IEEE

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

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Accredited Standards Committee on Electromagnetic Compatibility, C63

C63.5

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Secretariat

Institute of Electrical and Electronic Engineers, Inc.

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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 C63.4-2003. 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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American National Standard

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Introduction

This introduction is not part of ANSI C63.5-2006, American National Standard for Electromagnetic Compatibility—Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration of Antennas (9 kHz to 40 GHz).

ANSI C63.4-2003, 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.

In 2005, the C63 committee received a request for an interpretation of subclause 5.1 and an apparent conflict with the associated flowchart in Annex G (Figure G.2). The issue revolved around the apparent confusion of the process for antenna factor calibration for product testing versus the calibration process when making test-site attenuation 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.

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Ralph M. Showers, *Chair*
Donald N. Heirman, *Vice-Chair*
Robert L. Pritchard, *Secretary*

Organization Represented	*Representative*
Alliance for Telecom Ind. Solutions (ATIS)	C. Chrysanthou
	J. Turner
ACIL	M. Violette
	W. Stumpf
Amer. Radio Relay League (ARRL)	D. Bodson
	E. Hare
Curtis-Straus LLC	J. Curtis
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Dell, Inc.	E. Bronaugh
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ETS - Lindgren	M. Foegelle
	Z. Chen
Federal Commun. Commission (FCC)	W. Hurst
	A. Wall
Food and Drug Administration	J. Casamento
	J. L. Silbergerg
Hewlett-Packard	K. Hall
Info. Tech. Industry Council - ITIC	J. Hirvela
	J. Rosenberg
IEEE (Institute of Electrical and Electronics Engineers, Inc.)	D. Heirman
Inst. Elect. and Electronics Engrs. EMCS	S. Berger
	D. Sweeney
Lucent Technologies	D. Moogilan
National Institute of Standards & Technology	D. Camell
Southwest Research Institute	Vacant
	J. J. Polonis
SPAWAR - U.S. Navy	D. Southworth
	K. Rouzbehani
TUV-America, Inc.	J. Schneider
	G. Anderson
Underwriters Laboratories	M. Windler
	B. Delisi
U.S. Department Defense - Joint Spectrum Center	M. Shellman
	J. Snyder
INDIVIDUAL Member	R. Hofmann
	J. Lichtig
	W. Schaefer
	R. Showers
MEMBER EMERITUS	W. Kesselman
	H. Mertel
	N. Violette

At the time this standard was approved, Subcommittee 1 of C63 had the following membership:

Donald N. Heirman, *Chair*
Janet O'Neil, *Secretary*

Steve D. Bloom
Colin Brench
Edwin L. Bronaugh
Dennis Camell
Jon Casamento
Chris Chrysanthou
Cecil Gittens
Ross A. Hansen
H. Robert Hofmann
Daniel D. Hoolihan
James C. Klouda
Gregory A. Korytkowski
Victor Kuczynski
John F. Lichtig
Arthur Heath Light
Mirko Matejic
Herbert Mertel
Monrad Monsen
Adiseshu Nyshadham
William Rhoades
Werner Schaefer
J. B. (Bill) Scrivner
Ralph M. Showers
Jeffrey Silberberg
Douglas C. Smith
Clark Vitek
Barry Wallen
Michael J. Windler

At the time this standard was approved, members of the Task Group on Methods of Calibration of Antennas were as follows:

Donald N. Heirman, *Chair*

Dennis Camell
Zhong Chen
Charles Devor
Michael Foegelle
Robert German
Kenneth Hall
H. Robert Hofmann
Christopher L. Holloway
Michael W. Howard
Robert Johnk
Motohisa Kanda
Brian Lawrence
Paul McKenna
David Seabury
Donald Weber
L. Art Wall
Michael J. Windler

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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 C63.4-2003.[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. Normative 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 C63.2-1996, American National Standard for Electromagnetic Noise and Field Strength Instrumentation, 10 Hz to 40 GHz – Specifications.[2]

ANSI C63.4-2003, 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.

[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. (http://www.ansi.org/).

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

ANSI C63.7-2005, 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 (Reaff 2003), IEEE Standard Test Procedures for Antennas.[5, 6]

IEEE Std 291™-1991, IEEE Standard Methods for Measuring Electromagnetic Field Strength of Sinusoidal Continuous Waves, 30 Hz to 30 GHz.[7]

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][8].

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.

[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 publications are available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).
[6] The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.
[7] 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/).
[8] The numbers in brackets correspond to those of the bibliography in Annex J.

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.

3.6 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 C63.7-2005).

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 ±2dB of an ideal site when tested for site attenuation in accordance with ANSI C63.4-2003. 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 m 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.[9] 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 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 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.

[9] CISPR 16-1-1, clause 5.5.5.2.

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 C63.4-2003.

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 C63.4-2003 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 ANSI C63.4-2003. 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 ANSI C63.4-2003.

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 in this document yields near free space antenna factors. These factors shall be corrected to free space values using the correction factors provided in Table G.1. For biconical antennas, Table G.2 and Table G.3 are used to correct FSAF to take into account the different geometries used in performing NSA measurements. See Annex G or additional details.

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

Frequency [MHz]	E_D^{max} [dB(μV/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

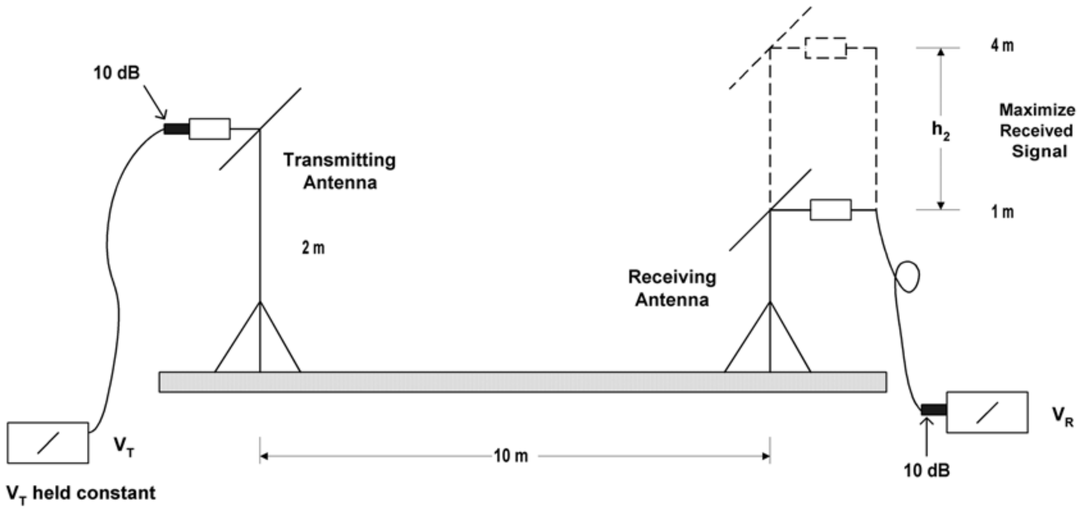
NOTE—The values of $\mathbf{E_D}^{max}$ were calculated for a metal ground plane assuming K=1, $\sigma=\infty$ (perfectly conducting) as defined in Annex A. Use Table 3 to calibrate horn antennas.[10]

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

A.1.1.1.1.1.1.1.1 R [m]	Units
h_1 [m]	≥2
h_2 [m]	≥2
f_M [GHz]	1.0-40.0
E_D^{max} [dB(μV/m)]	7.38

NOTE—E_D^{max} is defined in Annex A.

10 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 Chen and Foegelle [B2] and DiMarinis [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 Equation (1), Equation (2), and Equation (3).

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

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

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

(All equations in dB)

where

E_D^{max} is the maximum received field at separation distance R from the transmitting antenna, shown in Table 2 and Table 3, in dB (µV/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 Equation (1), Equation (2), and Equation (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:

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

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

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

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:

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

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.

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

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 Equation (4) through Equation (7) can be minimized by judicious selection of the measurement method since site attenuation is determined by measuring of the ratio V_{direct} : 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 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 C63.4-2003, 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.

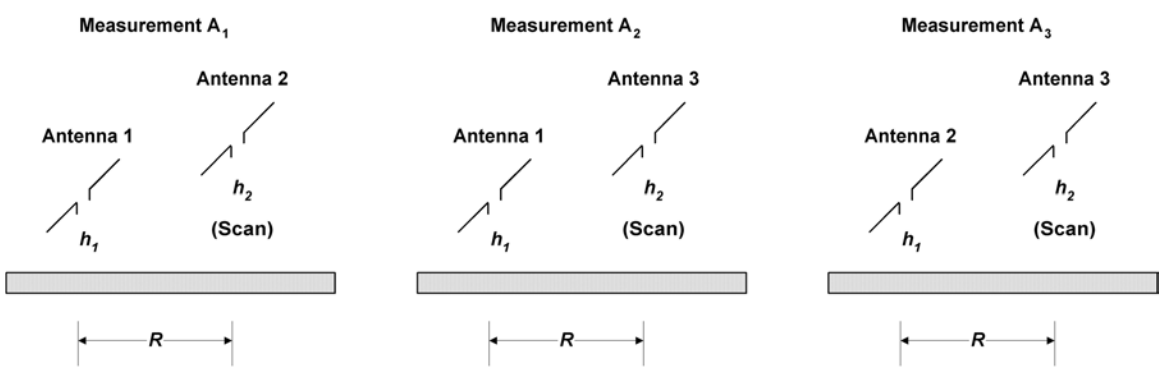


Figure 2—Three site attenuation measurements using three different antennas in pairs

5.3.1 Discrete frequency method

For the discrete frequency method, specific frequencies are measured. See Table 2 for frequencies from 30 MHz to 1000 MHz. At each frequency, the receiving antenna is scanned over the height range given in the appropriate table (Table 2 or Table 3) to maximize the received signal. These measured parameter values are inserted in Equation (4), Equation (5), and Equation (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 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 or 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 step 2) through step 4).

6) After all frequencies are measured, repeat step 2) through step 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 Equation (4) through Equation (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, σ = ∞ (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 receiving antennas are set to the required height and the frequency is scanned to obtain a stable maximum signal (spectrum analyzer "max hold").

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

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

5.3.2.1 Procedure

1) Allow the instrumentation to warm-up and stabilize 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 source at the generator output V_I, is held constant throughout the measurement.

2) Connect the transmit and receive cables directly together with a straight-through adapter and 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(μV). Ensure that the instrumentation has sufficient dynamic range available to record the difference between the direct cable measurement and the indirect measurement through the antennas (step 3). 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. This direct measurement shall be repeated anytime the temperature at the site changes by 5 °C or more.

3) At the selected separation distance and transmit height, connect the first pair of antennas via cables to their respective signal source (transmitting antenna) and receiver (receiving antenna). Raise the receiving antenna on the mast to the maximum height of the scan range. For horns, set both the transmitting and receiving antennas to the same required height.

4) Set the instrumentation to sweep the desired frequency range.

5) Slowly lower the receiving antenna to the minimum height of the scan range, allowing the instrumentation to maximize the signal at all frequencies. Ensure that the recorded maximum signal is at least 16 dB above the ambient signals and noise floor (see 4.3). Store or record the maximum received voltage display V_{site} in dB(μV).

   NOTE—For automated antenna masts, the signal can be maximized while moving from the minimum height to the maximum instead of from maximum to minimum, or during the entire motion from bottom to top and back.)

6) At each frequency, subtract the voltage measured in step 4) from the voltage measured in step 2) (all in dB). The result is the measured site attenuation over the range of frequencies used, which shall be stored.

7) Repeat step 2) through step 6) for each pair of antennas.

8) Calculate the resulting antenna factors at each frequency using Equation (4) through Equation (6) andAnnex A.

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

The Reference Antenna Method (RAM) provides a method of antenna calibration based on the use of a dipole with a well-matched balun whose construction is described in 6.2. This yields an antenna whose gain pattern and antenna factors are close to those predicted in theory.

6.1 Calibration of other antennas using the reference dipole antenna

The antenna factor of any other antenna may be derived by substitution against the reference dipole antenna. The geometry shown in Figure 3 shall be employed. The 10 m separation distance is employed to eliminate any significant antenna impedance variations caused by antenna-to-antenna mutual impedance coupling. Antenna A1 can be any type of antenna, including the reference antenna. Its purpose is to generate a field for measurement at A2. Set antenna A1 at 2.5 m to 4 m above the ground[11] and drive it with a signal generator. To calibrate the unknown antenna against the reference dipole antenna, first measure signal strength with the reference antenna at A2. The antenna 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. After the signal strength is noted with the reference dipole antenna, the antenna being calibrated shall be substituted for the reference dipole, keeping the antenna to be calibrated at exactly the same height and position, as was the reference dipole. (Scanning the receiving antennas in height while recording the maximum received voltages will facilitate the measurements, especially at higher frequencies where many peaks and nulls of the field are present.)

The ratio between the two measurements of the generated field strength is the difference (in dB) in the antenna factors 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 antenna factor of the reference antenna to obtain the antenna factor of the unknown antenna. If the signal measured with the unknown antenna is larger than the signal measured with the reference antenna, the difference shall be subtracted from the antenna factor of the reference antenna to obtain the antenna factor of the unknown antenna. Recommended frequency intervals are shown in Table 4.

The length of each element of the reference antenna and its antenna factors are tabulated versus frequency in Table 4.

[11]A lower transmitting antenna height, for example, 0.75 m may be used above approximately 500 MHz in order to reduce the number of field strength peaks and nulls.

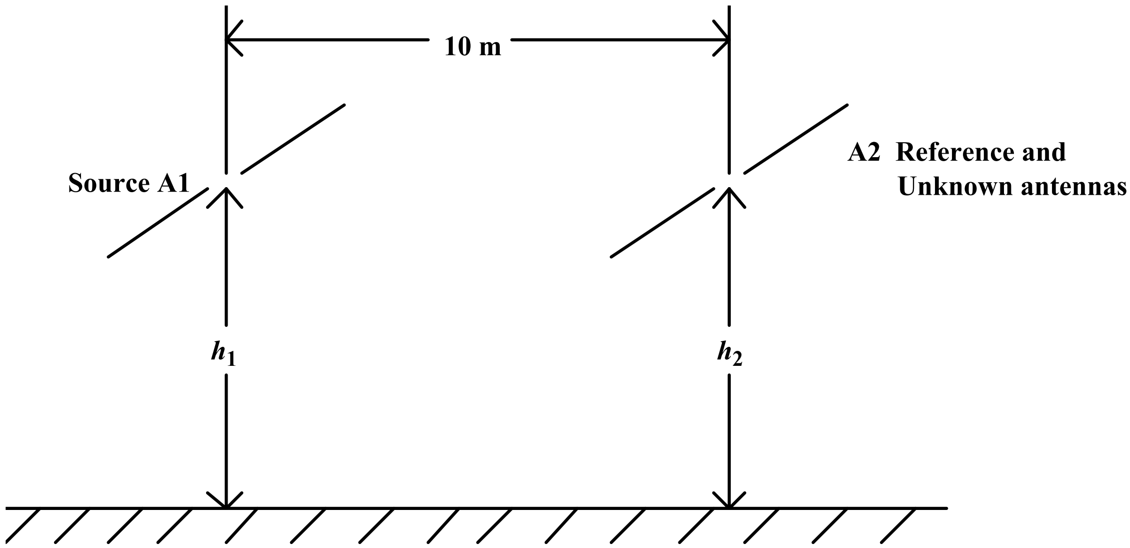


Figure 3—Geometry for calibrating antennas against the reference antenna

6.2 Description of the reference antenna

The reference antenna is a tuned, half-wavelength-resonant dipole with a series-parallel coaxial stub balun.

A four-antenna set can be used to cover the measurement range of 30 MHz to 1000 MHz. Physical construction details of the balun, antenna housings, and elements are shown in Figure E.1 through Figure E.9. (See also FCC Project 3235-16 [B4]; FCC Project 3235-33 [B5]; Roberts [B9]; Roberts [B10].) The dimensions that are electrically critical are those dimensions that influence the balun series and parallel stub construction. These dimensions are shown in Figure E.1. The baluns should be constructed from RG-58/U, RG-400 or a similar high quality 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 test shall also be performed before the baluns are installed in their housings by using the test setup of Figure E.10. The loss per balun in this test 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 will provide assurance of the 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 minimize antenna-to-ground coupling, and its elements tuned to resonance, using the measurements shown in Table 4. 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—Make sure that the reactance of the 70-Ω resistor is much smaller than its resistance.

Antenna factors for the reference antenna are tabulated in Table 4 and were computed from Equation (9), the formula for the antenna factor of a loss less dipole. This shall be combined with an averaged loss for the matching balun of 0.5 dB (FCC Project 3235-16 [B4], FCC Project 3235-33 [B5]).

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

where f_M is in MHz.

Experimental data (FCC Project 3235-33 [B5]) have shown that the antenna-to-antenna variation to be expected due to construction tolerances is of the order of ±0.3 dB.

Table 4—Length of each element of the reference dipole antenna for resonant setting and antenna factor versus frequency

Frequency MHz	Length of each antenna element measured from center of antenna			*AF* dB(1/m)
	Metric	English		
	(m)	(ft)	(in)	
30	2.413	7	11	-1.8
35	2.080	6	9-7/8	-0.5
40	1.803	5	11	0.6
45	1.600	5	3	1.7
50	1.438	4	8-5/8	2.6
60	1.197	3	11-1/8	4.2
70	1.026	3	4-3/8	5.5
80	0.889	2	11	6.7
90	0.791	2	7-1/8	7.7
100	0.714	2	4-1/8	8.6
120	0.589	1	11-1/8	10.2
140	0.500	1	7-5/8	11.5
160	0.438	1	5-1/4	12.7
180	0.389	1	3-1/4	13.7
200	0.352	1	1-7/8	14.6
250	0.283		11-7/8	16.6
300	0.235		9-1/4	18.1
400	0.175		6-7/8	20.6
500	0.143		5-5/8	22.6
600	0.117		4-5/8	24.2
700	0.102		4	25.5
800	0.089		3-1/2	26.7
900	0.079		3-1/8	27.7
1000	0.076		3	28.6

7. Equivalent capacitance substitution method

The Equivalent Capacitance Substitution Method (ECSM) shall be used to calibrate monopole antennas from 9 kHz to 30 MHz. In this method, a dummy antenna consisting of a capacitor equal to the self-capacitance of the monopole is used in place of the actual element (see 2.4 of IEEE Std 291-1991). This dummy antenna is fed by a signal generator and the output from the coupler or base unit of the antenna is measured. For a lower uncertainty, the input voltage to the dummy antenna is also measured. The antenna factor in dB(1/m) is given by Equation (10). The test configurations are shown in Figure 4.

$$AF = V_D - V_L + 6.02 \qquad (10)$$

where

V_D is the measured output of the signal generator in dB(μV)

V_L is the measured output of the coupler in dB(μV)

The factor 6.02 corrects for the effective height of the monopole (see Annex D). For practical purposes use 6.0 dB in the Equation (10), above.

NOTE—The effective height of the 1.04m monopole is 0.5 m. The value of the dummy antenna (capacitor) used with Equation (10) is 10 pF. This value is correct for the 1.04 m (41 in) monopole antennas usually used in EMC measurements. However, see Annex D to calculate the self-capacitance of monopole antennas of unusual dimensions.

Two procedures may be used - one using a signal generator and a radio-noise meter, the other using a network analyzer. The same dummy antenna (equivalent capacitance) is used in both procedures. (See Annex D for guidance in making the dummy antenna.) The measurements shall be made at a sufficient number of frequencies to obtain a smooth curve of antenna factor vs. frequency over the operating frequency range of the antenna of 9 kHz to 30 MHz, whichever is smaller.

7.1 Radio-noise meter and signal generator procedure

1) Set up the antenna to be calibrated and the test equipment as shown in Figure 4(a).

2) With the equipment connected as shown and a 50-Ω termination on the T-connector (A), measure the received signal voltage V_L in dB(μV) at the signal output port (B).

3) Leaving the RF output of the signal generator unchanged, transfer the 50 Ω termination to the signal output port (B) and transfer the receiver input cable to the T-connector (A). Measure the drive signal voltage V_D in dB(μV).

4) Subtract V_L from V_D and add 6 dB to obtain the antenna factor (in dB) of the antenna.

NOTE—The signal generator does not have to be calibrated, but it shall be stable (e.g., thermal stability attained in accordance with the equipment manufacturer instructions). The 50-Ω termination shall have low VSWR. The radio-noise meter shall be calibrated and have low VSWR.

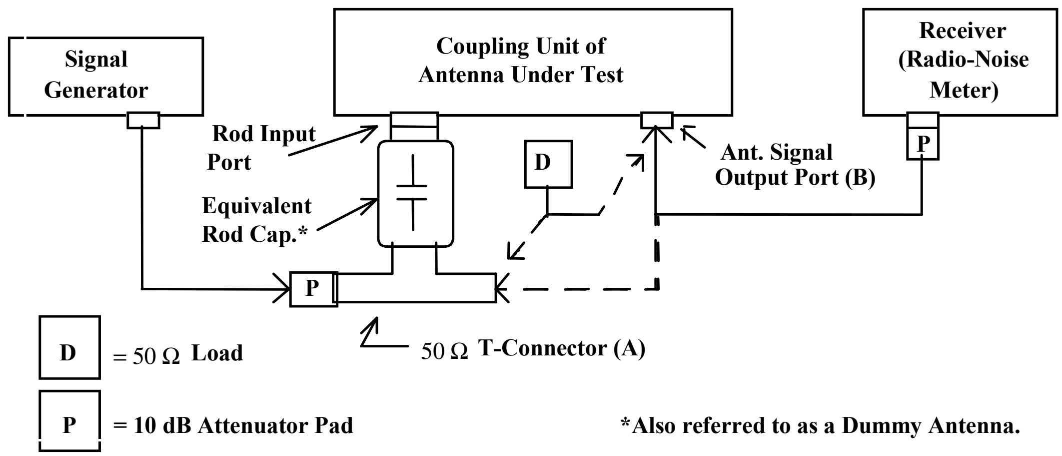
7.2 Network analyzer procedure

1) Calibrate the network analyzer with the cables to be used in the measurements.

2) Set up the antenna to be calibrated and the test equipment as shown in Figure 4(b).

3) Subtract the signal level (in dB) in the reference channel from the signal level (in dB) in the test channel and add 6 dB to obtain the antenna factor (in dB) of the antenna.

NOTE—Attenuator pads can be used with the network analyzer if long cable length causes variations in the results. If an attenuator is used, it must be accounted for in the uncertainty analysis.

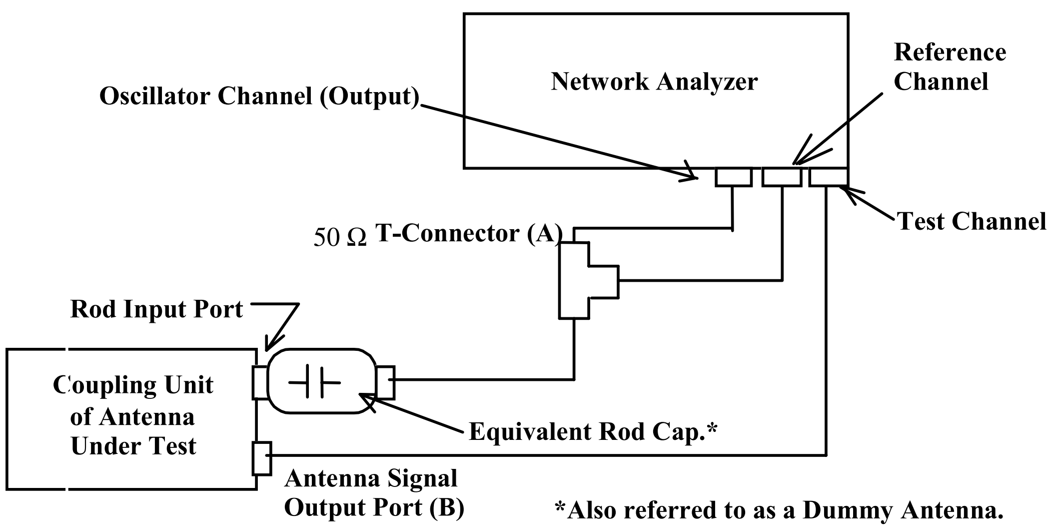


NOTE 1—If VSWR of receiver or signal generator is low, pads may not be needed or may be reduced to 6 dB or 3 dB.

NOTE 2—The T-connector may be built into the dummy antenna.

NOTE 3—The dummy antenna may incorporate other matching components to control VSWR at its input and signal generator measuring ports.

(a) Method using receiver and signal generator



NOTE 1—Attenuator pads not used with network analyzer. Place T-connector as close to dummy antenna port as possible. Use same length and type cables between T-connector and reference channel input and antenna signal output port and test channel.

NOTE 2—The T-connector may be built into the dummy antenna.

NOTE 3—The dummy antenna may incorporate other matching components to control VSWR at its reference channel and oscillator channel ports.

(b) Method using network analyzer

Figure 4—Measurement of monopole antenna factor

Annex A

(informative)

Determination of the maximum received field (Table 2 and Table 3)

For Table 2:

The following expressions for E_D^{max} are derived in Smith [B11]. Refer to Figure A.1 for the geometry.

For horizontal polarization, E_D^{max} is given by

$$E_{DH}^{\max} = \frac{\sqrt{49.2}\left\{d_2^2 + d_1^2\left|\rho_h\right|^2 + 2d_1d_2\left|\rho_h\right|\cos\left[\phi_h - \beta\left(d_2 - d_1\right)\right]\right\}^{1/2}}{d_1 d_2} \tag{A.1}$$

maximized over the interval $h_2^{min} \le h_2 \le h_2^{max}$,

where

$d_1 = [R^2 + (h_1 - h_2)^2]^{1/2}$
$d_2 = [R^2 + (h_1 - h_2)^2]^{1/2}$

$$\rho_h = \frac{\sin\gamma - \left(K - j60\lambda\sigma - \cos^2\gamma\right)^{1/2}}{\sin\gamma + \left(K - j60\lambda\sigma - \cos^2\gamma\right)^{1/2}} = \left|\rho_h\right| e^{j\varphi_h}$$

$$\gamma = \arccos\left(\frac{h_1 + h_2}{R}\right)$$

K is the relative dielectric constant of the ground plane
σ is the conductivity of the ground plane, siemens per meter (S/m)
γ is the grazing angle (see Figure A.1)
ϕ is the phase angle of reflection coefficient
$\beta = 2\pi/\lambda$
λ is the wavelength, meters

Equation (A.1) is the maximum value over the receiving antenna height scan range h_2^{min} and h_2^{max} of the space wave fields radiated by a half-wave dipole antenna emitting one picowatt of radiated power. The transmitting dipole and the receiving antenna are spaced a distance R apart, and the transmitting dipole is at height h_1.

For Table 3:

The effects of the ground plane can be verified as negligible by performing the calibration at two significantly different heights (with difference > 0.5 m or 10% of the test height, whichever is larger) and verifying that the resulting antenna factors are within the expected measurement uncertainty. For this geometry, the theoretical E_D^{max} value is used in lieu of E_D^{max} in the above equations and is given below. For horn antennas where the ground reflection is negligible or is not picked up by the antenna being calibrated, $\rho_h = 0$ and

$$E_D^{max} = 10 \log 49.2 - 20 \log R = 16.9 - 20 \log R, \text{ dB}(\mu V/m) \tag{A.2}$$

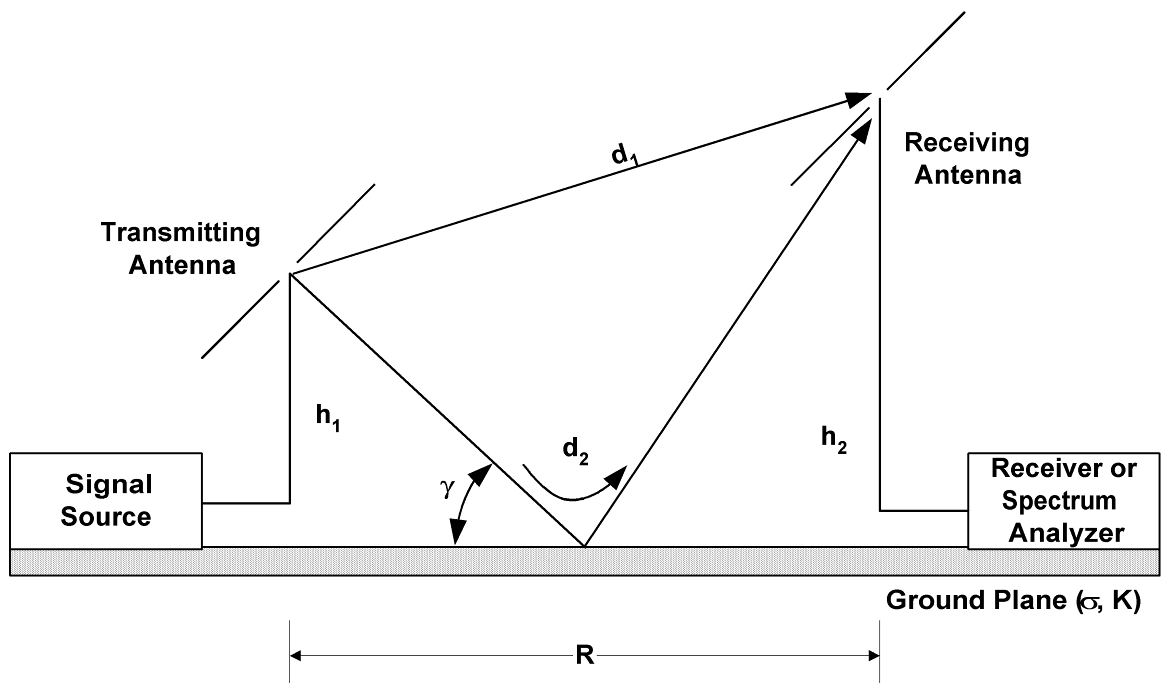


Figure A.1—Site attenuation measurement setup dipole and log-periodic antennas

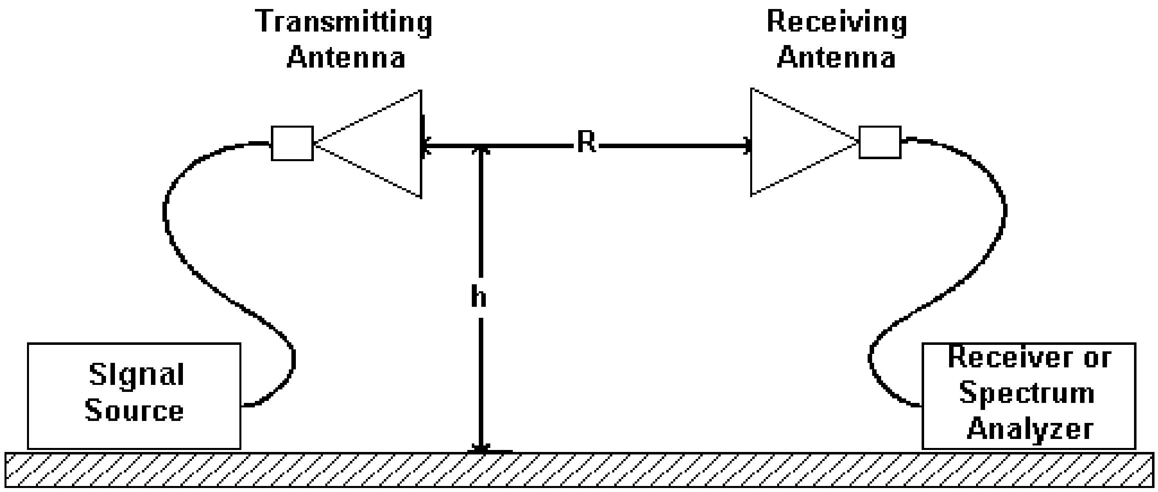


Figure A.2—Site attenuation measurement setup horn antennas

Annex B

(informative)

The discrete frequency calibration method

The discrete frequency method may be performed using a worksheet approach. The simple worksheets: (1) order the site attenuation measurements, and (2) direct the application of the simultaneous equations. Refer to Figure 2 for the measurement geometry.

Figure B.1 and Figure B.3 contain the recommended worksheets for making the necessary measurements and calculations for determining the antenna factors. The worksheet in Figure B.1 is filled out for illustrative purposes for each pairing of antennas (Figure B.2). Then the data are extracted from these worksheets to fill out the worksheet in Figure B.3. The computations in this worksheet provide the antenna factors for each of the three antenna pairs. The following is an example for using the worksheets.

Three biconical dipole antennas are to be calibrated. For the purpose of the example, data are shown at only one frequency. The usual calibration would be carried out at the number of frequencies indicated in Table 2 (Table 3 for horn antennas at 1 GHz and higher). The results are shown in Figure B.4. (The antennas could have been any three different types in their suitable frequency range; e.g., a biconical dipole, a half wavelength resonant dipole, and a broadband dipole could have been used.)

Test setup data

Frequency (f_M)	30 MHz
Spacing (R)	10 m
Source Height (h_1)	2 m
Search Height (h_2)	1-4 m

Steps (Substitution Method):

1) Allow the signal generator, amplifier or preamplifier and measuring instrument to warm up and stabilize 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.

2) A site attenuation measurement including height search for maximum signal strength is made through the antennas, and the substitution attenuators are adjusted for a reference indication on the measuring instrument. These data are then recorded on the worksheet of Figure B.1.

3) The antenna cables [each containing an in-line attenuator) are disconnected from the antennas and connected directly together. The substitution attenuators are adjusted to give the same reference indication as in step 2)], and the data are recorded on the worksheet.

4) The difference in attenuation is found by subtracting “attenuation for antenna-to-antenna mode” from the “attenuation for direct connection mode” and is recorded in the “difference” column on the worksheet.

5) Two more sets of measurements are then made, one for each of the remaining antenna pairings, and a Figure B.1 worksheet is filled out for each (see Figure B.2).

6) The numbers from the "difference" columns of each of the Figure B.1 worksheets are extracted and entered in the appropriate columns of the Figure B.3 worksheet (see Figure B.4), and the remaining steps indicated in the columns are performed to find the three antenna factors. The values of column E are obtained from Table 2 (Table 3 for horn antennas at 1 GHz and higher).

DATE: _______/____
PAGE:_____OF_____

FREQ. MHz	HEIGHT OF RECEIVING ANTENNA (m)	ATTENUATION FOR ANT. - ANT. MODE V_{site} dB	ATTENUATION FOR DIRECT CONNECTION MODE V_{direct} dB	DIFFERENCE IN DIRECT CONNECTION MODE ATTENUATION AND THE ANT. - ANT. MODE ATTENUATION, dB A_1, A_2, or A_3 (see equations (4), (5), and (6)]	ANTENNA PAIR:_______________ ANTENNA 1: ANTENNA 2: ANTENNA 3: SEPARATION DISTANCE: TRANSMIT HEIGHT:
					NOTES:
					LIST EQUIPMENT SERIAL NUMBERS

Figure B.1—Data sheet for three-antenna method for insertion loss determination

DATE: ____/____/____ PAGE:_____OF_____

FREQ. MHz	HEIGHT OF RCV. ANTENNA (m)	ATTENUATION FOR ANT. - ANT. MODE V_{site} dB	ATTENUATION FOR DIRECT CONNECTION MODE V_{direct} dB	DIFFERENCE IN DIRECT CONNECTION MODE ATTENUATION AND THE ANT. - ANT. MODE ATTENUATION, dB, A_1, A_2, or A_3 [see equations (4), (5), and (6)]	ANTENNA PAIR: 1 - 2 ________ ANTENNA 1: *Biconical (Mfg. SN)* ANTENNA 2: *Biconical (Mfg. SN)* ANTENNA 3: *Biconical (Mfg. SN)* SEPARATION DISTANCE: *10 m* TRANSMIT HEIGHT: *2 m*
30	4	37.5	101.0	63.5	NOTES:

DATE: ____/____/____
PAGE:_____OF_____

FREQ. MHz	HEIGHT OF RCV. ANTENNA (m)	ATTENUATION FOR ANT. - ANT. MODE V_{site} dB	ATTENUATION FOR DIRECT CONNECTION MODE V_{direct} dB	DIFFERENCE IN DIRECT CONNECTION MODE ATTENUATION AND THE ANT. - ANT. MODE ATTENUATION, dB, A_1, A_2, or A_3 [see equations (4), (5), and (6)]	ANTENNA PAIR: 1 - 3 ________ ANTENNA 1: *Biconical (Mfg. SN)* ANTENNA 2: *Biconical (Mfg. SN)* ANTENNA 3: *Biconical (Mfg. SN)* SEPARATION DISTANCE: *10 m* TRANSMIT HEIGHT: *2 m*
30	4	37.1	101.3	64.2	NOTES:

DATE: ____/____/____
PAGE:_____OF_____

FREQ. MHz	HEIGHT OF RCV. ANTENNA (m)	ATTENUATION FOR ANT. - ANT. MODE *V*site dB	ATTENUATION FOR DIRECT CONNECTION MODE V_{direct} dB	DIFFERENCE IN DIRECT CONNECTION MODE ATTENUATION AND THE ANT. - ANT. MODE ATTENUATION, dB, *A*1, *A*2, or *A*3 [see equations (4), (5), and (6)]	ANTENNA PAIR: 2 - 3 ________ ANTENNA 1: *Biconical (Mfg. SN)* ANTENNA 2: *Biconical (Mfg. SN)* ANTENNA 3: *Biconical (Mfg. SN)* SEPARATION DISTANCE: *10 m* TRANSMIT HEIGHT: *2 m*
30	4	36.8	101.3	64.5	NOTES:

Figure B.2—Examples of use of data sheet for insertion loss determination

DATE:____/_____/_____ SEPARATION DISTANCE: ___________

FREQ.	A	B	C	F	G	H	D	E	AF1	AF2	AF3
MHz	Attn. Data Antenna Pair 1 2 *A*1	Attn. Data Antenna Pair 1 3 *A*2	Attn. Data Antenna Pair 2 - 3 *A*3	A + B - C	A + C - B	B + C - A	10 log[F] – 24.46	E_D^{max}	$D + \frac{E+F}{2}$	$D + \frac{E+G}{2}$	$D + \frac{E+H}{2}$

NOTE—See Equations 4, 5 and 6.

Figure B.3—Three antenna method: Antenna factors computation chart

DATE:_____/_____/_____ SEPARATION DISTANCE: *10 m*__________.

FREQ.	A	B	C	F	G	H	D	E	AF_1	AF2	AF3
MHz	Attn. Data Antenna Pair 1 2 *A*1	Attn. Data Antenna Pair 1 3 *A*2	Attn. Data Antenna Pair 2 3 *A*3	A + B – C	A + C – B	B + C – A	10 log[F] – 24.46	E_D^{max}	$\boldsymbol{D + \frac{E+F}{2}}$	$\boldsymbol{D + \frac{E+G}{2}}$	$\boldsymbol{D + \frac{E+H}{2}}$
30	*63.5*	*64.2*	*64.5*	*63.2*	*63.8*	*65.2*	*–9.7*	*–22.3*	*10.8*	*11.1*	*11.8*

Figure B.4—Example of antenna factors computation chart use

Annex C

(informative)

The reference antenna

The reference antenna is a tuned, half-wavelength-resonant dipole with a series-parallel coaxial stub balun. Figure C.1(a) shows the balun structure in a pictorial way. The equivalent circuit, shown in Figure C.1(b), shows the impedances seen at the feedpoint to the balun. The shorted balanced line and the open coaxial sections appear in parallel and series with the load, respectively. The parallel section forces the load to be fed in a balanced manner. Although the use of a parallel shorted stub alone will affect a balanced to unbalanced transformation, it provides a useful match only over the narrow range where the stub presents a high impedance. The combined action of the series open stub and parallel shorted stub extends the range of approximate match. The two matching stubs are one-quarter of an electrical wavelength at the center of the frequency band in which the balun is intended to operate. At the center of this band, where both stubs are resonant, the series coaxial-line open stub looks like a short circuit, while the parallel balanced-line shorted stub looks like an open circuit. Equations for the stub impedance are

For a series stub,

$$Z_s = jZ_o \cot \theta_s \tag{C.1}$$

For a parallel stub,

$$Z_p = jZ_o \tan \theta_p \tag{C.2}$$

where

θ_s, θ_p are the electrical length of series and parallel stubs respectively, and
Z_o, Z_p are the coaxial and balanced line characteristic impedance, respectively.

Figure C.1 (c) shows how compensation occurs. Assume that the electrical angle is slightly above 90°, corresponding to a frequency slightly above stub resonance. The lag introduced by Z_s is nearly canceled by the lead produced by Z_p. At frequencies below resonance the roles of the stubs are reversed, as shown in Figure C.1 (c). It is shown in FCC Project 3235-33 [B5] that a nearly perfect match exists when Equation (C.3) is satisfied, and that a VSWR of under 1.5:1 can be expected over a frequency range of nearly 3:1.

$$\theta = \arcsin (Z_o/R_a)^{1/2} \tag{C.3}$$

where

Z_o is the characteristic impedance of the coaxial line, and

R_a is the radiation resistance of the resonant antenna.

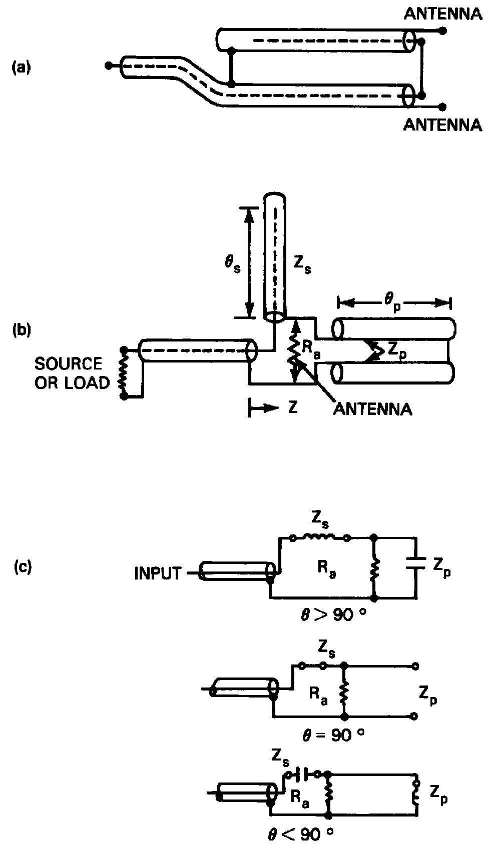


Figure C.1—Reference antenna balun construction, equivalent circuit, and explanation of compensation mechanism

Annex D

(informative)

Monopole performance equations

D.1 Effective height and self-capacitance

The following equations may be used to determine the effective height and the self-capacitance of monopole antennas of unusual dimensions. For these equations to hold, the antenna element shall be shorter than λ/4.

$$h_e = \frac{\lambda}{2\pi} \tan \frac{\pi h}{\lambda}, m \tag{D.1}$$

$$C_a = \frac{55.6h}{\ln \frac{2h}{a} - 1} \frac{\tan \frac{2\pi h}{\lambda}}{\frac{2\pi h}{\lambda}}, pF \tag{D.2}$$

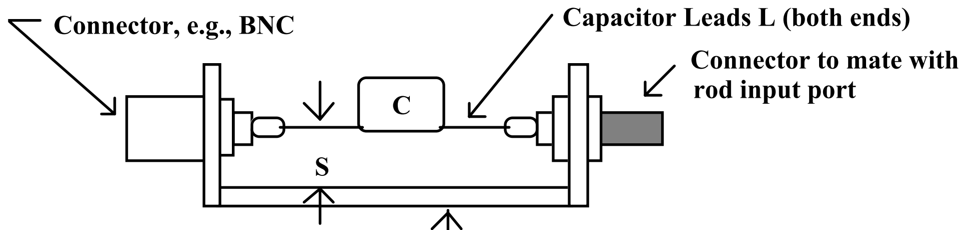
where

h_e is the effective height of the antenna, *m*
h is the actual length of the monopole element, *m*
a is the average radius of the antenna element, *m*
λ is the wavelength, *m*
C_a is the capacitance of the dummy load

D.2 Dummy antenna considerations

The capacitor used as the equivalent capacitance in the dummy antenna should be mounted in a small metal box or on a small metal frame. The leads shall be kept as short as possible and kept close to the surface of the metal box or frame. A spacing of 5 mm to 10 mm is suggested. Figure D.1 shows an example.

The T-connector used in the antenna factor measurement setup may be built into the dummy antenna box. Also, a resistor network to provide matching to the generator and the RF voltmeter (receiver) may be built into the dummy antenna box.



C: 10 pF 5 %, Silver Mica.

S: Lead Spacing, 5 to 10 mm (10 mm from all surfaces if enclosed in box).

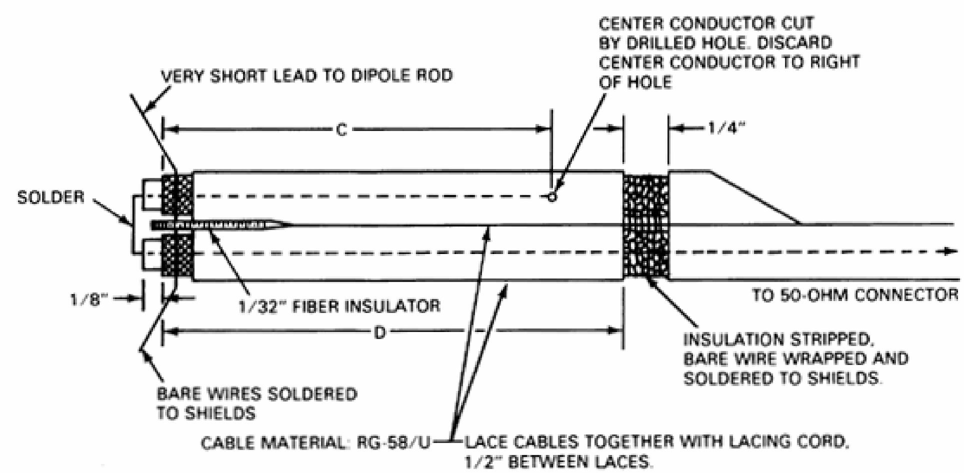
L: Lead length, as short as possible but not greater than 12 mm. (Total lead length not greater than 40 mm including both capacitor leads and length of rod port connector.)

Figure D.1—Example of mounting of capacitor in dummy antenna

Annex E

(informative)

Example drawings of reference antenna [B5]



FREQUENCY RANGE (MHz)	LENGTH C (in)	LENGTH D (in)
20-65	43.3	43.3
65-180	14.2	16.25
180-400	6.125	7.5
400-1000	2.7	3.0

Figure E.1—Reference antenna balun dimensions

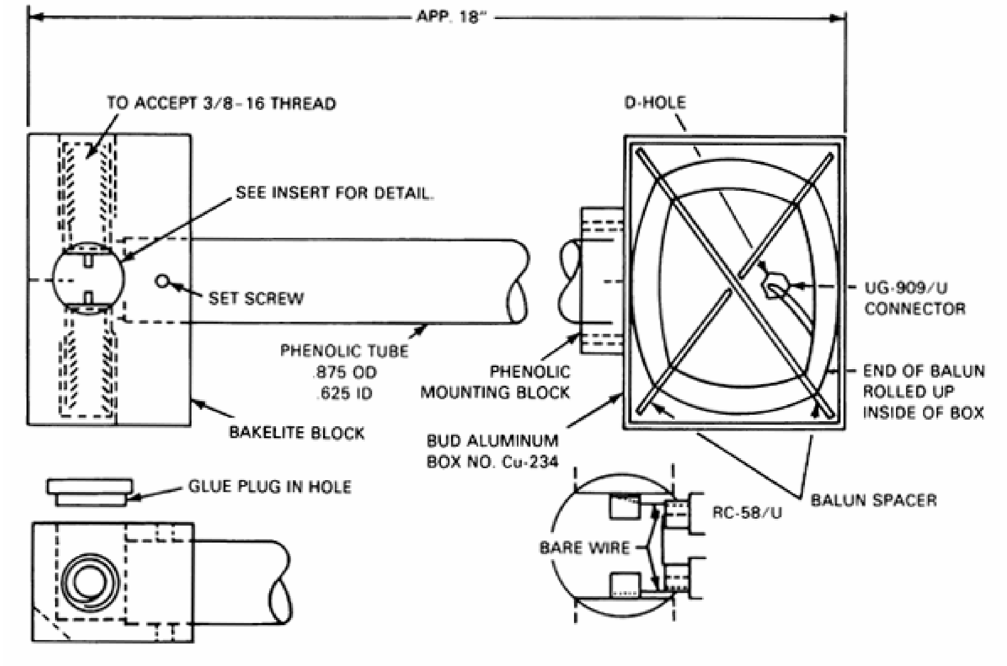


Figure E.2—20 MHz – 65 MHz reference dipole assembly (dimensions in inches)

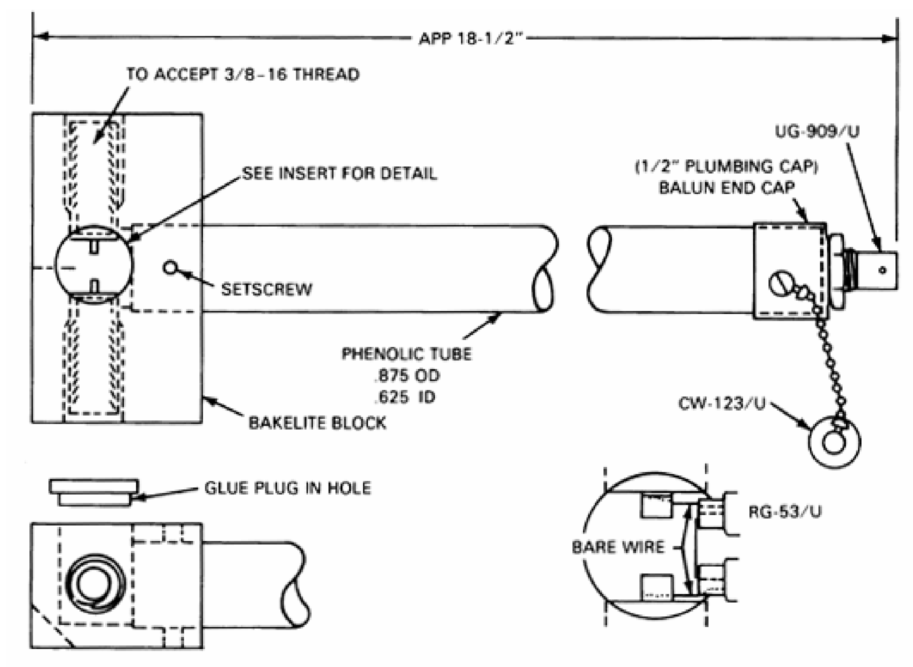


Figure E.3—65 MHz–180 MHz and 180 MHz–400 MHz reference dipole assembly (dimensions in inches)

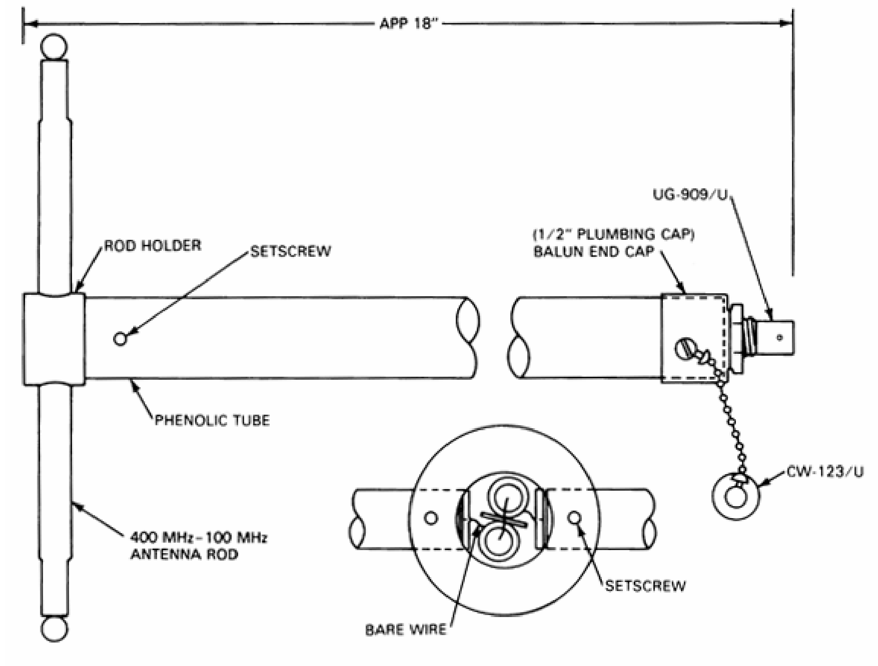


Figure E.4—400 MHz–1000 MHz reference dipole assembly

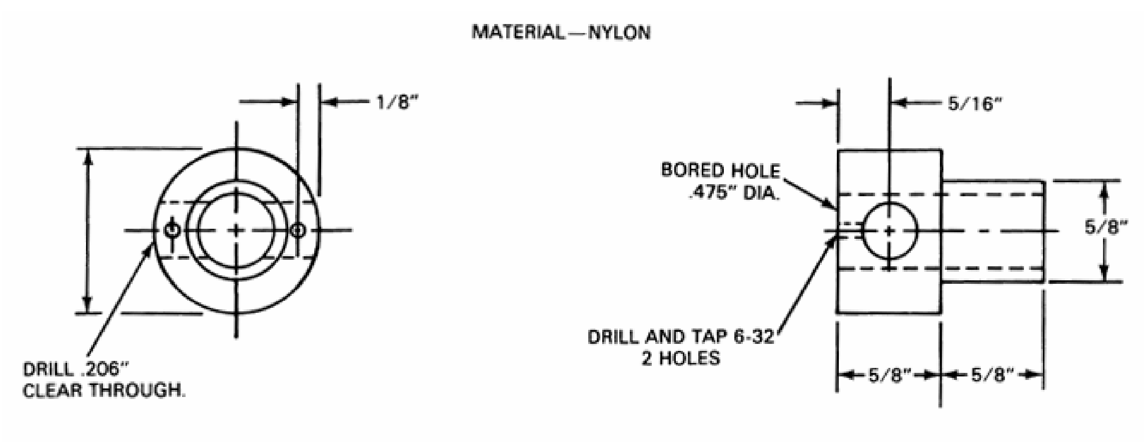


Figure E.5—Dipole rod holder, 400 MHz–1000 MHz

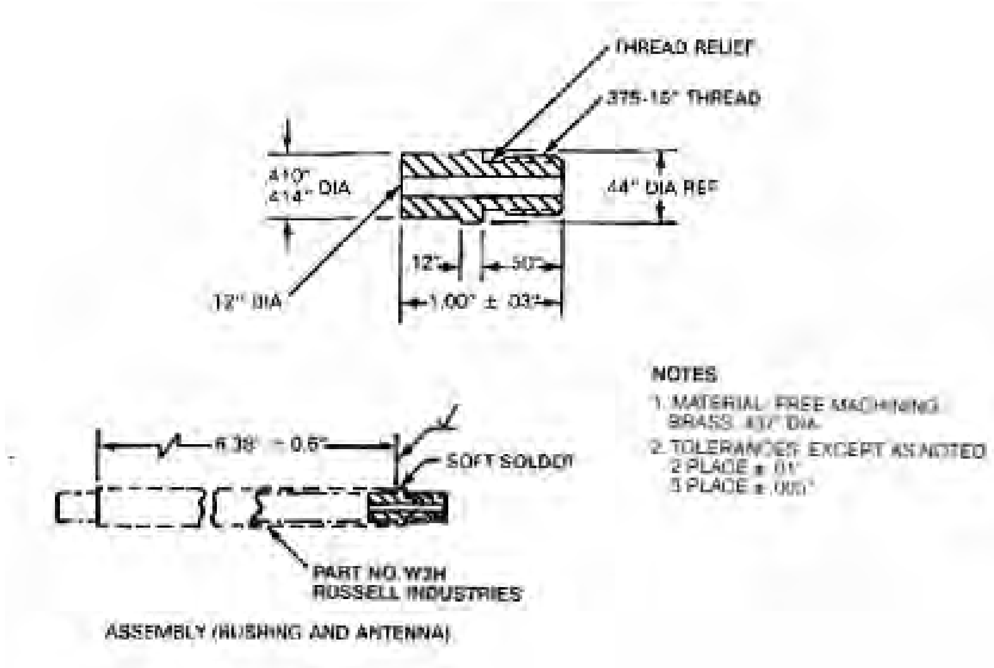


Figure E.6—Antenna rods, 65 MHz–180 MHz

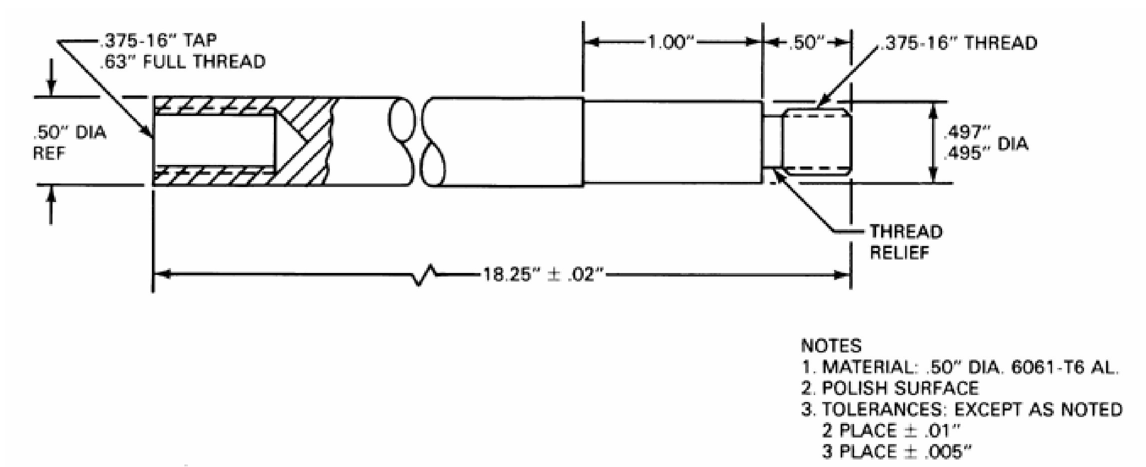


Figure E.7—Antenna rod extenders, 25 MHz–65 MHz

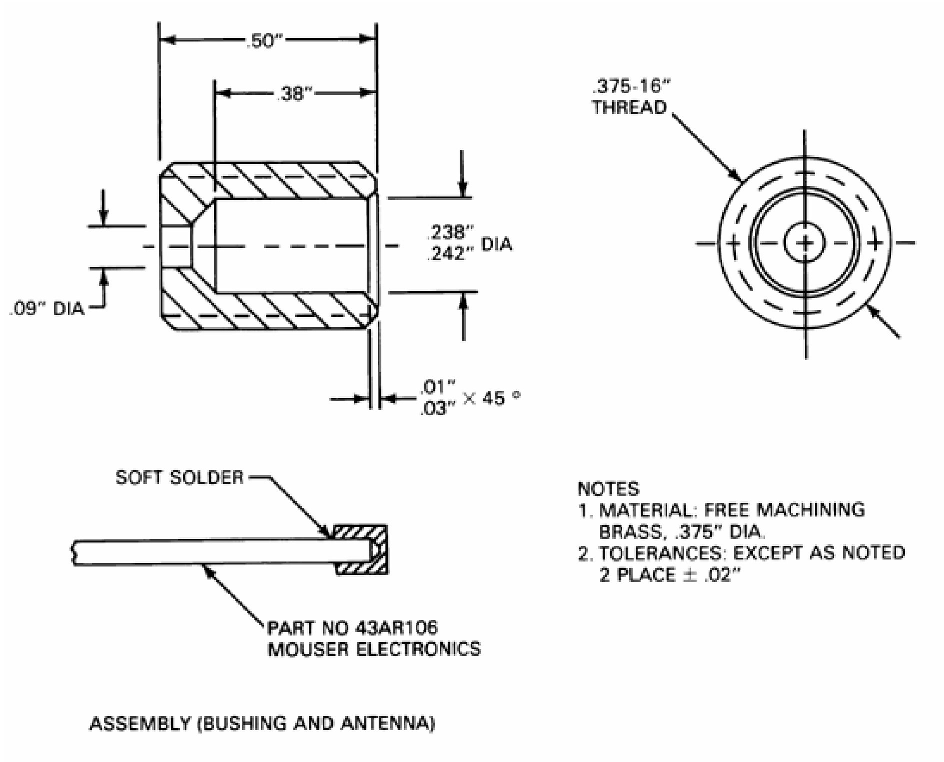


Figure E.8—Antenna rods, 180 MHz–400 MHz

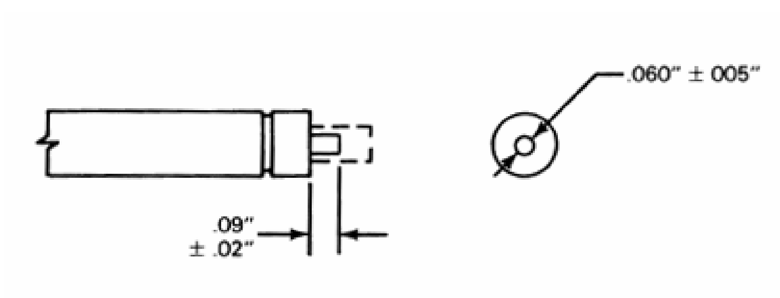
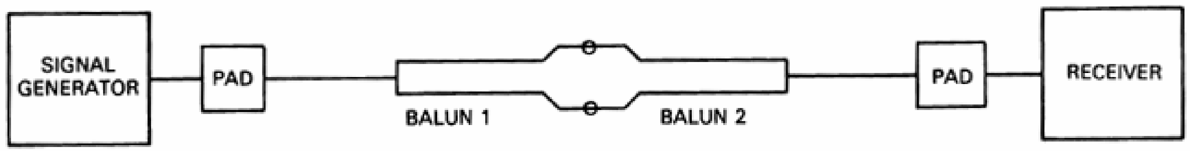


Figure E.9—Antenna rods, 400 MHz–1000 MHz



NOTE: All cabling and instrumentation are 50 Ω impedance. Use shortest possible connections between baluns.

Figure E.10—Pre-assembly balun loss check

Annex F

(informative)

Rationale for geometry-specific correction factors for biconical dipoles used in the normalized site attenuation test

F.1 General

The theoretical site-attenuation model described in ANSI C63.4-2003 assumes that both antennas are electrically short dipoles and that the receive antenna is in the far field of the transmit antenna. Hence, the $1/r^2$ and $1/r^3$ radiation terms, mutual coupling between the antennas, mutual coupling between the antennas and the ground plane, the actual radiation patterns of the antennas, and non-uniform illumination of the receive antenna are neglected [B14, B15]. These approximations result in the following errors when using biconical dipole antennas from 30-200 MHz with a separation distance (R), transmit antenna height (h_1), and receive antenna height (h_2) scanned from 1 to 4 m:

Table F.1—Example error values associated with biconical dipole antennas used in normalized site attenuation measurements

Polarization	R (m)	h_1 (m)	Error (dB)
Horizontal	3	1.0	2.00
Horizontal	3	2.0	1.76
Vertical	3	1.0	1.83
Vertical	3	1.5	2.39
Horizontal	10	1.0	1.24
Horizontal	10	2.0	0.98
Vertical	10	1.0	1.47
Vertical	10	1.5	1.17

These errors can be removed using the correction factors in Annex G.

The NSA equation provided in ANSI C63.4-2003, Equation (F.1) below, includes a variable ΔAF_{TOT}.

$$A_N = V_{Direct} - V_{Site} - AF_T - AF_R - \Delta AF_{TOT} \quad \text{(F.1)}$$

The term ΔAF_{TOT} was originally defined to correct only for mutual coupling of two dipole antennas used in the NSA test at a three-meter measurement distance. However, other effects have been found that warrant consideration and must be included for certain antennas and geometries. This refinement requires a redefinition and renaming of this correction term to cover all effects. GSCF will be used in place of ΔAF_{TOT} for this correction term giving:

$$A_N = V_{Direct} - V_{Site} - FSAF_T - FSAF_R - GSCF \quad \text{(F.2)}$$

Brief outlines of the effects studied are given below with the details constrained to the references. Several of these effects are interrelated.

F.2 Ground plane effects

A ground plane is intended to provide a consistent reflection surface during product measurements. The coupling of the antenna to the ground plane is a function of the antenna height above the ground plane, ground plane conductivity, antenna polarization, and its construction features. During the NSA test the transmitting antenna is 1 m, 1.5 m, or 2 m above the ground plane and either vertically or horizontally polarized. This difference in height causes changes in the transmitting antenna's impedance resulting in AF variations. Consequently, the correction factor will need to vary depending on the geometry of the test and the frequency of interest.

F.3 Mutual coupling

Another coupling effect occurs between the transmitting antenna and receiving antenna. This mutual coupling effect is a function of the antenna construction features and the measurement distance between the transmitting and receiving antennas. This effect varies as the receiving antenna is scanned from 1 m to 4 m. This effect is more significant at a 3 m separation distance than at a 10 m separation distance.

F.4 Dipole pattern

The ideal values provided in ANSI C63.4-2003 for the NSA test are based on a theoretical antenna. This theoretical antenna is infinitely small and transmits in a perfect dipole pattern at all frequencies. A broadband antenna's ohmic construction features and the frequencies at which it is used will affect the degree to which it approximates a dipole antenna pattern.

F.5 Plane wave illumination

Another assumption in the theoretical model of the ideal test site used in ANSI C63.4-2003 is that the receiving antenna will always be illuminated by a uniformly polarized plane wave. The degree to which this assumption is valid depends on the pattern of the transmitting antenna and the effect of the ground plane on the polarization of the reflected wave. The field strength at the receiving antenna is a vector sum of the direct wave and ground-plane reflected wave from the transmitting antenna. This vector sum can change rapidly with small changes in geometry and with it the uniformity of the electromagnetic fields over the surface of the receiving antenna. In general, the greater the measurement distance, the closer to a plane wave illumination the receiving antenna will experience.

F.6 Near field effects

The ideal NSA values in ANSI C63.4-2003 also assume the receiving antenna is in the far field of the transmitting antenna. At those distances the E-field falls off as an inverse function of R (distance). If the transmitting and receiving antennas are relatively close to each other as compared to the wavelength of the transmitting signal there are additional $1/r^2$ and higher-order terms that are not included in ANSI C63.4-2003. These additional terms due to near field effects will adversely affect the results and are frequency dependent.

F.7 Summary

The aforementioned effects have a significant adverse effect on the measurement accuracy during antenna calibrations and NSA evaluations. Numerical modeling studies (Stecher [B15]) and empirical validation studies (Smith [B14]) have quantified these effects to be as large as 2.6 dB for 200 Ω biconical dipole antennas and 2.3 dB for 50 Ω biconical dipole antennas.

Annex G

(normative)

Biconical dipole antenna correction factors (30 – 200 MHz) for calibration and normalized site attenuation

Near free-space antenna factors can be obtained for biconical dipole antennas from 30 MHzto 200 MHz using the methods specified in this standard. However, the approximations inherent in the SSM can result in antenna-factor errors as large as 0.49 dB. These approximations can also result in NSA errors as large as 2.39 dB when verifying the performance of a radiated emissions test-site. A wire-based moment method Numerical Electromagnetic Code (NEC 2) has been used to calculate Geometry-specific Correction Factors (GSCF) to correct for these errors. This code modeled a biconical dipole antenna with the dimensions shown in Figure G.1. Figure G.2 provides guidance on the application of these correction factors.

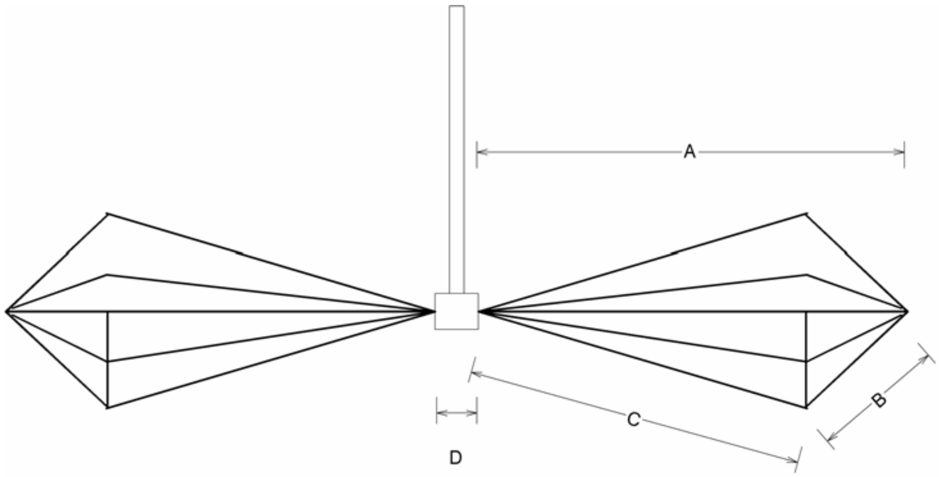
The value of the correction factors depends on test distance, frequency, and impedance of the antenna balun. Computed AF curves of biconical dipole antennas using 50 Ω and 200-Ω baluns are shown in Figure G.3.

Table G.1 contains the correction factors to free space (ΔAF) for a biconical dipole antenna. This table is necessary for biconical dipole antenna calibrations using the standard site method in a test setup with horizontal polarization, R=10 m, h_1=2 m, and h_2=1 m to 4 m. These correction factors shall be subtracted from the measured near free space antenna factor developed from the SSM.

Antenna Factor recorded (SSM) - ΔAF (Table G.1) = FSAF, dB. (G.1)

Table G.2 and Table G.3 contain the correction factors (GSCF) for a pair of biconical dipole antennas when used in a NSA evaluation of a site in accordance with ANSI C63.4-2003. Table G.2 and Table G.3 assume the transmitting and receiving antennas have already been calibrated to free space values. These correction factors (GSCF) shall be subtracted from the measured normalized site attenuation as shown in the revised NSA equation

$A_N = V_{Direct} - V_{Site} - FSAF_T - FSAF_R – GSCF$ (G.2)



Dimension	Original MIL STD 461A -cm (in.)	Minimum - cm (in.)	Maximum - cm (in.)
A	60.6 (23-7/8)	60.0 (23-5/8)	64.3 (25-5/16)
B	28.7 (11-5/16)	28.0 (11)	30.0 (11-13/16)
C	50.2 (19-3/4)	52.5 (20-2/3)	54.0 (21-1/4)
D	12.7 (5)	4.0 (1-3/4)	13.0 (5-1/8)

Figure G.1—Dimensions of biconical dipole antennas evaluated for numerical correction

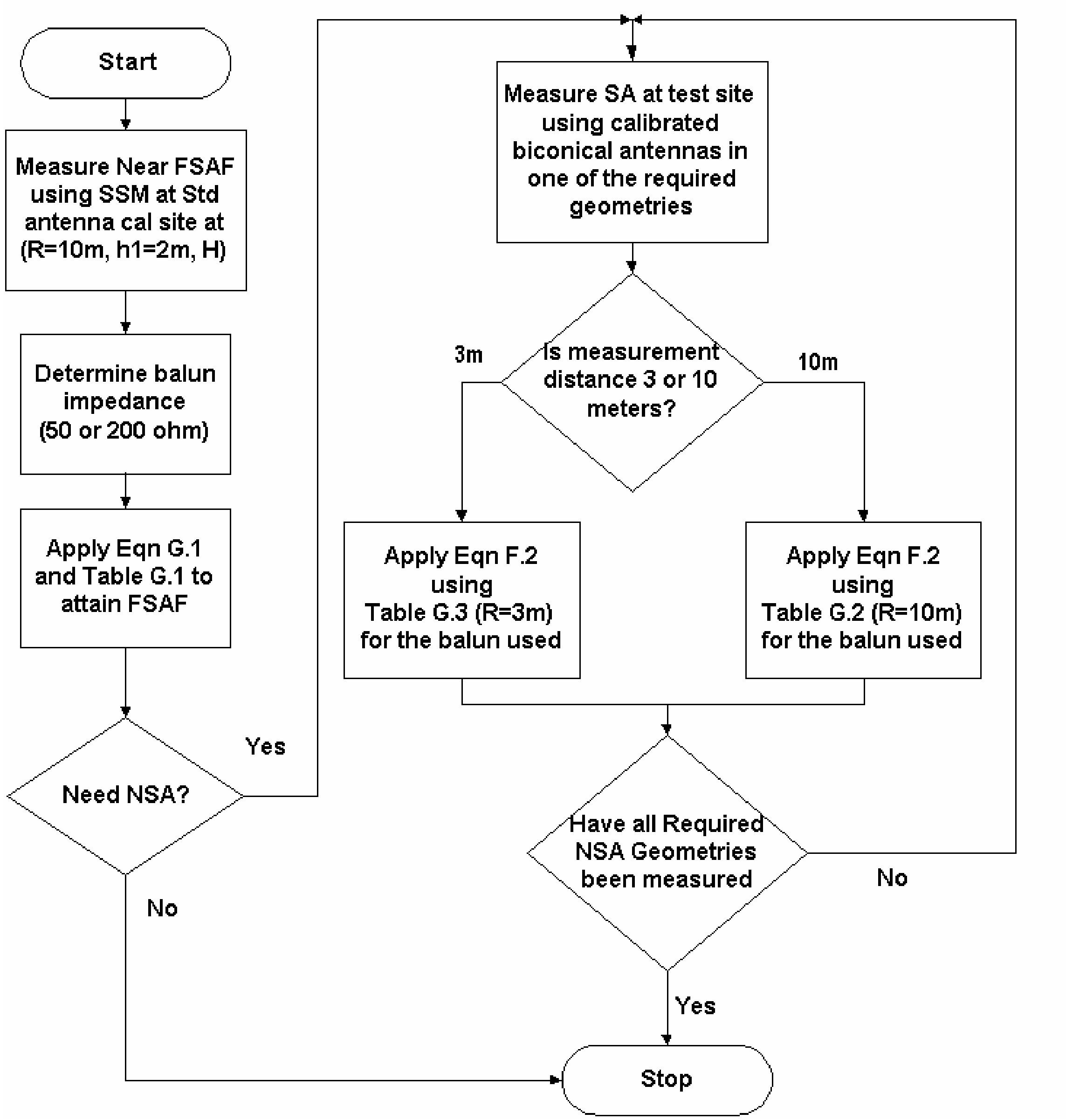


Figure G.2—Biconical dipole antenna usage flow chart

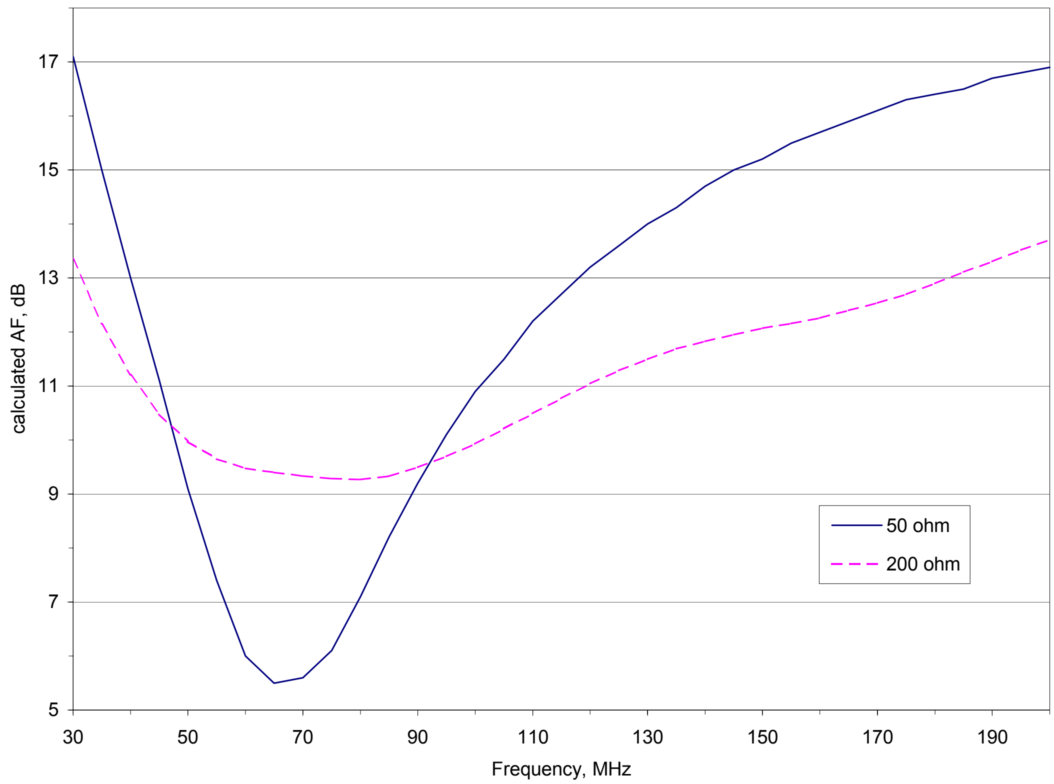


Figure G.3—Computed AF curves of biconical dipole antennas using 50 Ω and 200 Ω baluns

Table G.1—Correction factors to free space (ΔAF) for a biconical dipole antenna calibrated using SSM horizontal polarization with R=10 m, h_1=2 m, h_2=1-4 m scan.

Frequency MHz	50 Ω Balun dB	200 Ω Balun dB
30	0.13	0.15
35	0.09	0.11
40	0.06	0.08
45	0.02	0.06
50	0.03	0.07
55	0.13	0.11
60	0.37	0.17
65	0.49	0.20
70	0.25	0.16
75	-0.14	0.05
80	-0.45	-0.08
85	-0.44	-0.17
90	-0.34	-0.19
95	-0.21	-0.18
100	-0.06	-0.16
105	0.05	-0.10
110	0.13	-0.04
115	0.19	0.03
120	0.20	0.10
125	0.17	0.12
130	0.13	0.13
135	0.07	0.11
140	-0.01	0.07
145	-0.06	0.00
150	-0.11	-0.07
155	-0.13	-0.14
160	-0.12	-0.21
165	-0.10	-0.24
170	-0.06	-0.25
175	0.00	-0.24
180	0.05	-0.18
185	0.09	-0.12
190	0.12	-0.05
195	0.14	0.03
200	0.15	0.08

NOTE—Computed for biconical dipole antennas with standard cage elements using NEC. These correction factors account for the effects of non-plane wave illumination of receive antenna, direct mutual coupling between transmit and receive antenna and mutual coupling between the antennas and their images in the ground plane.

Table G.2—Correction factors (GSCF) for NSA using Two biconical dipole antennas with R = 10 m, h_2 = 1-4 m scan.

	50 Ω Balun				200 Ω Balun			
	Horizontal	Horizontal	Vertical	Vertical	Horizontal	Horizontal	Vertical	Vertical
Frequency	h_1 = 1.0 m	h_1 = 2.0 m	h_1 = 1.0 m	h_1 = 1.5 m	h_1 = 1.0 m	h_1 = 2.0 m	h_1 = 1.0 m	h_1 = 1.5 m
MHz	dB	dB	dB	dB	dB	dB	dB	dB
30	0.30	0.26	-0.72	-0.40	0.31	0.30	-0.38	-0.17
35	0.18	0.18	-0.77	-0.41	0.18	0.22	-0.29	-0.09
40	-0.01	0.12	-0.75	-0.34	0.03	0.16	-0.14	0.03
45	-0.32	0.04	-0.57	-0.15	-0.12	0.12	0.05	0.17
50	-0.71	0.06	-0.15	0.19	-0.23	0.14	0.25	0.30
55	-0.93	0.26	0.52	0.65	-0.22	0.22	0.44	0.40
60	-0.60	0.74	1.33	1.17	-0.10	0.34	0.60	0.48
65	0.16	0.98	1.47	0.99	0.06	0.40	0.70	0.50
70	0.67	0.50	1.41	0.63	0.16	0.32	0.73	0.48
75	0.76	-0.28	1.14	0.29	0.18	0.10	0.71	0.44
80	0.73	-0.90	0.76	0.01	0.18	-0.16	0.65	0.36
85	0.90	-0.88	0.50	-0.06	0.24	-0.34	0.57	0.29
90	1.13	-0.68	0.22	-0.14	0.40	-0.38	0.50	0.23
95	1.24	-0.42	0.01	-0.15	0.61	-0.36	0.40	0.16
100	1.14	-0.12	-0.11	-0.12	0.77	-0.32	0.31	0.13
105	0.84	0.10	-0.25	-0.13	0.80	-0.20	0.23	0.11
110	0.47	0.26	-0.33	-0.12	0.70	-0.08	0.14	0.08
115	0.19	0.38	-0.36	-0.08	0.53	0.06	0.08	0.08
120	0.04	0.40	-0.39	-0.06	0.39	0.20	0.02	0.09
125	0.03	0.34	-0.37	-0.02	0.33	0.24	-0.03	0.08
130	0.04	0.26	-0.31	0.03	0.37	0.26	-0.05	0.10
135	-0.03	0.14	-0.26	0.06	0.40	0.22	-0.05	0.13
140	-0.19	-0.02	-0.19	0.10	0.35	0.14	-0.05	0.13
145	-0.39	-0.12	-0.09	0.14	0.19	0.00	-0.01	0.16
150	-0.57	-0.22	-0.01	0.16	-0.06	-0.14	0.04	0.19
155	-0.63	-0.26	0.07	0.19	-0.32	-0.28	0.07	0.19
160	-0.58	-0.24	0.17	0.22	-0.47	-0.42	0.13	0.22
165	-0.50	-0.20	0.24	0.24	-0.54	-0.48	0.19	0.24
170	-0.41	-0.12	0.32	0.27	-0.59	-0.50	0.24	0.25
175	-0.32	0.00	0.39	0.30	-0.62	-0.48	0.29	0.27
180	-0.24	0.1	0.45	0.32	-0.65	-0.36	0.35	0.30
185	-0.24	0.18	0.51	0.35	-0.68	-0.24	0.39	0.31
190	-0.25	0.24	0.56	0.38	-0.66	-0.10	0.43	0.34
195	-0.20	0.28	0.60	0.41	-0.76	0.06	0.48	0.36
200	-0.13	0.30	0.63	0.43	-0.69	0.16	0.49	0.37

NOTE—Calculated for biconical dipole antennas with standard cage elements using NEC. These correction factors account for the effects of non-plane wave illumination of receive antenna, direct mutual coupling between transmit and receive antenna and mutual coupling between the antennas and their images in the ground plane.

Table G.3—Correction factors (GSCF) for NSA using two biconical dipole antennas, R = 3 m, h_2 = 1-4 m scan.

	50 Ω Balun				200 Ω Balun			
	Horizontal	Horizontal	Vertical	Vertical	Horizontal	Horizontal	Vertical	Vertical
Frequency	h_1 = 1.0 m	h_1 = 2.0 m	h_1 = 1.0 m	h_1 = 1.5 m	h_1 = 1.0 m	h_1 = 2.0 m	h_1 = 1.0 m	h_1 = 1.5 m
MHz	dB	dB	dB	dB	dB	dB	dB	dB
30	1.99	1.73	-0.19	-0.26	2.00	1.76	0.16	-0.02
35	1.42	1.24	-0.46	-0.46	1.44	1.29	0.04	-0.14
40	1.01	0.97	-0.58	-0.52	1.06	1.03	0.05	-0.15
45	0.63	0.89	-0.49	-0.42	0.76	0.91	0.14	-0.09
50	0.16	0.99	-0.09	-0.11	0.52	0.85	0.28	-0.02
55	-0.28	1.19	0.61	0.37	0.34	0.82	0.42	0.04
60	-0.51	1.18	1.37	0.76	0.22	0.76	0.53	0.05
65	-0.38	0.69	1.79	0.79	0.18	0.65	0.58	0.02
70	0.04	-0.05	1.83	0.55	0.20	0.49	0.59	-0.04
75	0.53	-0.55	1.63	0.28	0.27	0.31	0.58	-0.11
80	0.91	-0.68	1.29	0.02	0.37	0.14	0.54	-0.19
85	1.12	-0.66	0.84	-0.27	0.49	0.01	0.48	-0.27
90	1.18	-0.61	0.36	-0.55	0.61	-0.05	0.39	-0.37
95	1.13	-0.54	-0.07	-0.76	0.71	-0.06	0.27	-0.47
100	1.00	-0.42	-0.39	-0.89	0.78	-0.03	0.13	-0.58
105	0.84	-0.25	-0.58	-0.96	0.80	0.04	-0.02	-0.69
110	0.69	-0.07	-0.68	-0.99	0.79	0.13	-0.16	-0.79
115	0.54	0.10	-0.71	-1.03	0.74	0.23	-0.27	-0.88
120	0.43	0.20	-0.71	-0.39	0.66	0.35	-0.36	-0.29
125	0.35	0.22	-0.70	0.39	0.58	0.45	-0.42	0.47
130	0.28	0.15	-0.70	1.14	0.49	0.53	-0.46	1.20
135	0.22	0.03	-0.69	1.80	0.41	0.55	-0.49	1.72
140	0.09	-0.14	-0.69	1.86	0.34	0.49	-0.53	1.81
145	0.00	-0.31	-0.70	1.91	0.27	0.35	-0.57	1.89
150	-0.06	-0.46	-0.71	1.94	0.19	0.15	-0.64	1.95
155	-0.07	-0.55	-0.75	1.97	0.09	-0.13	-0.72	1.99
160	-0.04	-0.55	-0.80	2.00	-0.03	-0.40	-0.83	2.02
165	0.02	-0.48	-0.89	2.04	-0.19	-0.61	-0.96	2.04
170	0.07	-0.36	-1.00	2.09	-0.35	-0.70	-1.11	2.08
175	0.14	-0.22	-1.16	2.14	-0.49	-0.68	-1.28	2.13
180	0.21	0.13	-1.20	2.19	-0.59	-0.36	-1.33	2.18
185	0.31	0.53	-0.64	2.21	-0.64	0.13	-0.76	2.23
190	0.39	0.64	-0.12	2.23	-0.58	0.48	-0.24	2.27
195	0.49	0.73	0.36	2.28	-0.45	0.71	0.25	2.33
200	0.59	0.79	0.80	2.35	-0.24	0.89	0.69	2.39

NOTE—Calculated for biconical dipole antennas with standard cage elements using NEC. These correction factors account for the effects of non-plane wave illumination of receive antenna, direct mutual coupling between transmit and receive antenna and mutual coupling between the antennas and their images in the ground plane.

Annex H

(normative)

Procedure for measuring geometry-specific correction factors for broadband antennas and reference-site requirements

This annex describes the measurement procedure and reference site requirements in order to measure Geometry-specific Correction Factors (GSCF) for a pair of antennas intended to be used in NSA testing. Use of this annex assumes the user cannot apply the calculated GSCFs in Annex G. For example, calculated GSCFs have not yet been developed for hybrid broadband antennas and therefore this Annex would apply.

Near free-space antenna factors can be obtained for log-periodic, biconical dipole and linearly polarized hybrid antennas using the methods specified in this standard. Although the approximations inherent in the SSM can result in antenna-factor errors, these errors are considered negligible when the antennas are used to perform radiated emission measurements as specified in ANSI C63.4–2000. Calculated GSCF for log-periodic and linearly polarized hybrid antennas would be useful for correcting SA measurements, however the complex geometries of these antennas make these factors difficult to compute. Hence, this Annex provides an alternate method to obtain GSCFs. This method does not improve the accuracy of the near free-space antenna factors used to perform radiated emissions measurements; therefore, GSCF shall not be used to adjust these antenna factors. However, it does provide accurate reference SA measurements to which the radiated emissions test site SA can be compared (Taggart and Workman [B16]). The tables of correction factors for biconical dipole antennas are provided in Annex G and shall be used unless the biconical dipole antenna being used does not meet the dimension criteria in Figure G.1 or otherwise varies from the modeled biconical dipoles. The procedure described in this annex was used to validate the modeled correction factors provided in Annex G.

H.1 Measurement procedure summary

Three steps are needed to ensure the quality of the Standard Antenna Calibration Site (SACS). First, the calibration site shall meet the SA requirements of ANSI C63.4-2003 using biconical dipole antennas or dipole antennas. Second, the site shall meet the construction guidelines of ANSI C63.7-2005 and this annex. Third, the site shall comply with the statistical criteria described in this annex.

Two measurements are needed to determine GSCF for a pair of antennas: (1) measure the SA in the near-free-space geometry and (2) measure the SA in any additionally required geometry. These SA values are applied as shown in Equation (H.1).

$$\mathrm{GSCF} = [E_d^{max}{}_{GS} + A_{GS}] - [E_d^{max}{}_{NFS} + A_{NFS}] \qquad \text{(H.1)}$$

where

A = site attenuation at SACS for specified geometry
E_d^{max} = computed maximum E-field for a specified geometry (Annex A)

To achieve the greatest possible accuracy, the same antennas, antenna masts, cables and instrumentation shall be used for both the SACS and the radiated emissions test-site measurements. Moreover, the placement of the cables, positions of the ferrite cores, and locations where the cables penetrate the ground plane shall be similar on the SACS and the emissions test-site.

H.2 SACS requirements

SACS used for geometric specific antenna calibrations shall comply with the guidelines in ANSI C63.7-2005. The site shall be void of buildings, electric lines, fences, trees, underground cable, pipelines, etc., except as required to perform the test. In addition, the reference SACS shall meet the following requirements:

1) The ground plane shall be of metal with no holes or gaps larger than 3 cm (1/10 λ at 1000 MHz) in any dimension.
2) The ground plane shall be electrically continuous and shall be flat (e.g., unevenness: within ±4 cm.) Any welds and joints in the ground plane should be staggered.
3) The ground plane shall be at least 20 m wide by 30 m long.
4) The SACS shall not include a weather protection enclosure.
5) There shall be no objects including standing trees within 10 m of every edge of the ground plane.
6) The measuring instrumentation shall be located under the ground plane or at least 20 m from every edge of the ground plane.
7) Temperature variance during measurements shall be less than 5 °C between direct measurements. This includes all cables.

Relatively low ambient noise levels are recommended to achieve the recommended 16 dB signal-to-noise ratios. Lower site attenuation deviations from ideal are also recommended.

H.3 Measurement configuration

Prior to beginning the measurement set up take the following steps:

1) Distinguish between transmit and receive antennas. Mark the antennas for future reference.
2) Determine and mark the direction of each antenna's elements for horizontal and vertical polarization shown below as an example in Figure H.1.
3) The same antenna element setup condition must be applied at the SACS and the qualifying site measurement.

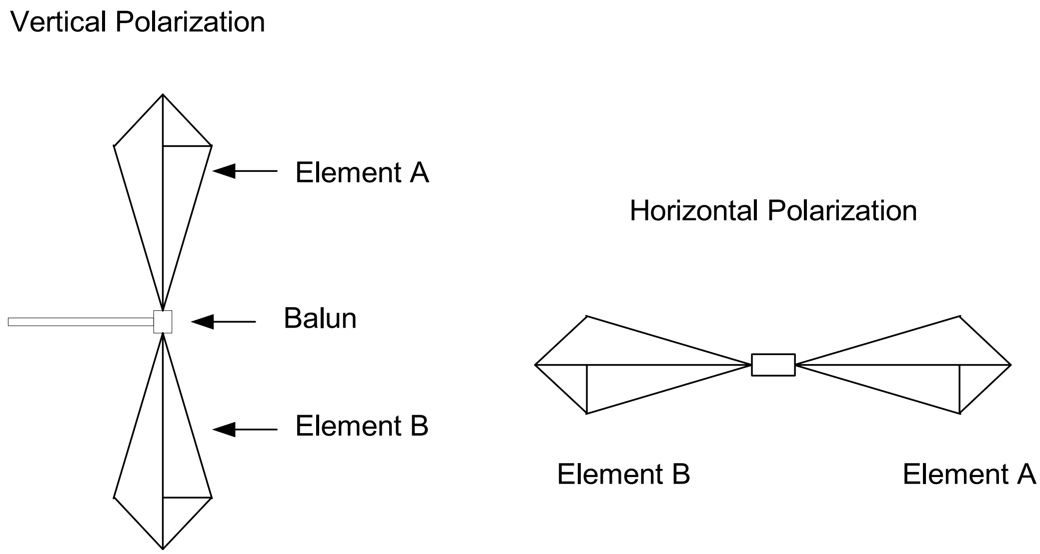


Figure H.1—Example of antenna polarization designations

H.3.1 Cables

Cable location (lie) for transmit and receive antenna shall be in accordance with Figure H.2. Cables shall be matched to 50 Ω, relatively low loss and adequately shielded against leakage (i.e., > 100 dB at 1 GHz) such as RG-214/U or better. The following steps shall be taken to reduce undesired effects such as secondary radiation and mutual coupling between antenna and the attached cable.

Care should be taken to ensure the cable drape (e.g., lay of the cable on the ground plane) is consistent between measurements

Ferrite cores properly sized to fit the cable used (e.g., minimum air gap between core and cable) shall be attached approximately every 20 cm to the cables as noted below and in Figure H.3.

Length of the transmitting antenna Cable: > 4 m (2 m horizontal plus 2 m vertical)

Length of the receiving antenna cable: > 6 m (2 m horizontal plus 4 m vertical)

Each cable shall be routed back (horizontal) at least 2 m behind its attached antenna.

Cables for transmit and receive antenna should be routed separately (not in the same trough) to avoid leakage between cables. By doing so, variations in voltage measurements due to cable placement are not expected to exceed the measurement uncertainty.

H.3.2 Antennas

Two identical antennas, *i.e.*, of the same model, shall be used for broadband measurements.

An attenuator of at least 6 dB and low VSWR shall be connected to both the transit and receive antennas to reduce the uncertainty due to VSWR. The attenuator values used may vary depending on the antennas, dynamic range and signal strength.

H.3.3 Connectors

Inspect all connectors (antennas, cables and instruments) and keep them clean to maintain repeatability.

NOTE—when mating connectors, turn only the threaded collar NOT the body of the connector. Turning the body of the connector within the mating connector may damage the leaves or fingers of the pin and sleeve mates.

H.3.4 Receive antenna mast

Any antenna mast components containing substantial amounts of metal, such as, motor base assembly or wheels that are significantly above the ground plane, shall be moved away from the antenna or covered with ferrite tiles.

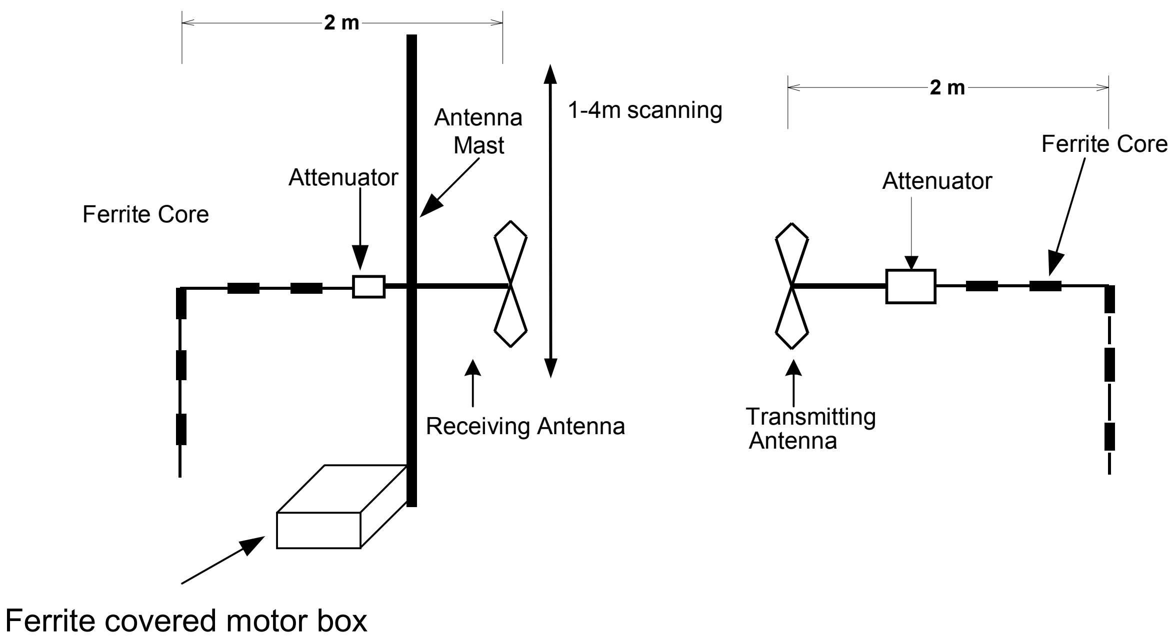


Figure H.2—Antenna and cable configuration

H.3.5 Transmit antenna support

Antenna support for transmit antenna shall be made of clear or white (to reduce reflections due to pigments) styrene foam or the equivalent (e.g., Plastic or Resin hollow pipe).

H.3.6 Instrumentation

All measuring instrumentation and any amplifiers shall be kept in a stable temperature environment during testing. The measuring instrument shall be calibrated in accordance with the manufacturer's instructions at the intervals recommended by the manufacturer.

H.4 Measurement procedure

The measuring instruments shall be self-calibrated (if this feature is available) after warming up for approximately one hour. This is done to ensure stability in the receiving equipment and any amplifier used.

SA for each combination of polarization, transmitting height and distance, as required in ANSI C63.4-2003 for characterization of emission test sites, shall be measured. Equation (H.1) shall be applied to determine GSCFs for each measured geometry.

At least five site attenuation tests shall be made for each geometry using the volumetric pattern shown in Figures 8(a) and 8(b) of ANSI C63.4-2003 by moving the antenna to different locations on the SACS and also by dismantling and reconstructing the test set up between measurements. It is recommended that more than five locations as shown in Figure H.3 be used to increase the statistical sample size. The transmitting and receiving locations are correlated with the numbers shown in Figure H.3 (e.g., transmit location C with receive location C). This method will provide a distribution of values based upon site imperfections and set up variations.

The transmitting and receiving positions shall not be aligned with any welds or joints that that run the length or width of the ground plane.

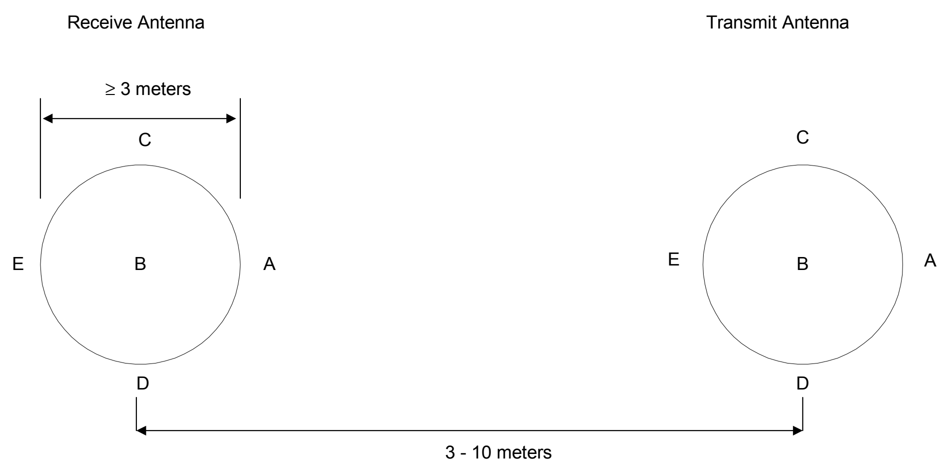


Figure H.3—Example of reference SACS measurement locations

The range of the standard deviation in site attenuation values for a suitable reference SACS shall be as follows:

Horizontal polarization:	0.0 dB to 0.3 dB
Vertical polarization:	0.0 dB to 0.6 dB

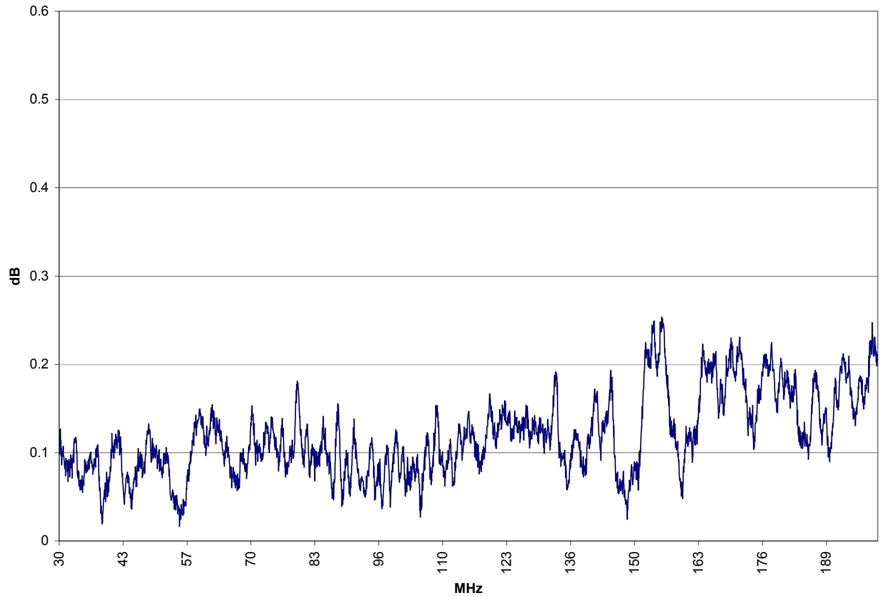


Figure H.4—Example of standard deviation of five antenna calibrations at different locations; polarization = V, D = 10 m, transmit Ht = 1 m

If an ambient signal obstructs the measurement signal, a reliable value can be determined from the neighboring frequency values using a straight-line interpolation with $\Delta f \leq 5$ MHz. The same measuring instruments and set up conditions used at the SACS shall be used for the qualifying emission site measurement.

H.4.1 Swept RF receiver

The measuring instrumentation shall have a frequency resolution of 360 kHz, or smaller, (i.e., 3 times QP bandwidth) and an amplitude resolution of 0.2 dB for measurements from 30 to 1000 MHz.

Linearity of the receiver and total measuring system shall be verified before calibrating the antennas using a calibrated attenuator (0-70 dB) at 30 MHz. Linearity for a 50 dB dynamic range shall be 0.2 dB or less.

Figure H.5a and Figure H.5b illustrate a typical equipment configuration.

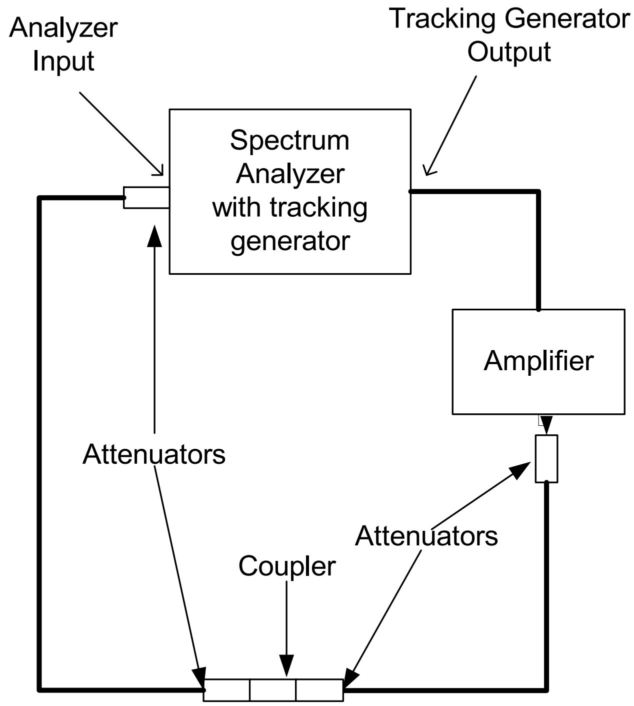


Figure H.5a—Typical equipment configurations

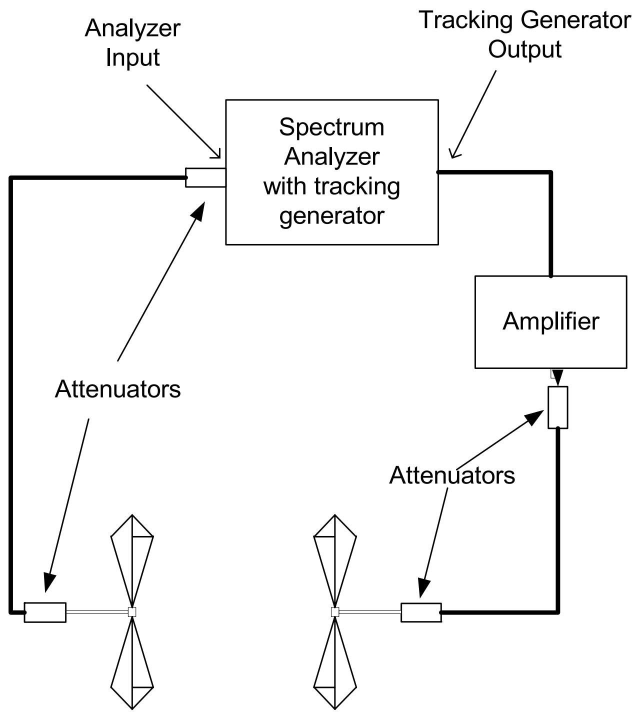


Figure H.5b—Typical equipment configurations

Annex I

(informative)

Guideline for computing estimated measurement uncertainties in SSM antenna calibrations

The calculations of the estimated measurement uncertainties for antenna calibrations can be either type A or B evaluations. Type A evaluations in most cases will not be practical considering the sample size and associated costs. This annex is intended to provide guidance on the sources of uncertainty to be considered (German and Devor [B8]).

The antenna calibration process includes a measurement instrument (radio receiver or spectrum analyzer), signal source (tracking generator or signal generator), amplifiers or pre-amplifiers, cables, attenuators, measurement site imperfections, signal-to-noise ratio and antenna specific factors. Either a swept or a discrete frequency method may be used.

It is important to note that if the discrete method is used, the uncertainties stated for product measurements will include a more significant uncertainty contribution due to a larger antenna factor interpolation than would be needed if a swept measurement were used.

Table I.1—Uncertainty calculation worksheet

Row	√	Contribution	Designation	Probability Distribution	K	Uncertainty (dB)
1		Spectrum analyzer relative amplitude accuracy	u_A^{SpA}	Rectangular	√3	
2		Swept Method Spectrum analyzer frequency span accuracy	u_f^{SpA}	Rectangular	√3	
3		Discrete Frequency Method without pre-scan, frequency accuracy	$u_f^{\text{no pre-scan}}$	Rectangular	√3	
4		Discrete Frequency Method with pre-scan, frequency accuracy	$u_f^{\text{w/ pre-scan}}$	Rectangular	√3	
5		Signal source amplitude stability	u_A^{SS}	Rectangular	√3	
6		Signal source frequency accuracy	u_f^{SG}	Rectangular	√3	
7		Amplifier gain stability	u_G^{AMP}	t-distribution	*	
8		Cable attenuation variations	u_L^{Cables}	Rectangular	√3	
9		Transmit side mismatch	u_{VSWR}^{XMT}	U-shaped	√2	
10		Receive side mismatch	u_{VSWR}^{RCV}	U-shaped	√2	
11		Site imperfections and system repeatability	$u^{\text{Site \& System}}$	t-distribution	*	
12		Variations in antenna phase center	$u^{\text{phase center}}$	Rectangular	√3	
13		Antenna directivity	$u^{directivity}$	Rectangular	√3	
14		Transmit pattern variations from dipole	$u^{pattern}$	Rectangular	√3	
15		Combined standard uncertainty				
16		Expanded Uncertainty		Normal	2	

NOTE—t-distribution values are based on the degrees of freedom.

I.1 Measurement instrument contributions

I.1.1 Spectrum analyzers

Spectrum analyzers automated tuned receivers and spectrum analyzer/receiver hybrids have two primary sources of uncertainty that shall be considered with respect to the calibration procedure. These sources are amplitude accuracy and frequency accuracy. An antenna calibration may be conducted in either a swept method or discrete frequency method. For both methods, the amplitude uncertainty contribution (u_A^{SpA}) is based on the instruments relative amplitude uncertainty as a function of the reference level. This contribution may be assessed using either the instruments specifications or through a type A evaluation. If the published data are used, the contribution is considered a rectangular distribution. If a type A evaluation is used, the distribution can be considered normal with the appropriate degrees of freedom (n-1). The magnitude of this uncertainty contribution can be reduced through the use of a calibrated precision attenuator, inserted in the direct measurement that is nearly equal to the antenna losses.

Table I.1 row 1: u_A^{SpA} = Receiving instrument relative amplitude accuracy (dB) (provided by the manufacturer or calibration laboratory)

(I.1)

The contribution resulting from frequency error is dependent on the method. If a swept frequency method is used, this contribution u_f^{SpA} can be computed by multiplying the frequency span accuracy times the slope of the antenna factor over the frequency span measured. This contribution has a rectangular distribution.

Table I.1 row 2: Swept Method u_f^{SpA} = Receiving instrument frequency span accuracy (MHz) * AF slope (dB/MHz)

(I.2)

If a discrete frequency method is used, a sweep with an appropriate span must first be made to ensure the fundamental frequency is properly identified before narrowing the resolution and scanning the antenna tower. Using this process provides an uncertainty contribution that is computed by multiplying the instruments frequency accuracy specification times the slope of the antenna factor at the frequency measured. However, if a sweep is not made, two uncertainty contributions exist, one from the frequency error of the source and a second from the frequency error of the analyzer. The contribution from the source, resulting from the analyzer and signal source not being tuned to the same frequency, can be computed as the sum of the signal source frequency accuracy and the spectrum analyzer frequency accuracy times the slope of the antenna factor at the frequency of interest. For some antennas the use of a spectrum analyzer, automated tuned receivers and spectrum analyzer/receiver hybrids may require more than one value of uncertainty to be stated as a function of frequency due to the antenna factor slope.

NOTE—Spectrum analyzers save a limited number of frequency data per span. The user should be careful to set the span to ensure an adequate frequency resolution.

Discrete Frequency Method without a pre-scan

Table I.1 row 3: $u_f^{\text{no pre-scan}}$ = (Spectrum analyzer or receiver frequency accuracy + signal source frequency accuracy) * AF slope (dB/MHz)

(I.3)

Discrete Frequency Method with a pre-scan

Table I.1 row 4: $u_f^{\text{w/ pre-scan}}$ = Spectrum analyzer or receiver frequency accuracy * AF slope (dB/MHz)

(I.4)

I.1.2 Tuned receivers

Manually tuned receivers are only used for the discrete frequency method. The sources of uncertainty associated with receivers are essentially the same as a spectrum analyzer used in the discrete frequency method as shown above.

I.1.3 Signal sources contributions

Two types of signal sources are commonly used, tracking generators and signal generators. Signal generators are used only for the discrete frequency method. Tracking generators may be either internal to the SA or receiver or separate external devices.

Signal sources may have uncertainty contributions associated with both output amplitude and frequency uncertainty. These uncertainties are introduced as the relative difference between the direct and indirect measurements, so long as the output level is not changed between direct and indirect measurements. A signal source has an output amplitude stability that is usually a function of ambient temperature and output power. Consequently, ambient temperatures in the test environment shall be held relatively constant in accordance with the equipment manufacturer's guidelines and the output power shall not exceed the manufacturers rating.

Table I.1 row 5: u_A^{SS} = Signal source amplitude stability (dB)

(I.5)

I.1.4 Signal Generators

A signal generator's uncertainty contribution from frequency accuracy is a function of the deviation of the carrier frequency and ambient temperature between the direct and indirect measurements. The magnitude of this uncertainty contribution is the frequency accuracy times the slope of the antenna factor in the indirect measurement in the frequency range measured since the direct measurement slope is probably near zero. The uncertainty contribution as a function of the signal generator frequency accuracy may be computed from the signal generator specifications or from a type A evaluation. Note however, that a type A evaluation is applicable only if the same drive levels and frequencies are used for both the direct and indirect measurements.

Table I.1 row 6: u_f^{SG} = Signal generator frequency accuracy * AF slope (dB/MHz)

(I.6)

I.1.5 Tracking generators

The output amplitude contribution to uncertainty associated with a tracking generator is similar to the signal generator as described above. The frequency uncertainty is not a concern when a swept method is used. However, tracking generators have an additional potential source of uncertainty associated with misalignment between the tracking generator output signal and the spectrum analyzer intermediate frequency. This uncertainty will be negligible if the user adjusts for tracking changes after the warm-up period of the instruments and before making any measurements and the user makes no changes to the instrument settings between the direct and indirect measurements.

I.1.6 Amplifier or pre-amplifier

The use of pre-amplifiers and amplifiers is often necessary to ensure acceptable amplitude in the presence of ambient radio frequency signals and attenuators used to reduce VSWR. The measurement uncertainty contribution from an amplifier is based on the gain stability of the amplifier (after it is warmed up) in both the direct and indirect measurements. The amplifier gain stability is primarily a function of temperature. Consequently, a constant ambient temperature (within the manufacturer's guidelines) shall be maintained during all measurements. If a gain stability value is not provided in the specifications from the manufacturer, a Type A evaluation is needed. Care should be taken if multiple band amplifiers are used. These amplifiers may require additional time to warm up when switching bands since different transistors may be used in each band and are not necessarily stable when the band is switched.

Table I.1 row 7: u_G^{AMP} = Amplifier gain stability (dB)

(I.7)

I.1.7 Cable and attenuators

The impedance, phase constant, and attenuation constant of cables used in the measurement process vary with temperature of the ground plane of the site. Attenuators are used to reduce the VSWR of the measurement system.

I.1.8 Cable loss uncertainty

The measurement uncertainty contribution from changes in the cable losses can be reduced to a negligible value by monitoring the temperature of the ground plane and repeating the direct measurement when the cable temperature variations warrant it. The uncertainty contribution associated with changes in the cable losses can be computed directly from the cable manufacturers rated temperature stability and the temperature variations experienced between direct and indirect measurements.

Table I.1 row 8: u_L^{Cables} = Cable attenuation variations (dB/°C) * ground plane temperature variations (direct vs. indirect) (°C)

(I.8)

I.1.9 VSWR uncertainty

The contribution to measurement uncertainty of the VSWR of the system can be determined by computing the VSWR contribution at each end of the cables. This contribution is a U-shaped distribution function. The formula for computing the contribution at each end of the cable is:

$20*\text{Log}_{10}(1 \pm |\Gamma_S| * |\Gamma_L|)$ where

(I.9)

$|\Gamma_S|$ = reflection coefficient of the source = ($VSWR_{source}$ - 1) / ($VSWR_{source}$ + 1)

(I.10)

$|\Gamma_L|$ = reflection coefficient of the load = ($VSWR_{load}$ - 1) / ($VSWR_{load}$ + 1)

(I.11)

The contributions for the transmitting and receiving cables are:

Table I.1 row 9: $u_{VSWR}^{XMT} = 20*\text{Log}_{10}(1 \pm |\Gamma_{\text{Source or pad}}| * |\Gamma_{\text{XMT antenna or pad}}|)$

(I.12)

Table I.1 row 10: $u_{VSWR}^{RCV} = 20*\text{Log}_{10}(1 \pm |\Gamma_{\text{RCV antenna or pad}}| * |\Gamma_{\text{instrument or pad}}|)$

(I.13)

I.1.10 System and site contributions

The contribution to measurement uncertainty from the site and system can be determined using a type A evaluation. This evaluation requires conducting the volumetric Normalized Site Attenuation as described in ANSI C63.4-2003. This evaluation requires five measurements that are taken at different locations on the ground plane for each geometry and antenna. The standard deviation of these five values at each frequency represents the worst-case contribution to uncertainty that can be associated with the site imperfections, cable lay variations, distance measurement errors, antenna height start/stop errors, antenna travel smoothness (directivity) and height vs. frequency variations. Amplifier gain stability would also be included in this value if the same amplifier was used during calibrations. The standard deviation in the data of the five locations shall be calculated for each frequency. The contribution to measurement uncertainty is then the maximum value of these standard deviations for the geometry of interest (for example, 2 m horizontal transmitting height, 10 m distance for standard calibrations). A t-distribution is assumed with n = 5 and a 95% confidence interval, yielding a value of t equal to 2.87.

Table I.1 row 11: $u^{\text{Site \& System}}$ = Site imperfections and system repeatability

(I.14)

I.1.11 Signal plus Noise-to-Noise Ratio errors

The peak signal measured during antenna calibrations is the sum of the signal plus noise of the measurement system. An error term is introduced that can be expressed mathematically as:

$$Error = {(S+N)}/{S}\,(dB) = SNR[dB] - 10 \times Log\left\{10^{\left[SNR[dB]/10\right]} - 1\right\}$$

(I.15)

where: $SNR[dB] = (S+N)/N\,[dB]$

(I.16)

For accurate antenna calibrations, this error term can be minimized through a sufficient SNR value. A SNR of 16 dB reduces this error term to 0.11 dB, well below the expected measurement uncertainty. This 0.11 dB must be subtracted from the indicated value to find the unbiased measured value. The uncertainty introduced by the superposition of an ambient signal during the antenna calibration is under further study.

I.1.12 Antenna-specific contributions

Antenna-specific contributions to uncertainty may include antenna phase center variations, antenna directivity and non-dipole pattern variations. These factors and their magnitude must be determined based on the specific antenna being evaluated.

Table I.1 row 12: $u^{\text{phase center}}$ = Variations in antenna phase center

(I.17)

Table I.1 row 13: $u^{\text{directivity}}$ = Antenna directivity

(I.18)

Table I.1 row 14: u^{pattern} = Transmit pattern variations from dipole

(I.19)

The combined uncertainty is:

Table I.1 row 15: $u_c = \sqrt{\sum (u/k)^2}$

(I.20)

The expanded uncertainty is:

Table I.1 row 16: $U = 2 * u_c$

(I.21)

I.2 Example calculations of uncertainties

The total measurement uncertainty for an antenna calibration is computed from the applicable contributions above as shown in the following example:

An antenna calibration is conducted using a swept method, a spectrum analyzer with internal tracking generator, an amplifier and attenuators on the ends of the transmitting and receiving cables. Precision calibrated attenuation of 40 dB was added during the direct measurements to reduce the measurement uncertainty associated with the relative amplitude accuracy. The antennas are 50 Ω balun biconical dipole antennas.

I.2.1 Spectrum analyzer

The spectrum analyzer published relative amplitude accuracy was 0.3 + 0.01*(dB down from reference). The use of a precision calibrated attenuator results in a relative amplitude (direct - indirect) of 20 dB. The resulting amplitude uncertainty of the analyzer is:

$u_A^{SpA} = 0.3 + 0.01*(20dB) = 0.5$ dB

Since the calibrated uncertainty of the precision attenuator is less than 0.1, it is considered negligible.

The swept measurement was made from 30 to 200 MHz in four sweeps. Each sweep had a span of 170/4 = 42.5 MHz. The rated frequency accuracy of the spectrum analyzer was 3% of span or in this case, 1.275 MHz. The worst-case antenna factor slope is from 30 MHz to 70 MHz where the antenna factor changes from 12 to 6 dB. Hence the uncertainty contribution from frequency error is:

$$u_f^{SpA} = 1.275MHz * (12dB - 6dB) / (70MHz - 30MHz) = 0.19 \text{ dB}$$

I.2.2 Signal source

The tracking generator's amplitude stability specification is:

$u_A^{SS} = 0.1$ dB.

I.2.3 Amplifier

A type A evaluation of the amplifier's gain stability was conducted. Gain measurements were made every five minutes after the amplifier had warmed up for one hour. A total of 5 readings were taken after warm-up. The effective degrees of freedom is n-1 = 4. The coverage factor k, based on the t-distribution tables, would be 2.87. The standard deviation of the 5 readings was 0.15. This value includes the repeatability of the measurement instrument.

$u_G^{AMP} = (2.87/2)*0.15$ dB

I.2.4 Cable loss uncertainty

The temperature on the ground plane during the direct measurement and indirect measurements differed by 5 °C. The cable rating is rated 95 % to 103 % impedance changes over 0 – 40 °C. Consequently, the cable attenuation variance was deemed negligible in contrast to the signal source amplitude uncertainty.

I.2.5 VSWR

The attenuators placed at each end of the transmitting and receiving cables had a rated VSWR of 1.15:1. The reflection coefficient at the end of each cable was:

$$\Gamma = (1.15 - 1) / (1.15 + 1) = 0.07$$

The resulting uncertainty contribution for the transmitting and receiving cables are:

$u_{VSWR}{}^{XMT} = u_{VSWR}{}^{RCV} = 20 * Log(1 \pm 0.07 * 0.07) = 0.04$ dB

This is a negligible value in contrast to the signal source amplitude accuracy.

I.2.6 System and site contribution

The site used for the calibration had undergone a volumetric normalized site attenuation test. The standard antenna calibration was conducted with a transmitting height of 2 meters and a horizontal polarization. The volumetric site attenuation data provided 5 values of site attenuation for each frequency point measured. The standard deviation of those values is illustrated below in Figure I.1. The maximum standard deviation was 0.12 dB.

$u^{\text{Site \& System}} = 0.12$

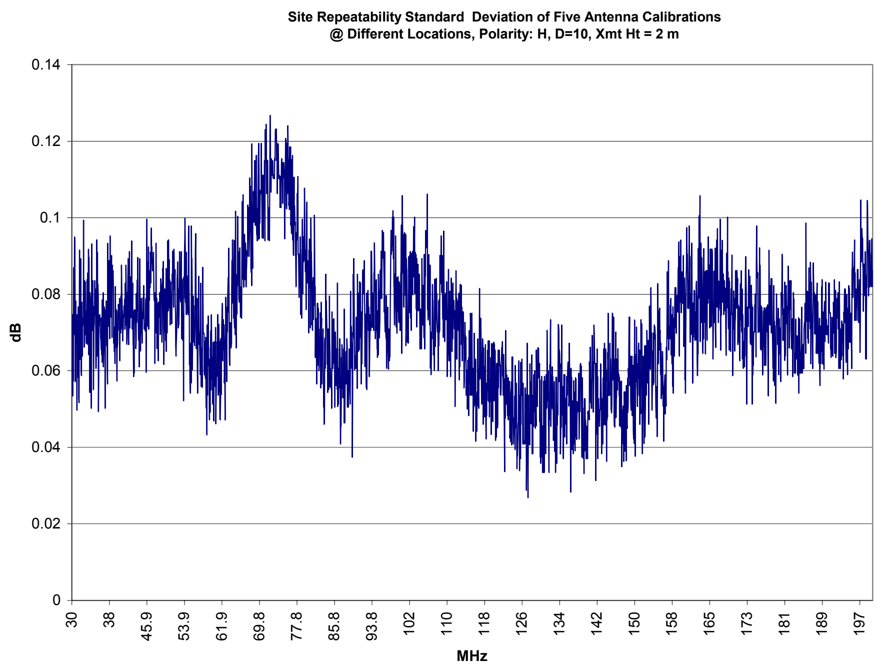


Figure I.1—Typical standard deviation values

Table I.2—Summary of example uncertainty calculation

Row	√	Contribution	Designation	Probability Distribution	K	Uncertainty (dB)
1	√	Spectrum analyzer relative amplitude accuracy	u_A^{SpA}	Rectangular	√3	0.5
2	√	Swept Method Spectrum analyzer frequency span accuracy	u_f^{SpA}	Rectangular	√3	0.19
3		Discrete Frequency Method without pre-scan, frequency accuracy	$u_f^{no\ pre\text{-}scan}$	Rectangular	√3	
4		Discrete Frequency Method with pre-scan, frequency accuracy	$u_f^{w/\ pre\text{-}scan}$	Rectangular	√3	
5	√	Signal source amplitude stability	u_A^{SS}	Rectangular	√3	0.1
6		Signal source frequency accuracy	u_f^{SG}	Rectangular	√3	
7	√	Amplifier gain stability	u_G^{AMP}	t-distribution*	2/2.87	0.15
8		Cable attenuation variations	u_L^{Cables}	Rectangular	√3	
9	√	Transmit side mismatch	u_{VSWR}^{XMT}	U-shaped	√2	0.04
10	√	Receive side mismatch	u_{VSWR}^{RCV}	U-shaped	√2	0.04
11	√	Site imperfections and system repeatability	$u^{Site\ \&\ System}$	t-distribution*	2/2.87	0.12
12		Variations in antenna phase center	$u^{phase\ center}$	Rectangular	√3	
13		Antenna directivity	$u^{directivity}$	Rectangular	√3	
14		Transmit pattern variations from dipole	$u^{pattern}$	Rectangular	√3	
15		combined standard uncertainty	u_c			0. 42
16		Expanded Uncertainty	U	Normal	2	0. 84

NOTE—t-distribution values are based on the degrees of freedom, in this case 4 degrees of freedom for a sample size of 5. This is an example only should NOT be copied and applied to a measurement. See Table I.1.

For this example combined standard uncertainty

u_c=

$$\sqrt{\left(\frac{0.5}{\sqrt{3}}\right)^2+\left(\frac{0.19}{\sqrt{3}}\right)^2+\left(\frac{0.1}{\sqrt{3}}\right)^2+\left(\frac{2.87*0.15}{2}\right)^2+\left(\frac{0.04}{\sqrt{2}}\right)^2+\left(\frac{0.04}{\sqrt{2}}\right)^2+\left(\frac{2.87*0.12}{2}\right)^2}$$

$u_c = 0.42$

For this example the expanded uncertainty is:

$U=2*u_c$

As this example illustrates, a type A evaluation of the signal source amplitude stability or manufacturers amplitude repeatability specifications would significantly reduce the uncertainty of this example calibration.

Annex J

(informative)

Bibliography

[B1] Austin, B. A., and Fourie, A. P. C., “Characteristics of the wire biconical antenna used for EMC measurements,” *IEEE Transactions on Electromagnetic Compatibility,* vol. 33, no. 3, pp. 179-187, Aug. 1991.

[B2] Chen, Z. and Foegelle, M. D., “A Numerical Investigation of Ground Plane Effects on Biconical Antenna Factors,” IEEE International EMC Symposium, pp. 802-806, Denver, CO, 1998.

[B3] DeMarinis, J., “The antenna cable as a source of error in EMI measurements,” *IEEE 1988 International Symposium on Electromagnetic Compatibility Record,* 88CH2623-7, pp. 9-14, Seattle, Wash., Aug. 2-4, 1988.

[B4] DeMarinis, J., “Quality control of antenna calibration and site-attenuation data from open area test sites,” *IEEE 1988 International Symposium on Electromagnetic Compatibility Record,* 88CH2623-7, pp. 290-294, Seattle, Wash., Aug. 2-4, 1988.

[B5] FCC Project 3235-16, “A new wideband balun,” Federal Communications Commission, Washington, D.C., 1957.

[B6] FCC Project 3235-33, “Construction of general purpose receiving antenna dipole sets and balun assemblies,” Federal Communications Commission, Washington, D.C., 1980.

[B7] Fitzgerrel, R. G., “Linear gain Standard antennas below 1000 MHz,” *NBS Technical Note 1098,* U.S. Department of Commerce.

[B8] German, R. F. and C. L. Devor Jr., “Comparison of Methods to Evaluate Semianechoic Chamber Performance,” Compliance Engineering Magazine, Volume XVI, No. 7, Nov./Dec. 1999, pp. 61-67.

[B9] Goedbloed, J. J., “Progress in standardization of CISPR antenna calibration procedures,” *EMC Zurich '95,* 1995.

[B10] IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition.

[B11] *NIST Technical Note 1297*, “Guidelines for evaluating and expressing the uncertainty of NIST measurement results,“ 1994.

[B12] Roberts, W. K., “A new wide-band balun,” *Proceedings of the Institute of Radio Engineers,* pp. 1628-1631, Dec. 1957.

[B13] Roberts, W. K., “A guide to FCC equipment authorizations,” New Smyrna Beach, Fla., 1980.

[B14] Smith, A. A., Jr., “Standard site method for determining antenna factors,” *IEEE Transactions on Electromagnetic Compatibility*, EMC-24, pp. 316-322, no. 3, Aug. 1982.

[B15] Stecher, M., “Mutual impedance correction factors for broadband antennas for correct and easy measurement of site attenuation,” *ITEM,* pp. 184-189, 334; 1993.

[B16] Taggart, H. E., and Workman, J. L., "Calibration principles and procedures for field strength meters (30 Hz to 1 GHz)," *NBS Tech. Note 370,* U.S. Department of Commerce.

[B17] Windler, M. and Chen, Z., "Systematic Errors in Normalized Site Attenuation Testing," *Compliance Engineering,* pp. 38-48, vol. XVII No. 1, Jan-Feb 2000.

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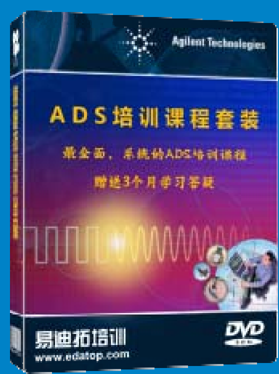

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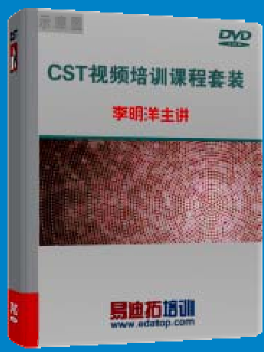

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