distance R of 10 m is required for antenna calibration measurements up to 1 GHz (per 5.1.2), and a separation distance R as given in 5.1.3.1 is required for frequencies above 1 GHz. Values of $E_D^{\max}$ for use in the equations of 5.2.1 are given in Table 3 and Table 4. Broadband horn antennas may be calibrated

using the SSM method, with the exception that height scanning is not necessary for geometries in which the ground reflection point is not within the beams of the antennas, i.e., for frequencies above 1 GHz.

5.3 SSM antenna calibration measurement procedures

5.3.1 General

Two basic measurement approaches may be used to determine SA for antenna calibrations: 1) a *discrete frequency method*, and 2) a *swept frequency method*. The discrete frequency method requires a signal generator and a receiver or spectrum analyzer, and may be used with broadband antennas or tunable dipole antennas. The swept frequency method requires a tracking generator and an automatic spectrum analyzer, or a network analyzer, and is used only with broadband antennas. For the swept-frequency method, the frequency step size shall be as specified in 4.4.4.

NOTE—Due to variations in $E_{DH}^{\max}$ as a function of receive antenna height h_2 , special attention is needed to avoid errors due to an insufficient antenna mast speed as a function of measurement instrument sweep speed. One frequency sweep every 5 cm is suggested. This 5 cm value is based on the worst-case $E_{DH}^{\max}$ variations as a function of height at 1000 MHz with a 3 m measurement distance R .

5.3.2 Discrete frequency method (30 MHz to 1 GHz)

5.3.2.1 General

With the discrete frequency method, specific frequencies are measured; see Table 3 of 5.1.2 for the measurement frequencies from 30 MHz to 1 GHz. At each frequency, the receive antenna is scanned over the height range given in Table 3 to obtain the maximum received signal. These measured parameter values are inserted in Equation (4), Equation (5), and Equation (6) to obtain the measured AFs. Refer to Figure 2 (5.1.1) and Figure 3 (5.2.1) for the measurement geometry and antenna pairing scheme.

Convenient worksheet templates for carrying out the associated calculations are given in Annex B. Figure B.1 is a data recording and SA calculation worksheet template; Figure B.2 is an example of the use of Figure B.1. Figure B.3 is the AF calculation worksheet, and Figure B.4 is an example of the use of Figure B.3.

5.3.2.2 Procedure

- a) The signal generator output, V_I , is held constant throughout the measurements.
 - 1) Allow the signal generator, amplifier or preamplifier, and measuring instrument to warm-up as specified by the manufacturer of the equipment.
 - 2) Care should be taken if multiple band-specific amplifiers are used. These amplifiers can require additional time to warm up when switching bands, because different components can be used in each band and those components are not necessarily stable when the band is switched.
 - 3) Check that the instrumentation has sufficient dynamic range available to record the difference between the direct cable measurement (step c) and the indirect measurement through the antennas (step b).

- b) At the selected separation distance R , transmit antenna height h_1 , and frequency, connect the first pair of antennas (antenna 1 and antenna 2) via cables and any attenuators to their respective signal source (transmit antenna) and measuring instrument (spectrum analyzer or receiver). Tune the measuring instrument to receive the maximum received signal. Adjust the receive antenna height h_2 for the maximum received signal. Check that the recorded maximum signal is at least 16 dB above the ambient level (see 4.3). Record these data as V_{site} in the template of Figure B.1.
- c) Disconnect the cables and attenuators from the antennas then connect the cables and attenuators directly together with a straight-through adapter. Record the data as V_{direct} in the template of Figure B.1. This direct measurement shall be repeated whenever the temperature at the site changes by 5 °C or more.
- d) Find the difference in attenuation by subtracting the “attenuation for antenna-to-antenna mode” in step b) from the “attenuation for direct connection mode” in step c) in the Figure B.1 template and record this as A_1 in the Figure B.3 template.
- e) Change the frequency (see Table 3 of 5.1.2) then repeat steps b) through d).
- f) After all frequencies are measured, repeat steps b) through d) two more times, once for each of the remaining antenna pairings (antenna 1 and antenna 3; antenna 2 and antenna 3) to get the values for A_2 and A_3 , respectively. Enter the results in the Figure B.3 template.
- g) Calculate the resulting AFs at each frequency using Equation (4), Equation (5), Equation (6), and the parameters from Table 3. GSCFs shall be applied as specified in Table 1 of 4.1 and 4.4.2.

5.3.3 Swept frequency method (30 MHz to 40 GHz)

5.3.3.1 General

For the swept frequency method, measurements using broadband antennas may be made using an automatic measuring instrument having a peak hold (maximum hold) storage capability, and a tracking signal source. In this method, the frequency is scanned or swept over the desired range, holding the maximum signal, while the receive antenna height h_2 is scanned over the required range. For horn antennas and LPDA antennas measured above 1 GHz, the transmit antenna and the receive antenna are set to the required equal fixed height. Two procedures are given in the following subclauses using: 1) a spectrum analyzer or measuring receiver and a tracking generator, or 2) a network analyzer.

NOTE 1—The automatic measuring instrument may be computer controlled provided the software produces the same results as non-automated measurements.

NOTE 2—Transient effects can add significant error to the data; therefore, care should be taken to check for such effects.

5.3.3.2 Procedure using spectrum analyzer or receiver and tracking generator

The following procedure is based on using a spectrum analyzer or a receiver and a tracking generator:

- a) The signal generator output, V_i , is held constant throughout the measurements.
 - 1) Allow the instrumentation to warm-up and stabilize as specified by the manufacturer of the equipment.
 - 2) Care should be taken if multiple band-specific amplifiers are used. These amplifiers can require additional time to warm up when switching bands, because different components can be used in each band and those components are not necessarily stable when the band is switched.

- 3) Check that the instrumentation has sufficient dynamic range available to record the difference between the direct cable measurement (step b) and the indirect measurement through the antennas (step c).
- b) Connect the transmit antenna cable and the receive antenna cable directly together with a straight-through adapter then allow the instrumentation to sweep the desired frequency range until a stable maximum signal is recorded. Store or record the resulting voltage display, V_{direct} in dB(μ V). This direct measurement shall be repeated whenever the temperature at the site changes by 5 °C or more during the measurement.
- c) At the selected separation distance R and transmit antenna height h_1 , connect the first pair of antennas (antenna 1 and antenna 2) via cables to their respective signal source (transmit antenna) and receiver (receive antenna). Raise the receive antenna on the mast to the maximum height h_2 of the scan range. For horn antennas and LDPA antennas measured above 1 GHz, set both the transmit antenna and the receive antenna to the required equal height.
- d) Set the instrumentation to sweep the desired frequency range.
- e) Slowly lower the receive antenna to the minimum height h_2 of the scan range, allowing the instrumentation to acquire the maximum signal at all frequencies. During the antenna height scan, the antenna shall not travel by more than 5 cm during the time it takes for the analyzer to complete one frequency sweep cycle. Check that the recorded maximum signal is at least 16 dB above the ambient level (see 4.3). Store or record the maximum received voltage display, V_{site} in dB(μ V).

NOTE—For automated antenna masts, the maximum signal can be acquired while moving the receive antenna from the minimum height to the maximum height, rather than from maximum to minimum, or during the entire motion from bottom to top and back.
- f) At each frequency, subtract the voltage measured in step d) from the voltage measured in step b) (all in dB). The result is the measured SA over the range of frequencies used, which shall be stored.
- g) Repeat steps b) through f) for each pair of antennas.
- h) Calculate the AFs at each frequency using Equation (4), Equation (5), Equation (6), and the parameters from Table 3 of 5.1.2 or Table 4 of 5.1.3.1. GSCFs shall be applied as specified in Table 1 of 4.1 and 4.4.2.

5.3.3.3 Procedure using network analyzer

The following procedure is based on using a network analyzer:

- a) Allow the network analyzer to warm-up and stabilize as specified by the manufacturer of the equipment.
- b) Set up the network analyzer to measure S_{21} or S_{12} with the desired frequency range. Calibrate the transmit antenna cable and the receive antenna cable using the calibration kit provided for the network analyzer. A through calibration can be sufficient for well-matched antennas.¹⁸ Lower measurement uncertainties can be attained by performing a full two-port calibration to the end of the transmit antenna cable and the receive antenna cable. Measurement uncertainties can be further improved by using time-domain processing to remove unwanted signals from the SA measurement results.

¹⁸ Through calibration (marked as “THRU” on some instruments) for user error correction of network analyzer measurement results involves measurement of a so-called through standard; further details are given for example in Keysight Technologies 5965-7709E [B33].

- c) At the selected separation distance R and transmit antenna height h_2 , connect the first pair of antennas (antenna 1 and antenna 2) via cables to their respective signal source (transmit antenna) and receiver (receive antenna). Raise the receive antenna on the mast to the maximum height h_2 of the scan range. For horn antennas and LDPA antennas measured above 1 GHz, set both the transmit antenna and the receive antenna to the required equal height. For fixed-height measurements, by applying proper time-gating techniques to the insertion loss data, reflections from surrounding environment can be mathematically removed (see 5.1.3.2 and Annex K).
- d) For a network analyzer with maximum hold capability, slowly lower the receive antenna to the minimum height h_2 of the scan range, allowing the instrumentation to acquire the maximum signal at all frequencies. Check that the recorded maximum signal is at least 16 dB above the ambient level (see 4.3). Store or record the maximum S_{21} .

NOTE—For automated antenna masts, the maximum signal can be acquired while moving the receive antenna from the minimum height to the maximum height, rather than from maximum to minimum, or during the entire motion from bottom to top and back.

During the antenna height scan, the antenna shall not travel by more than 5 cm during the time it takes for the analyzer to complete one frequency sweep cycle. Alternatively, a height stepping method may be used, where the antenna stops at a fixed height and completes a frequency sweep, before moving to the next height. Care shall be taken so that the antenna is stable (not “bouncing”) at each stopped height. The S_{21} at each height is transferred back to the computer, which performs the maximum hold function. The maximum step size for height stepping shall be less than or equal to 5 cm.

- e) The inverse of S_{21} (in linear terms) from step d) is the SA; or in dB, the SA is $-S_{21}$ (dB). The result is the measured SA over the range of frequencies used, which shall be stored.
- f) Repeat steps b) through e) for each pair of antennas.

Calculate the AFs at each frequency using Equation (4), Equation (5), Equation (6), and the parameters from Table 3 of 5.1.2 or Table 4 of 5.1.3.1. GSCFs shall be applied as specified in Table 1 of 4.1 and 4.4.2.

6. Reference antenna method (30 MHz to 1 GHz)

6.1 Introduction

The reference antenna method (RAM) is an antenna calibration method based on an antenna as a known (i.e., calculable) quantity.¹⁹ A comparison of received signals is made between the unknown antenna and the reference antenna. One such antenna is the Roberts dipole, i.e., a dipole with a well-matched balun whose construction is described in 6.3.

- a) A reference antenna shall be an antenna with AFs that are calculable and have been validated.
- b) Reference antennas shall be Roberts dipoles or calculable dipoles.

¹⁹ Note that this reference antenna method for antenna calibration is different than and separate from the use of a reference antenna for radiated emission measurements, as can be required by some regulatory and purchasing agents; see, e.g., NOTE to 4.5.4 of ANSI C63.4-2014.

6.2 Calibration of antennas using a reference antenna

6.2.1 General

The AF of any other antenna may be derived by substitution against a reference antenna.

- An ACS shall be used for RAM measurements.
- The measurement geometry shown in Figure 4 shall be used.
- The 10 m separation distance R is employed to eliminate any significant antenna impedance variations caused by antenna-to-antenna mutual impedance coupling. Antenna A1 may be any linearly polarized antenna, including the reference antenna. Its purpose is to generate a field for measurement at antenna A2. Recommended frequency increments for Roberts dipoles and similar antennas are shown in Table 5 in 6.3.

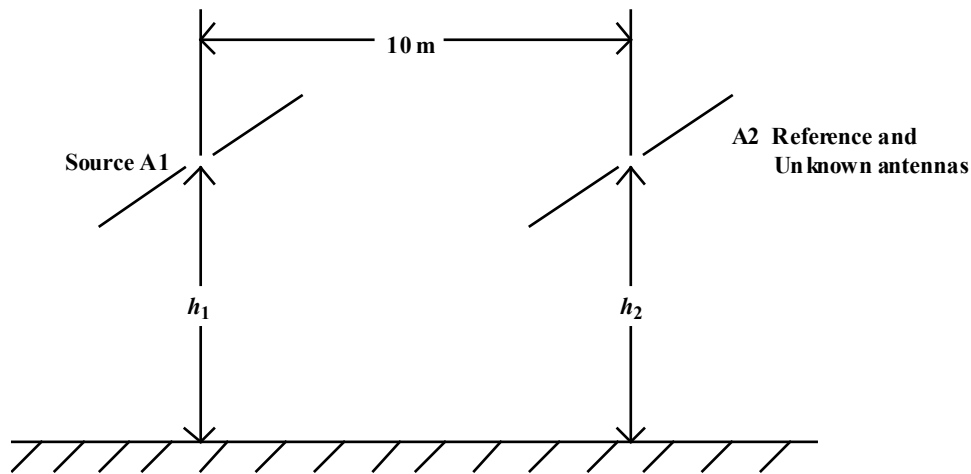


Figure 4—Measurement geometry for calibrating antennas against a reference antenna

6.2.2 Procedure

- Position antenna A1 at 2.5 m to 4 m above the ground and connect it to a signal generator.

NOTE 1—A lower transmit antenna height h_1 , for example, 0.75 m, may be used above approximately 500 MHz, to reduce the number of field strength peaks and nulls.

- To calibrate the unknown antenna against the reference antenna, first measure signal strength with the reference antenna as A2. The antenna height h_2 should be between 2.5 m and 4 m above the ground. It is not important to position the antenna to a signal maximum, but it is important to avoid the region around a null where readings will be changing rapidly with the antenna position. Find a position in the 2.5 m to 4 m range where the signal amplitude is varying slowly with height.

NOTE 2—Scanning the receive antenna in height while recording the maximum received voltages will facilitate avoiding the region around a null, especially at higher frequencies where many peaks and nulls of the field are present.

- After the signal strength is noted with the reference antenna, the AUC shall be substituted, keeping the AUC at exactly the same height and position, as was the reference antenna.
- The ratio between the two measurements of the generated field strength is the difference (in dB) in the AFs between the reference antenna and the unknown antenna. If a lower signal is measured

with the unknown antenna, the difference (in dB) shall be added to the AF of the reference antenna to obtain the AF of the unknown antenna. If the signal measured with the unknown antenna is larger than that measured with the reference antenna, the difference shall be subtracted from the AF of the reference antenna to obtain the AF of the unknown antenna.

6.3 Description of an example reference antenna—Roberts dipole

One type of reference antenna is a tuned, half-wavelength-resonant dipole with a series-parallel coaxial stub balun, conventionally referred to as a Roberts dipole. The length of each element of the reference antenna and its AFs are tabulated versus frequency in Table 5.

A set of four balun assemblies and adjustable-length dipole elements can be used to cover the frequency range of 30 MHz to 1000 MHz. Physical construction details of the balun, antenna housings, and elements are shown in Figure D.1 through Figure D.9. (See also FCC Project 3235-16 [B16]; FCC Project 3235-33 [B17]; Roberts [B37]; Roberts et al. [B38].) The dimensions that are electrically critical are those that influence construction of the balun series stub and parallel stub. These dimensions are shown in Figure D.1 in Annex D. The baluns should be constructed from RG-58/U, RG-400, or other similar high-quality coaxial cable.

After construction, a preliminary ohmic check shall be performed. The resistance from the center conductors to the shield should be very large, that is, an open circuit. A preliminary back-to-back balun measurement shall also be performed before the baluns are installed in their housings by using the measurement setup of Figure D.10 in Annex D. The loss per balun in this measurement is one-half of the total loss measured, and should be between 0.2 dB and 0.5 dB per balun over its frequency range.

A VSWR check shall be performed to confirm proper performance of the assembled antennas. VSWR shall be measured with the antenna assembled and its elements tuned to resonance. The antenna shall be placed at least 4 m above the ground, to reduce antenna-to-ground coupling, and its elements tuned to resonance using the lengths shown in Table 5. It is sufficient to check the VSWR of the antennas at frequencies in the low, middle, and high end of their frequency ranges. Below 100 MHz, the function of the baluns may also be checked by removing the elements, placing a 70 Ω resistor across the terminals of the element mounting block, and measuring the VSWR of the terminated balun.

NOTE—Check that the reactance of the 70 Ω resistor is much smaller than its resistance.

AFs for this reference antenna are tabulated in Table 5 and were computed from Equation (9), i.e., the formula for the AF of a lossless dipole. The AF shall be combined with an averaged loss for the matching balun of 0.5 dB (FCC Project 3235-16 [B16], FCC Project 3235-33 [B17]).

$$AF = 20 \log f_M - 31.4 \quad (9)$$

where f_M is in MHz.

Experimental data (FCC Project 3235-33 [B17]) have shown that the antenna-to-antenna variation to be expected due to construction tolerances is of the order of ± 0.3 dB.