

ANSI C63.5-2004
(Revision of
ANSI C63.5-1998)

IEEE Standards

C63.5

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

Accredited by the American National Standards Institute

Sponsored by the
Accredited Standards Committee on Electromagnetic Compatibility, C63



3 Park Avenue, New York, NY 10016-5997, USA

20 December 2004

Print: SH95289

PDF: 559249



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**Accredited Standards Committee on Electromagnetic Compatibility, C63
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Secretariat

Institute of Electrical and Electronic Engineers, Inc.

Approved 24 June 2004

American National Standards Institute

Abstract: Methods for determining antenna factors of antennas used for radiated emission measurements of electromagnetic interference (EMI) 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, hybrid linearly polarized arrays, broadband horns, etc., which are used in measurements governed by ANSI C63.4-2001. The methods include standard site (i.e. 3-antenna), reference antenna, equivalent capacitance substitution, standard transmitting loop, standard antenna, and standard field methods.

Keywords: antenna factors, equivalent capacitance substitution, linearly polarized antennas, near free space, reference antenna, standard antenna, standard site, standard transmitting loop

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Print: ISBN 0-7381-4514-9 SH95289
PDF: ISBN 0-7381-4515-7 SS95289

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Introduction

[This introduction is not part of ANSI C63.5-2004, American National Standard for Electromagnetic Compatibility—Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration of Antennas (9 kHz to 40 GHz).]

ANSI C63.4-2001, American National Standard for Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronics Equipment in the Range of 9 kHz to 40 GHz, has undergone several revisions since the original document covering methods of measurement was produced in 1940. Although many improvements were made in the standard from time to time, the reproducibility of measurements of radiated interference from one test site to another has not been completely satisfactory.

In 1982 a concerted effort was organized in Subcommittee One of the Accredited Standards Committee C63 to determine how the technique could be improved. 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, associated cabling, and balun and device under test characteristics, and (c) consideration of mutual coupling effects between the device under test and the receiving antenna and their images in the ground plane. Accordingly, ANSI C63.4 has been revised, and ANSI standards C63.5, C63.6, and C63.7 were prepared to provide additional information. This standard provides methods of calibration of antennas for use on the test site.

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. During the ensuing discussions, it became apparent that several features of ANSI C63.5 were not acceptable to the international community. In particular, calibration measurements at 3 m were unacceptable. Furthermore, while ANSI C63.5 recommends that only horizontal polarization be used for antenna calibration, it included information on calibration using vertical polarization. This was considered ambiguous and unacceptable by CISPR Subcommittee A. During the use of ANSI C63.5 over the last several years a number of errors were discovered and these needed to be corrected. ANSI standards C63.2 and 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, ANSI C63.5 has been revised to eliminate those features that the international community found objectionable, and thus provides harmonization with international standards while allowing a US National deviation from those standards. This revision corrects errors which use of the standard has shown, and extends it to cover all of the antennas specified in ANSI standards C63.2 and C63.4 from 9 kHz to 40 GHz.

In 1999 a collaborative effort was organized in Subcommittee One of the Accredited Standards Committee C63 to determine how the technique could be improved. Evidence showed that significant errors are introduced into the NSA results when non-free space antenna factors of biconical dipole antennas are used for NSA testing. These errors are due, in part, to mutual coupling effects between the antennas and between the receiving antenna and the image of the transmitting antenna in the ground plane. Corrections for this occurrence are submitted for use with biconical dipoles. An alternate measurement technique is also provided for other types of antennas. Minor editorial corrections have been made to this document.

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

1. Scope

This standard provides methods for determining antenna factors of antennas used for radiated emission measurements of electromagnetic interference (EMI) from 9 kHz to 40 GHz. Antennas included are linearly polarized antennas, such as loops, rods (monopoles), tuned dipoles, biconical dipoles, log-periodic dipole arrays, hybrid linearly polarized arrays, broadband horns, etc., that are used in measurements governed by ANSI C63.4-2001.¹ The methods include standard site, reference antenna, equivalent capacitance substitution, standard transmitting loop, standard antenna, and standard field methods. The latter three methods are incorporated by reference in 4.5.

Harmonization of this standard with international standards is achieved by providing one measurement geometry in the 30 MHz to 1000 MHz frequency range. The word “shall” is used in this document to indicate mandatory requirements. The words “should” or “may” are used to indicate that among several possibilities one is strongly recommended but not mandatory.

2. References

The following references shall form a part of this standard to the extent referenced. When the standards referred to in this standard are superseded by a revision, the revision shall apply.

ANSI C63.4-2001, 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.²

ANSI C63.6-1996, American National Standard Guide for the Computation of Errors in Open-Area Test Site Measurements.

¹ Information on references can be found in Clause 2.

² ANSI C63 publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331 USA.

ANSI C63.7-1992, American National Standard Guide for Construction of Open-Area Test Sites for Performing Radiated Emission Measurements.

ANSI C63.14-1998, American National Standard Dictionary for Technologies of Electromagnetic Compatibility (EMC), Electromagnetic Pulse (EMP), and Electrostatic Discharge (ESD).

ANSI/NCSL Z540-1-1994, American National Standard for Calibration-Calibration Laboratories and Measuring and Test Equipment-General Requirements.^{3, 4}

ANSI/NCSL Z540-2-1997, American National Standard for Expressing Uncertainty — U.S. Guide to the Expression of Uncertainty in Measurement.”

CISPR Publication 16 Part 1-1999, CISPR Specifications for radio disturbance and immunity measuring apparatus and methods – Part 1: Radio disturbance and immunity apparatus, 2nd ed.

IEEE Std 149™-1979 (R2003), IEEE Standard Test Procedures for Antennas.

IEEE Std 291™-1991, IEEE Standard Methods for Measuring Electromagnetic Field Strength of Sinusoidal Continuous Waves, 30 Hz to 30 GHz.⁵

3. Definitions

The following definitions apply specifically to the subject treated in this standard. For additional definitions, see ANSI C63.14-1998 and *The Authoritative Dictionary of IEEE Standards Terms*, 7th Edition [B10]⁶.

3.1 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.

3.2 antenna factor: Ratio of the electric field in the polarization direction of the antenna to the voltage induced across the load connected to the antenna and expressed in decibel form ($20 \log (E/V_o)$).

3.3 free-space antenna factor (FSAF): Antenna factor that is not influenced by adjacent objects (in dB).

3.4 Geometry Specific Correction Factors (GSCF): Correction factors (in dB) that are calculated or measured for each frequency at a specific geometry. These factors are subtracted from the site-attenuation that has been calculated using the theoretical model that employs near free-space or free space antenna factors. These correction factors include the effect of the $1/r^2$ and $1/r^3$ radiation terms, non-uniform illumination of the receive antenna, mutual coupling between the transmitting and receiving antennas, and mutual coupling between the antennas and the ground plane.

3.5 near free-space antenna factors: Antenna factors (in dB) that are minimally affected by the test environment. The test setup for this condition is horizontal polarization, $R=10$ m, $h_1=2$ m, and $h_2=1$ to 4 m. This value will represent the free-space antenna factor within an error smaller than the measurement uncertainty. This error is negligible when these antenna factors are used for product emission measurements.

³ NCSL standards are available from National Conference of Standards Laboratories, 1800 30th Street, Suite 305B, Boulder, CO 80301 USA.

⁴ DoD has withdrawn MIL-STD-45662A and directed the use of ANSI/NCSL Z540-1-1994 instead.

⁵ IEEE Std 291-1991 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181 (<http://global.ihs.com/>).

⁶ The numbers in brackets correspond to those of the bibliography in Annex J.

3.6 ground plane: A conducting surface or plate used as a common reference point for circuit returns and electric or signal potentials.

3.7 ideal site: A test site on which the reflective surface is flat, level and has infinite conductivity and size.

3.8 measurement geometry: A specified polarization, separation distance, transmitting height, and receiving height(s) for a pair of antennas during their antenna factor measurement.

3.9 normalized site attenuation (NSA): Site attenuation divided by the free-space antenna factors of the transmitting and receiving antennas (all in linear units). Results can be stated in decibel units.

3.10 radiated emissions test site: A site with specified requirements suitable for measuring radio interference fields radiated by a device, equipment, or system under test.

3.11 site attenuation: 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.

3.12 standard antenna calibration site: A site comprised of a flat, open-area, devoid of nearby scatterers such as trees, power lines, and fences, that has a large metallic ground plane (see ANSI C63.7-1992).

4. General test conditions

4.1 Introduction

This standard provides a means of measuring antenna factors for most types of antennas used in emissions testing. These antenna factors can be used for either vertically or horizontally polarized measurement at distances from the equipment under test of 3 m or more. Table 1 provides an index of antenna type to measurement method.

Free space antenna factors can be developed for biconical dipole antennas 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 than the use of Clause 5 alone. See Annex F for additional information on the rationale of GSCF for biconical dipole antennas.

Near free space antenna factors can be developed for broadband antennas using the methods specified in Table 1. Annex H provides a measurement procedure to determine GSCF for broadband antennas. Annex H also provides the requirements for a reference site used to measure GSCFs for complex antennas or other broadband antennas where the GSCFs in annex G cannot be applied.

The general test conditions for antenna calibration are described in 4.1 through 4.4. This standard also provides additional guidance on the estimation of measurement uncertainties in antenna calibrations.

Table 1—Calibration methods for antennas

Antenna Type	Antennas for Product Test				Antennas for Normalized Site Attenuation			
	Clause 5	Clause 5 + Annex G	Clause 6	Clause 7	Clause 5	Clause 5 + Annex G	Clause 6	Annex H
Monopole				X				
Tunable Dipole	X		X		X		X	
Biconical Dipole		X	X			X		X
Log Periodic Array	X		X		X		X	X
Broadband Hybrid	X		X					X
Horn	X						X	
Other	X							

4.2 Calibration measurement geometry

Accurate antenna calibrations require restrictions on measurement geometry. The antenna separation distance R shall be large enough to ensure that near-field effects and antenna-to-antenna mutual coupling effects are minimized. Antenna heights (h_1 , h_2) shall be great enough to minimize antenna-to-ground plane mutual impedance.

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, the separation distance shall be measured from the midpoint of the dipole elements. The separation distance between log-periodic array antennas shall be measured from the midpoint of the elements along the longitudinal axis of each antenna. For horn antennas, the separation distance shall be measured from the front face of the antennas.

4.3 Test site and instrumentation

The test site used for antenna calibrations shall be within ± 2 dB of an ideal site when tested for site attenuation in accordance with C63.4-2001. The normalized site attenuation test shall be evaluated over a volume (e.g., as an alternate test site) for the measurement distances the site will use to calibrate antennas. Measurement instrumentation should be located beneath the ground plane or at least 20 meters from the edge of the ground plane to reduce site and system contributions to uncertainty (see Annex I).

All test instrumentation including signal generators, radio noise meters, spectrum analyzers, tuned voltmeters, receivers, etc.-shall have a nominal 50- Ω impedance. Refer to ANSI C63.2-1996 or CISPR 16-1-1 and CISPR 16-1-4 for radio noise meter specifications.

An impedance mismatch at the output of signal sources or at the input of receivers, and at antennas may result in reflections that could cause antenna factor measurement errors. These errors can be minimized by the use of high-quality attenuators to provide a matched termination to the cable, which will reduce reflections due to mismatch. Attenuators should be used anytime the voltage standing wave ratio (VSWR) of the antenna exceeds 2:1.⁷ At least one attenuator should be provided at the antenna end of the transmitting cable and one at the measuring instrument or pre-amplifier input. Additional attenuators at the receiving antenna and the signal source or amplifier may improve the measurement uncertainty (see Annex I for the formula to compute this error term). The signal sources should provide sufficient power to produce

⁷ CISPR 16-1-1, clause 5.5.5.2

a signal at the receiver input of at least 16 dB above the equivalent receiver noise at the receiver input. A signal plus noise-to-noise ratio of 16 dB reduces this error term to 0.11 dB, significantly below the expected measurement uncertainty. This 0.11 dB must then be subtracted from the measured value. Power amplifiers may be used at the signal source output to raise the signal above both the ambient and receiver noise. See Annex I for further information on this minimum signal plus noise-to-noise ratio. Preamplifiers may be used at the receiver input to raise both the signal and ambient above the receiver noise and meet this requirement. The source power amplifier and/or preamplifier gain requirements will depend upon receiver and/or preamplifier sensitivity, antenna factors, cable losses, ambient signal level and measurement distance. Care shall be taken to avoid overloading pre-amplifiers or receivers with signals that are close to or higher than their maximum allowed input. Filters may be used to prevent out-of-band signals from saturating a preamplifier or receiver. Lossy ferrite material shall be applied to at least the first meter of both the transmitting and receiving antenna cables whenever dipole, biconical dipole or biconical hybrid antennas are calibrated, to serve as a common mode choke and to minimize induced currents on the cable shield from antenna coupling.

It is preferable to use preamplifiers at the receiver input rather than power amplifiers at the source output, whenever possible. 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 area. However, this will not improve the signal-to-ambient ratio of the test system, see Annex I.

Test equipment such as signal sources, antennas, and receiving equipment (receivers and preamplifiers), etc., shall be calibrated at regular intervals. Calibration shall include amplitude uncertainty, frequency uncertainty, and drift, where applicable. Effects of drift, especially during the measurement time, shall be compensated or corrected (See Annex I for compensation and/or computation of uncertainty associated with drift). These calibration standards shall be traceable to a national standard. An example of an acceptable program for calibration of instrumentation can be found in ANSI/NCSL Z540-1-1994.

4.4 Antenna factors

These procedures are capable of producing free space antenna factors with relatively low uncertainty values. Antenna factors shall be measured for a particular antenna type as stated in the Table 1. See Annex F for information on biconical dipole antennas. See Annex I for further guidance on the estimation of measurement uncertainty. Antenna factors usually account for losses due to the balun, if used. If a separate balun is used, its effects shall be measured or otherwise accounted for and included with the data to ensure that the user understands how any such separate balun is to be used and how its effects are to be accounted for. If the measured antenna factors are adjusted to correct for fixed-length cable losses, this shall be clearly stated in the antenna-factor data supplied to the user.

4.4.1 Antenna symmetry

In addition to the antenna calibration procedure, it is prudent to check the balance of symmetrical antennas. Two antennas of similar type (i.e., same model) are required. Connect this pair of antennas to the test instrumentation as described in clause 4.3 and then

- a) Start by orienting the transmitting and receiving antennas vertically with respect to the ground plane at a height of 1 m to the antenna center. Close proximity to the ground plane is needed to maximize coupling effects. For larger antennas, the center height shall be raised until the bottom edge of the lower antenna element is 25 cm from the ground plane. Note the received signal in this position while keeping the transmit signal constant.
- b) Rotate the receive antenna (the antenna being checked for balance) 180° so that it is oriented vertically with the opposite element(s) facing up. Note the received signal with the transmit signal continuing to be held constant. The received signal should be within 1.0 dB of the received signal with the antenna in the original position.

If an unbalance (>1.0 dB) is found, it may be due to the antenna, the balun, or to cable problems. Determine which problem or problems exist and remedy them before going on to calibrate the antenna.

4.5 Methods of antenna factor determination

Antenna factors can be accurately determined in several ways. The decision as to which approach is best in a particular case shall be based upon the time, instrumentation, facilities, and personnel [B1, B2, B3, B7, and B12].

Three commonly used methods are

- Standard Site Method (SSM)
- Reference Antenna Method (RAM)
- Equivalent Capacitance Substitution Method (ECSM)

These methods are described in Clause 5, Clause 6, and Clause 7. The uncertainty of these methods can be estimated using the guidance provided in Annex I. In addition, the estimated uncertainty will depend on (1) the quality of the test 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 can be used for calibration of monopole antennas from 9 kHz to 30 MHz to use in the measurements in ANSI C63.4-2001.

Three additional methods are

- Standard Field Method (SFM) (IEEE Std 291-1991)
- Standard Antenna Method (SAM) (Fitzgerrel [B6], Taggart and Workman [B13], IEEE Std 149-1979)
- Standard Transmitting Loop Method (STLM), a specialized version of the Standard Antenna Method (IEEE Std 291-1991)

These additional methods are incorporated in this standard by these references. ANSI C63.4-2001 uses the STLM for calibration of loop antennas from 9 kHz to 30 MHz for use in the required measurements.

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

5.1 General

The Standard Site Method (SSM) (based solely on horizontally polarized measurements) provides antenna factor measurements from 30 MHz to 1000 MHz for both US domestic use and international use. The measurement method is the same in both cases. For either use, the measurement distance is 10 m, the transmitting antenna height is 2 m, and the receiving antenna search heights are from 1 m to 4 m. These dimensions are annotated in Table 2, which provides values for $E_D^{\max}$ and ideal site attenuation (SA) (Figure 1 provides the measurement geometries).

The SSM for determining antenna factors (Smith [B11]) requires a standard antenna calibration site. This procedure provides near free space antenna factors for biconical dipole, tuned dipole, log periodic dipole

array, and linearly polarized hybrid array antennas. For biconical dipole antennas, corrections to free space shall be applied for product measurements and are provided in Annex G. Mutual coupling correction factors for tuned dipoles shall be applied and are provided in C63.4-2001. The near free-space antenna factors for the remainder of the listed antennas shall be used without further correction for emission measurements as specified in C63.4-2001.

Antenna factor calibration errors caused by site anomalies can be evaluated using the procedure in Annex I.

Antenna factors shall be determined only for horizontal polarization on a standard antenna calibration site, hereafter referred to as a standard site, using the SSM. Horizontal polarization measurements are relatively insensitive to site variations and yield acceptable antenna factors even though the reflecting plane does not create a free-space environment during calibration. Horizontal polarization is preferred for antenna calibration because

- a) Mutual coupling between the antenna and the orthogonal cable is negligible
- b) Scattering from the cable is negligible
- c) The horizontally polarized ground reflection is less sensitive to differences in the ground plane conductivity and permittivity than the vertically polarized reflections.
- d) Ground screen edge reflections are smaller for horizontal polarization

Antenna factors obtained for biconical dipole antennas using the SSM that are used for either product testing or NSA testing shall be corrected to free space values using the correction factors provided in Annex G. It is unnecessary to calibrate standard gain horn antennas for use above 1 GHz; rather, they are used as gain standards to calibrate other antennas (see 12.3.1 of IEEE Std 149-1979).

Table 2—Tabulations of $E_D^{\max}$ and NSA for horizontal polarization, 2 m transmitting height, 1 to 4 m receive height scan at 10 m distance.

Frequency [MHz]	$E_D^{\max}$ [dB(μ V/m)]	NSA [dB]
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

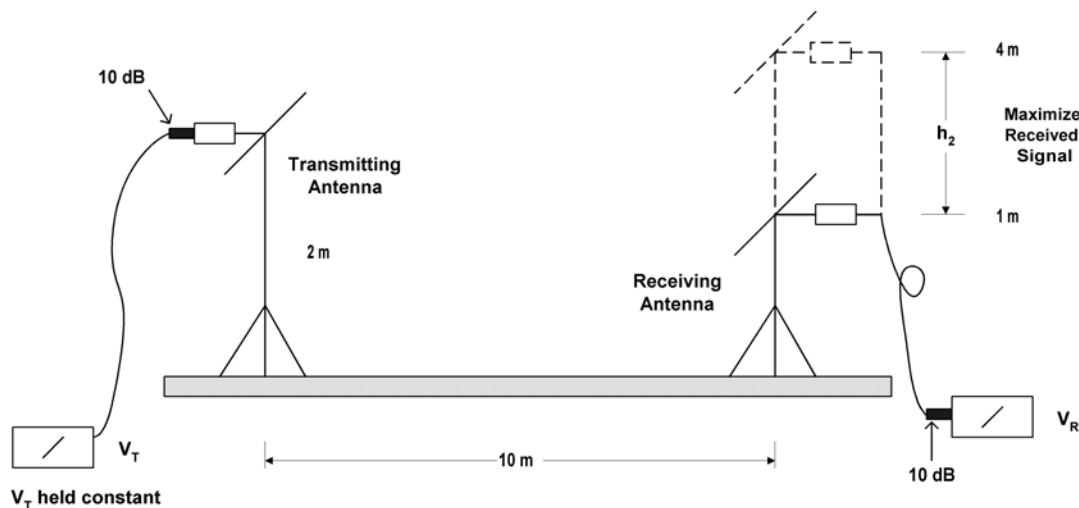
NOTE—The values of $E_D^{\max}$ were calculated for a metal ground plane assuming $K=1$, $\sigma=\infty$ (perfectly conducting) as defined in Annex A. Use Table 3 to calibrate horn antennas.⁸

Table 3—Tabulations of $E_D^{\max}$ for horn antennas (no ground reflections)

A.1.1.1.1.1.1.1 R [m]	3
h_1 [m]	≥ 2
h_2 [m]	≥ 2
f_M [GHz]	1.0-40.0
$E_D^{\max}$ [dB(μ V/m)]	7.38

Note: $E_D^{\max}$ is defined in Annex A.

⁸ Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the guide.



NOTE—Signal cables shall be dressed straight back from the antenna connector at least 1 m before being dressed vertically down to the ground plane. Signal cables that are dressed orthogonal to the antenna elements will have minimal coupling to the antenna field, but the cable shields may carry external currents caused by balun imperfections. Also, portions of the cables that are not straight down or straight back will couple to the antenna fields. See [B2] and [B3] for further discussion of these effects.

Figure 1—Site attenuation (horizontal polarization)

5.2 Description of method

The SSM requires three site attenuation measurements under identical geometries (h_1 , h_2 , R) using three different antennas taken in pairs, as shown in Figure 2. The three equations associated with the three site attenuation measurements are Equations (1), (2), and (3).

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

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

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

(All equations in dB)

where

$E_D^{\max}$ is the maximum received field at separation distance R from the transmitting antenna, shown in Tables 2 and 3, in dB ($\mu\text{V/m}$). (See Smith [B11] and Annex A.)

AF_1 , AF_2 , AF_3 are the antenna factors of antennas 1, 2, and 3 in dB (1/m).

A_1 , A_2 , A_3 are the measured site attenuation in dB. (See Figure 1 and 5.3)

f_M is the frequency in MHz.

Solving Equations (1), (2), and (3) simultaneously gives the desired expressions for the antenna factors in terms of the maximum total strength term, $E_D^{\max}$, and measured site attenuation, A_n . They are as follows:

$$AF_1 = 10 \log f_M - 24.46 + 1/2 [E_D^{\max} + A_1 + A_2 - A_3] \quad (4)$$

$$AF_2 = 10 \log f_M - 24.46 + 1/2 [E_D^{\max} + A_1 + A_3 - A_2] \quad (5)$$

$$AF_3 = 10 \log f_M - 24.46 + 1/2 [E_D^{\max} + A_2 + A_3 - A_1] \quad (6)$$

If two identical antennas are to be calibrated, their antenna factor, AF [dB(1/m)], can be obtained from a single site attenuation measurement, A (dB), using the following expression:

$$AF = 10 \log f_M - 24.46 + 1/2 [E_D^{\max} + A] \quad (7)$$

In practice, two antennas are never identical, and the antenna factor 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 so nearly identical that their factors are different by much less than the measurement uncertainty.

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

NOTE—The accuracy of equations (1-8) is dependent upon the completeness of the model used for computing site attenuation. Corrections to the model have been derived for use with biconical dipole antennas (see Annexes F and G for details). Near free-space antenna factors for other antenna types are obtained when the test geometry is $R=10$ m, $h_1=2$ m, $h_2=1-4$ m scan, and horizontal polarization.

Site attenuation measurement errors in Equations (4) through (7) can be minimized by judicious selection of the measurement method since site attenuation is determined by measuring of the ratio $V_{\text{direct}} : V_{\text{site}}$, 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 transmitting and receiving antennas. Recommended methods for discrete and swept frequency site attenuation measurements are identical to the methods for normalized site attenuation (NSA) measurements given in ANSI C63.4-2001, except that antenna factors are not subtracted to determine the measured NSA. Instead, the theoretical NSA is used to determine the antenna factors.

Scanning of the receiving antenna height h_2 is a practical requirement that eliminates the sensitivity of measurement to nulls. (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.) Antenna separation of 10 m is recommended for antenna calibration measurements. Values of $E_D^{\max}$ for this geometry over metal ground planes are given in Table 2. Broadband horn antennas may be calibrated using the same method with the exception that height search is not necessary in geometries in which the ground reflection point is not within the beams of the antennas. This can be verified by performing the calibration at two significantly different heights (difference > 0.5 m or 10 % of the test height whichever is larger) and verifying that the differences between the two resulting antenna factors are within the expected measurement uncertainty. For this geometry, the theoretical E_D value used in lieu of $E_D^{\max}$ in the above equations is given in Annex A. Horn

antennas shall be calibrated at a distance equal to or greater than $R = 2D^2/\lambda$; horn antennas shall not be calibrated at a distance less than $R = 0.5D^2/\lambda$. D is the largest linear dimension (e.g., width or height) of the aperture of the antenna and λ is the wavelength at the frequency being considered, both in meters.

NOTE—An antenna calibrated at a distance less than $R = 2D^2/\lambda$ shall be used only at the calibrated distance.

5.3 Measurement procedures

Two measurement procedures may be used to determine site attenuation: a *discrete frequency method* and a *swept frequency method*. The discrete frequency method requires a signal generator and receiver or spectrum analyzer, and may be used with broadband or tunable antennas. The swept frequency method requires a tracking generator and automatic spectrum analyzer, or other automatic measuring equipment, and is used only with broadband antennas. The minimum number of discrete frequency points to be measured for broadband antennas is under further study. However, the minimum number of points shall be sufficient to represent the shape of the antenna factor such that the interpolation error between points is less than 1/3 of the calibration measurement uncertainty stated for the antenna.

NOTE—Variations in $E_{DH}^{\max}$ as a function of receive antenna height can cause errors due to an insufficient antenna mast speed as a function of measurement instrument sweep speed. One frequency sweep every 5 cm is suggested, although this matter is under study. 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.

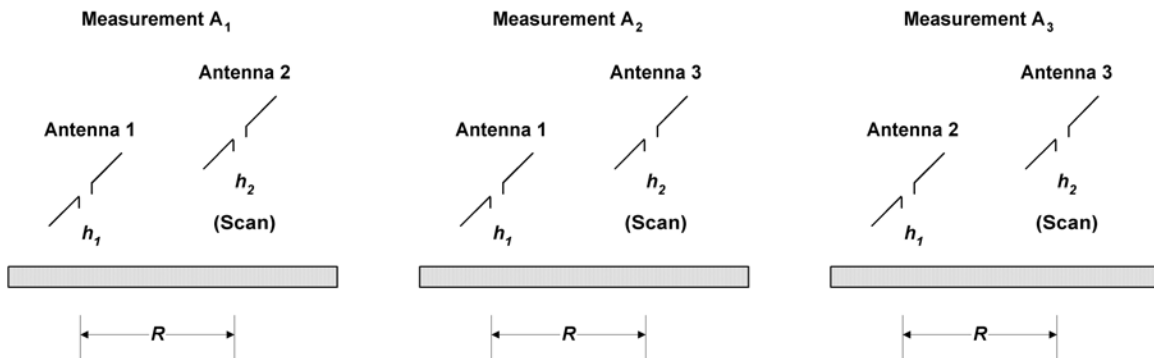


Figure 2—Three site attenuation measurements using three different antennas in pairs

5.3.1 Discrete frequency method

For the discrete frequency method, specific frequencies are measured. See Table 2 for frequencies from 30 to 1000 MHz. At each frequency, the receiving antenna is scanned over the height range given in the appropriate table (Table 2 or 3) to maximize the received signal. These measured parameter values are inserted in Equations (4), (5), and (6) to obtain the measured antenna factors. Refer to Figure 2 for the measurement geometry. For horn antennas, both the transmitting and receiving antennas are operated at fixed equal heights of 2 m or more.

Convenient worksheets for carrying out the necessary calculations are given in Annex B. Figure B.1 is a data recording and site attenuation calculation worksheet, Figure B.2 is an example of the use of Figure B.1, Figure B.3 is the antenna factor calculation worksheet, and Figure B.4 is an example of Figure B.3.

5.3.1.1 Procedure

- 1) Allow the signal generator, amplifier or pre-amplifier and measuring instrument to warm up as specified by the manufacturer of the equipment. Care should be taken if multiple band amplifiers are used. These amplifiers may require additional time to warm up when switching bands, since different components may be used in each band and those components are not necessarily stable when the band is switched. The signal at the generator output V_i , is held constant throughout the measurement. Ensure that the instrumentation has sufficient dynamic range available to record the difference between the direct cable measurement (step 3) and the indirect measurement through the antennas (step 2). It is recommended that high quality calibrated attenuators be used during the direct measurement that are nearly equal to the anticipated antenna losses. The use of these attenuators will ensure accuracy during a relative amplitude measurement, by reducing the uncertainty due to non-linearity of the instrumentation. (See Annex I for uncertainties associated with the selection of the substitution attenuator). The frequency response of the attenuators, if used, must be normalized from the direct measurement since they are not used during the indirect measurement. If attenuators are not used, the difference between the direct and indirect measurement can be as much as 60 dB or more.
- 2) At the selected distance, transmitting height and frequency, connect the first pair of antennas (antennas 1 and 2) via cables and any attenuators to their respective signal source (transmitting antenna) and measurement instrument (spectrum analyzer or receiver). Tune the measurement instrument to receive the maximum received signal. Adjust the height of the receiving antenna for the maximum received signal. Ensure that the recorded maximum signal is at least 16 dB above the ambient signals and noise floor (see Clause 4.3). Adjust the substitution attenuator for reference indication on the measuring instrument. Record these data as V_{site} in Figure B.1.
- 3) Disconnect the cables and attenuators from the antennas and connect the cables and attenuators directly together with the substitution attenuator and a straight-through adapter. Adjust or select the substitution attenuator to give the same receiver reference indication as in step 2) and record the data as V_{direct} in Figure B.1. (See annex I for uncertainties associated with the selection of the substitution attenuator) The signal generator output attenuator may be used in place of an external substitution attenuator in the path between the generator and the transmit antenna. This direct measurement shall be repeated anytime the temperature at the site changes by 5 °C or more.
- 4) Find the difference in attenuation by subtracting the "attenuation for antenna-to-antenna mode" in step 2) from the "attenuation for direct connection mode" in step 3) in Figure B.1 and record this as A_1 in Figure B.3.
- 5) Change the frequency (see Table 2 or Table 3) and repeat steps 2) through 4).
- 6) After all frequencies are measured, repeat steps 2) through 4) twice more, once for each of the remaining antenna pairings (antennas 1 and 3, antennas 2 and 3) to get the values for A_2 and A_3 , respectively. Enter the results in Figure B.3. Calculate the resulting antenna factors at each frequency using Equations (4-6) and Table 2 or Table 3 depending upon frequency.

The values of E_D^{max} listed in Table 2 were calculated for metal ground planes assuming $K = 1$, $\sigma = \infty$ (perfectly conducting) as defined in Annex A. This table has data up to 1 GHz. Use table 3 to calibrate horn antennas. Frequency coverage shall be every 500 MHz from 1GHz through 12 GHz, every 1 GHz from 12 GHz through 18 GHz, and every 2 GHz from 18 GHz through 40 GHz.

5.3.2 Swept frequency method

For the swept frequency method, measurements using broadband antennas may be made using automatic measuring equipment having a peak hold (maximum hold), storage capability, and a tracking generator. In this method, the frequency is scanned or swept over the desired range, holding the maximum signal, while the receiving antenna height is scanned over the required range. For horn antennas, the transmitting and