SAE International™

SURFACE VEHICLE STANDARD

SAE J1113-28

ISSUED NOV2004

Issued 2004-11

Electromagnetic Compatibility Measurements Procedure for Vehicle Components—Part 28—Immunity to Radiated Electromagnetic Fields—Reverberation Method (Mode Tuning)

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1. Scope

1.1 Vehicle electrical/electronic systems may be affected when immersed in an electromagnetic field generated by sources such as radio and TV broadcast stations, radar and communication sites, mobile transmitters, cellular phones, etc. Reverberation method is used to evaluate the immunity of electronic devices in the frequency range of 400 MHz – 18GHz. Pulse modulation is used for testing above 800 MHz.

1.2 This document provides the component design and test engineers with a test procedure and the performance requirements necessary to evaluate the immunity of electronic devices to radiated electromagnetic fields early in the design stage as well as pilot and production stages. Ensuring electromagnetic compatibility early in the development stage will minimize costly changes later in the program and will prevent excessive component level hardening during full-vehicle level testing.

1.3 The reverberation test method performs a dual function:

1.3.1 The primary function of the method is to provide a bench test procedure correlatable to vehicle-level radiated immunity testing in the anechoic chamber and at mobile transmitter sites.

1.3.2 The method can be used to evaluate the relative performance of different designs of the same device.

2. References

General information regarding this document, including definitions, references, and general safety considerations are found in SAE J1113-1.

2.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. Unless otherwise specified, the latest issue of SAE publications shall apply.

2.1.1 SAE PUBLICATIONS

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J1113-1—Electromagnetic Compatibility Measurement Procedures and Limits for Vehicle Components (Except Aircraft) (60 Hz go 18 GHz)
SAE J1812—Function Performance Status Classification for EMC Immunity Testing

2.1.2 IEC PUBLICATIONS

Available from International Electrotechnical Commission, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneve 20, Switzerland.

IEC 61000-4-21—Electromagnetic Compatibility (EMC)—Part 4: Testing and Measurement Techniques—Section 21: Reverberation Chamber Test Methods
[1] IEC 61000-4-3—Electromagnetic Compatibility (EMC)—Part 4: Testing and Measurement Techniques—Section 3: Radiated, "*Radio-Rrequency, Electromagnetic Field Immunity Test*"

2.1.3 NBS/NIST PUBLICATIONS

Available from NIST, U.S. Department of Commerce, Gaithersburg, MD 20899

[15] NBS Technical Note 1092—Design, Evaluation, and Use of a Reverberating Chamber for Performing Electromagnetic Susceptibility/Vulnerability Measurements
[14] NIST Technical Note 1506—Electromagnetic Theory of Reverberation Chambers
[16] NIST Technical Note 1508—Evaluation of the NASA Langley Research Center Mode Stirred Chamber Facility

2.1.4 MILITARY PUBLICATIONS

Available from the U.S. Government, DOD SSP, Subscription Service Division, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094

[11] MIL-STD-461E—Department of Defense Interface Standard—Requirements for the Control of Electromagnetic Interface Characteristics of Subsystems and Equipment, 1999
MIL-STD-1377—Effectiveness of Cable, Connector, and Weapon Enclosure Shielding and Filters in Precluding Hazards of Electromagnetic Radiation to Ordinance, Measurement of

2.1.5 IEEE PUBLICATIONS

Available from Institute of Electrical and Electronic Engineers, 445 Hoes Lane, Piscataway, NJ 08854.

[6] Olof Lunden, and Mats Backstrom, "Stirrer Efficiency in FOA Reverberation Chambers, Evaluation of Correlation Coefficients and Chi-Squared Tests," presented at the *IEEE International Symposium on EMC*, Washington, DC, August 2000.
[8] G. J. Freyer, M.O Hatfield, D.M. Johnson, and M.B. Slocum, "Comparison of Measured and Theoretical Statistical Properties of Complex Cavities," presented at the *IEEE International Symposium on EMC*, Santa Clara, CA, August 1996.
[12] J. M. Ladbury, and K.Goldsmith, "Reverberation Chamber Verification Procedures or How to Check if Your Chamber Ain't Broke and Suggestions on How to Fix it if it is," presented at the *IEEE International Symposium on EMC*, Washington DC, Aug 2000.
[13] J. M. Ladbury, "Reverberation Chamber Relationships: Corrections and Improvements or Three Wrongs Can (Almost) Make a Right," presented at the *IEEE International Symposium on EMC*, Seattle, WA, August 1999.
[4] T. H. Lehman, G.J. Freyer, M.L. Crawford, and M.O. Hatfield, "Statistical Theory of Reverberation I: Overmoded Case," *Proceedings of the 1997 Mode-Stirred Chamber, Anechoic Chamber, and OATS Users Meeting*, Vail, Colorado April 28-May 2, 1997.
[5] T. H. Lehman, G.J. Freyer, M.L. Crawford, and M.O. Hatfield, "Statistical Theory of Reverberation Chambers—Part II: Undermoded Case," *Proceedings of the 1997 Mode-Stirred Chamber, Anechoic Chamber, and OATS Users Meeting*, Vail, Colorado April 28-May 2, 1997.

2.1.6 RCTA PUBLICATION

Available from RCTA, Inc., 1140 Connecticut Avenue, NW, Suite 1020, Washington, DC 20036.

[10] RTCA/DO-160D, "Environmental Conditions and Test Procedures for Airborne Equipment" (Change Notice to Section 20), November 2000.

3. Definitions

3.1 Reverberation Chamber

A high Q shielded room (cavity) whose boundary conditions are changed via a stepped rotating paddle. This results in a time-averaged uniform electromagnetic field.

3.2 Paddle

A large metallic reflector capable of changing the electromagnetic boundary conditions in a reverberation chamber as it rotates or moves. As the paddle moves, the nulls and maximums in the field change location, ensuring the Device Under Test (DUT) is exposed to a time-averaged uniform field. The paddle has also been referred to as a tuner or stirrer.

3.3 Chamber Calibration Factor (CCF)

The normalized average received power over one tuner rotation with the DUT and supporting equipment present,

$$CCF = \left\langle \frac{P_{Avg\,Rec}}{P_{Input}} \right\rangle_n \qquad \text{(Eq. 1)}$$

where:

$P_{Ave\,Rec}$ = the average received power over one tuner rotation
P_{Input} = the forward power averaged over one tuner rotation
n = the number of antenna locations the CCF is evaluated for. Only one location is required; however, multiple locations may be evaluated and the data averaged over the number of locations, n.

NOTE—$\langle\ \rangle$ denotes arithmetic mean

3.4 Chamber Quality Factor (Q)

The chamber Quality factor or "Q" is a measure of how well the chamber stores energy[14]. For a given chamber, Q varies as a function of frequency and can be calculated using the following:

$$Q = \left(\frac{16\pi^2 V}{\eta_{T_x} \eta_{R_x} \lambda^3} \right) * CCF \qquad \text{(Eq. 2)}$$

where

η_{Tx} and η_{Rx} are the antenna efficiency factors for the transmit and receive antenna respectively and can conservatively be assumed to be 0.75 for a log periodic antenna and 0.9 for a horn antenna
V is the chamber volume (m^3)
λ is the free space wavelength (m) at the specific frequency.

3.5 Antenna Calibration Factor (ACF)

The ratio of the average received power to input power obtained in the antenna calibration in Appendix B, Section 1.2.

3.6 Chamber Loading Factor (CLF)

$$CLF = \frac{CCF}{ACF} \quad \text{(Eq. 3)}$$

4. Test Equipment

4.1 Reverberation Chamber

Sized large enough to test a DUT within the chamber's test volume.

4.2 Mechanical Tuner

As large as possible with respect to overall chamber size (at least three-quarters of the smallest chamber dimension) and test volume considerations. In addition each tuner should be shaped such that a non-repetitive field pattern is obtained over one revolution of the tuner.

4.3 Isotropic E-Field Probe

Capable of reporting electric field strength in three orthogonal axes.

4.4 RF Signal Generator

Capable of covering the frequency bands and modulations specified.

4.5 Transmit Antenna

Linearly polarized antenna capable of satisfying frequency requirements. The transmit antenna shall avoid direct illumination of the test volume.

4.6 Receive Antenna

Linearly polarized antenna capable of satisfying frequency requirements. The receive antenna shall avoid pointing at the transmit antenna and center of the test volume.

4.7 Power Amplifiers

To amplify the RF signal and provide the necessary power to the transmit antenna to produce the field strengths specified.

4.8 Associated equipment to record the power levels necessary for the required field strength and to control the generation of that level for testing.

4.9 DUT Monitoring Instrumentation

Instrumentation and/or observation is used to monitor the parameters of the DUT in order to determine its performance during the test. The monitoring instrumentation and technique shall be documented in the test report. Monitoring of particular DUT functions must not disturb its operation or couple in any extraneous RF energy that it would not normally experience.

5. Chamber Calibration

Following the initial construction or after any major modifications, a performance-based field uniformity calibration technique to demonstrate adequate reverberation chamber performance is carried out in accordance with Appendix B. The procedure is used to determine the lowest useable frequency (LUF) of the reverberation chamber employed. The chamber field uniformity calibration described is to be carried out over a test/working volume, which includes the location of the test bench and DUT within the reverberation chamber. The chamber calibration addresses mode tuned operation of the reverberation chamber: The field uniformity measurement should be carried out with all support equipment (including the test bench) removed from the reverberation chamber. The calibration is to be carried out at 9 locations for 3 individual axes (x,y,z) at each test location, i.e., 27 measurement points in total (B.1.1). The field within the chamber is considered uniform if the standard deviation is within 3dB above 400 MHz, 4dB at 100 MHz decreasing linearly to 3 dB at 400 MHz, and within 4 dB below 100 MHz.

5.1 The calibration technique permits the use of linear/passive field monitoring antennas during DUT testing. The antennas are calibrated against an isotropic E-field probe (calibrated in free space). The purpose of this aspect of the procedure is to allow continuous monitoring of the field during the test with an antenna and associated monitoring equipment with a fast response time. Again, this test is performed with the measurement bench removed and performed at the same time as the field uniformity test. In addition, following initial construction or after major modification to the reverberation chamber a check on the impact on field uniformity of chamber loading is performed (B.1.5) to determine the maximum acceptable loading of the chamber for future testing.

NOTE—If the chamber was initially tested under maximum loading conditions – an optional “quick check” chamber performance measurement may be made with the DUT and test bench installed in the chamber (B.2). The purpose of this test is to confirm that the loading of the chamber is less than that simulated during the initial chamber calibration.

5.2 Calculations based on the calibration measurements are used to determine the minimum pulse width (B.3) that can be sustained in a given chamber for pulse modulation testing. If the chamber time constant is greater than 0.4 times the required pulse width for more than 10% of the test frequencies, absorbers must be added or the pulse width increased (not to exceed 100 μs).

NOTE—The chamber calibration detailed in B.1 need only be undertaken after initial chamber construction, annually, and after major modification to the reverberation chamber. The maximum chamber loading verification (B.1.5) need only be undertaken after initial chamber construction or after major modifications to the reverberation chamber. Changes to the tuners/stirrers shall be considered a major modification if the changes result in changes in tuner efficiency as outlined in A.3.

6. *Test Setup*

6.1 The typical test setup should be as shown in Figure 1. The equipment layout should be representative of the actual installation. The DUT shall be at least λ/4 meter from the chamber walls at the lowest usable frequency (LUF) of the chamber. DUTs designed for tabletop operation must be located λ/4 meter from the chamber floor. Floor standing DUTs shall be supported 2.5 cm above the floor, in the area beneath the uniform volume, by a dielectric support.

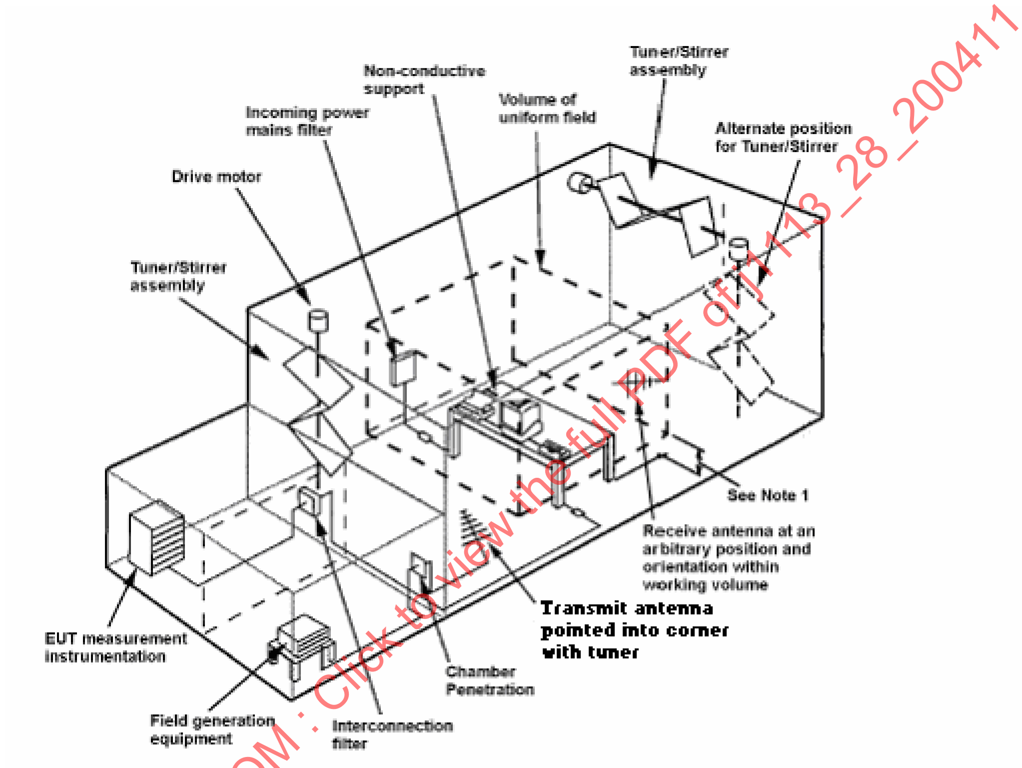

FIGURE 1— EXAMPLE OF SUITABLE TEST FACILITY

6.2 The transmit antenna should be in the same location as used for calibration. The transmit antenna shall not directly illuminate the DUT or the receive antenna. Directing the transmit and receive antennas into the corners of the chamber is a recommended configuration. Appropriate modes of operation, software installation, and stability of the DUT, test equipment, and all monitoring circuits and loads must be established.

6.3 If the DUT may load the chamber beyond that of the maximum loading verification, prior to collecting data a check must be performed to determine if the DUT and/or its support equipment have adversely loaded the chamber. This check shall be performed as outlined in Appendix B, Section B.2.

7. Test Procedures

CAUTION—RF fields can be hazardous. Observe applicable national RF exposure limits

7.1 Determining Chamber Input Power Requirements

7.1.1 Determine the chamber input power for the test requirements for the electric field intensity using the equation:

$$P_{input}(W) = \left[\frac{E_{Test}\left(\frac{V}{m}\right)}{\left\langle \overset{\leftrightarrow}{E} \right\rangle_{27or9} * \sqrt{CLF(f)}} \right]^2 \quad \text{(Eq. 4)}$$

where:

E_{Test} (V/m) is the required field strength
CLF(f) is the chamber loading factor from Appendix B (B.2.7) and
$\left\langle \overset{\leftrightarrow}{E} \right\rangle_{27or9}$ is the normalized E field from the empty chamber calibration from Appendix B (B.1.1.10.(b)or(c)). It will be necessary to interpolate (linear interpolation) between the calibration frequency points (calibration at a finer step interval is also an option).

7.2 Selecting Frequency Sweep/Step Rates/Intervals

Frequency sweep or step rates shall be selected with consideration of DUT response time, DUT susceptibility bandwidths, and monitoring test equipment response time. The scan rate selected shall be justified by this criterion, and documented in the test report.

7.2.1 DISCRETE FREQUENCY TESTING

For test equipment that generates discrete frequencies, the minimum number of test frequencies shall be 100 frequencies per decade. The test frequencies shall be logarithmically spaced. As an example (above 100 MHz), a formula which can be used to calculate these frequencies in ascending order is:

$$f_{n+1} = f_n * 10^{(1/99)} \quad \text{(Eq. 5)}$$

where:

f_n is a test frequency and n = 1 to 100,
f_1 is the start frequency,
and
f_{100} is the end frequency

The dwell time at each test frequency shall be at least seconds, exclusive of test equipment response time and the time required to rotate the tuner (to a full stop). Additional dwell time at each test frequency may be necessary to allow the DUT to be exercised in appropriate operating modes and to allow for the “off time” during low frequency modulation. At least two full cycles of modulation must be applied. For example, if the applied modulation is a 1 Hz square wave modulation (SW), the dwell time shall not be less than two seconds. The dwell time selected shall be justified based on DUT and test equipment response time, as well as applied modulation, and documented in the test report.

7.3 Performing the Test

For mode-tuned operation, the minimum number of steps is outlined in Table B1.. The tuner should be rotated in evenly spaced steps so that one complete revolution is obtained per frequency. Assure that the DUT is exposed to the field level for the appropriate dwell time.

Monitor and record P_{MaxRec} and P_{AveRec} with the receive antenna used in the calibration of each frequency band to ensure that the required field strength is being generated. Use P_{AveRec} to ensure that the chamber loading has not changed from the calibration in B.2. Differences greater than 3 dB in P_{AveRec} from that obtained in B.2 must be resolved.

Monitor and record the average values of P_{Input} and $P_{Reflected}$. Variations in P_{Input} over a tuner rotation greater than 3 dB should be noted in the test report.

Modulate the carrier as specified in the test plan. When modulation is applied, ensure that the peak amplitude complies with the definitions of the test plan.

Scan the frequency range to the upper frequency limit using the appropriate antennas and modulations.

NOTE 1—Linear interpolation between calibration points will be required.

NOTE 2—Test volume should be at least $\lambda/4$ at the LUF from any chamber surface, field generating antenna or tuner assembly. (See Note 5 of Figure B1, Appendix B)

NOTE 3—A non-conductive/non-absorbing support shall be utilized. Wooden tables should be avoided. Polystyrene foam is a suitable support in most cases. Foam materials may present a fire hazard if the DUT generates sufficient heat and/or when testing to field strengths that can induce arcing.

NOTE 4—The chamber should remain free of any unnecessary absorbing materials. Items such as wooden tables, carpeting, wall and floor coverings, and ceiling tiles should not be used. Also exposed light fixtures are a source of potential loading. For new chambers, it is recommended that an evaluation of the chamber be performed prior to installation of any support equipment other than doors, vents and access panels. Support equipment such as tables etc., should be non-metallic and non-absorbing. The DUT and all supporting equipments should not occupy more than 8% of the total chamber volume.

8. Test Severity Levels

A full description and discussion of the Function Performance Status Classification including Test Severity Levels are given in SAE J1113-1 Appendix A. Please review it prior to using the suggested Test Severity Levels presented in Appendix D.

9. Test Report

The test report should include the following parameters for each test frequency, in addition to the reporting requirements related to the DUT.

- Max received power from the receive antenna used to monitor the field in the chamber.
- Mean received power from the receive antenna used to monitor the field in the chamber.
- Forward power delivered to the chamber transmit antenna.
- Reflected power from the chamber transmit antenna.
- Variations in forward power during the data collection period greater than 3 dB.

PREPARED BY THE SAE EMI STANDARDS COMMITTEE

APPENDIX A
(INFORMATIVE)
REVERBERATION CHAMBER OVERVIEW

A.1 Introduction

Research on reverberation chambers has been performed for more than 20 years and has provided a significant increase in the understanding of the methodology[14,15]. Although the initial intent of this research was for measuring the shielding effectiveness of cables, connectors and enclosures, (MIL-STD-1377) the scope of the work was expanded to include susceptibility testing of electronic equipment, immunity testing of ordnance, and emissions testing.

A reverberation chamber is an electrically large, highly conductive enclosed cavity or chamber used to perform electromagnetic (EM) measurements (both emissions and immunity) on electronic equipment. Any facility that fits this description can be considered a reverberation chamber (also called a mode-stirred chamber). Other conditions, however, may be required before such a facility can be used with acceptable uncertainty[16].

In general, a reverberation chamber is a shielded enclosure with the smallest dimension being large with respect to the wavelength at the lowest useable frequency. The chamber is normally equipped with a mechanical tuning/stirring device whose dimensions are a significant fraction of the chamber dimensions and of the wavelength at the lowest useable frequency. When the chamber is excited with RF energy the resulting multi-mode electromagnetic environment can be "stirred" by the mechanical tuner/stirrer. The resulting environment is statistically uniform and statistically isotropic (i.e. having arrived from all aspect angles and at all polarizations) when averaged over a sufficient number of positions of the mechanical tuner/stirrer.

The chamber mode density and the effectiveness of the mechanical tuner/stirrer determine the lowest useable frequency. The lowest useable frequency is generally accepted to be the frequency at which the chamber meets operational requirements. This frequency generally occurs at a frequency slightly above 3 times the first chamber resonance. In practice the chamber size, tuner/stirrer effectiveness and the chamber quality factor determine the lowest useable frequency. For the reverberation chamber procedure described in this standard, it is the lowest frequency at which, the specified field uniformity can be achieved over a volume defined by an 9-location calibration data set.

Quality factor is used to describe the ability of a chamber or cavity to store energy. The ability of a chamber to store energy is determined by the losses present in the chamber. The dominant loss in an empty chamber is the chamber walls. The higher the conductivity of the materials used to construct the chamber walls the lower the chamber losses. Materials such as copper and aluminum sheet offer the highest conductivity and therefore the lowest losses. Other materials such as bare or painted steel or galvanized sheet are also common. Copper and aluminum screen and flame spray however, have large surface areas and do not result in high Q environments. Additional losses such as antennas, support structures, and the DUT also can affect the chamber Q. The chamber input power (P_{Input}) is normally taken to be the forward power delivered to the antenna terminals. In some cases it is necessary to take into account the reflected power caused by antenna/excitation induced mismatch. In such cases the input power shall be the net input power which is equal to:

$$P_{Net} = P_{Forward} - P_{Reflected} \quad \text{(Eq. A1)}$$

The amount of power needed to generate a specific field inside a chamber can be determined from the empty chamber calibration outlined in Appendix B. However, the DUT, the required support equipment, or any absorbing material present may load the chamber, reduce the chamber Q, and hence reduce the test fields for the same input power. Therefore, the fields in a loaded chamber must be monitored and input power increased, if necessary, to compensate for this loading as described in B.2.7.

The tuners should be adequate to provide the desired field uniformity. In some chambers, it may be necessary to use multiple tuners/stirrers to obtain the desired field uniformity at the required frequencies. Stepping motors with computer control are recommended. Variable speed, continuous motors are acceptable, but the time response of the DUT must be fast relative to tuner/stirrer speed for this option to be viable. A method of evaluating tuner/stirrer performance is given in Section A.3. In the past, testing was performed using 200 samples or steps of the mechanical tuner[15]. This resulted in uncertainties (i.e. inhomogeneity) in the field that varied as a function of frequency due to the increase in modal density at the higher frequencies. As shown in Figure A1, the uncertainty for a typical chamber varied considerably as a function of frequency as the number of tuner steps remained constant. The procedure developed for this standard optimises the number of steps or samples to obtain a fixed uncertainty as a function of frequency.

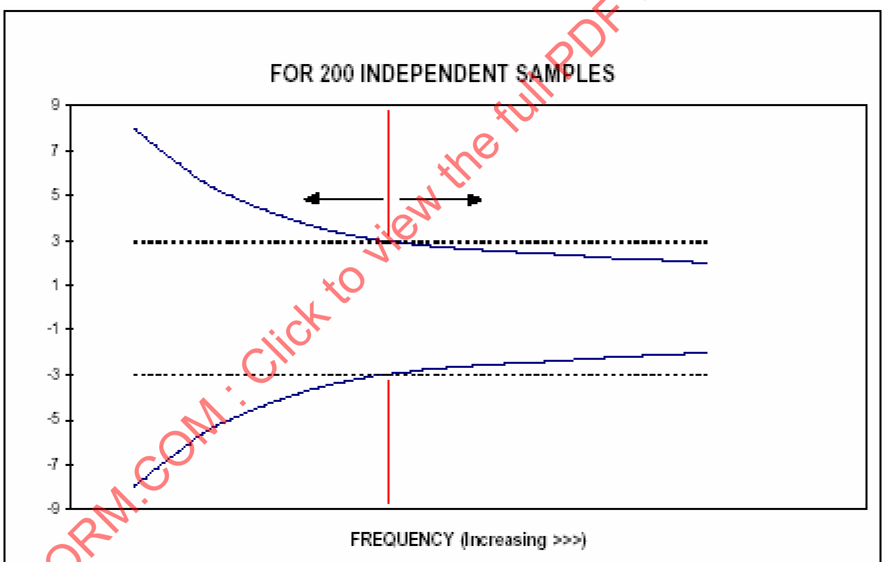

FIGURE A1—TYPICAL FIELD UNIFORMITY FOR 200 TUNER STEPS

A.2 Cavity Theory

The modes in a cavity are determined by the boundary conditions. For a rectangular cavity of dimensions L (length), W (width) and H (height), the mode frequencies $F_{l,m,n}$, in MHz, can be shown to be[15]

$$F_{l,m,n} = 150\sqrt{\left(\frac{l}{L}\right)^2 + \left(\frac{m}{W}\right)^2 + \left(\frac{n}{H}\right)^2} \qquad \text{(Eq. A2)}$$

where:
l, m and n are the mode indices,
L, W and H are the chamber dimensions in meters.

Figure A2 shows the theoretical mode distribution as a function of frequency for a 10.8m x 5.2m x 3.9m rectangular chamber. Each mode represents a unique field variation (modal structure) as a function of spatial location throughout the cavity. The first resonance of this chamber ($F_{l,m,n}$) occurs at a frequency of 32.096 MHz.

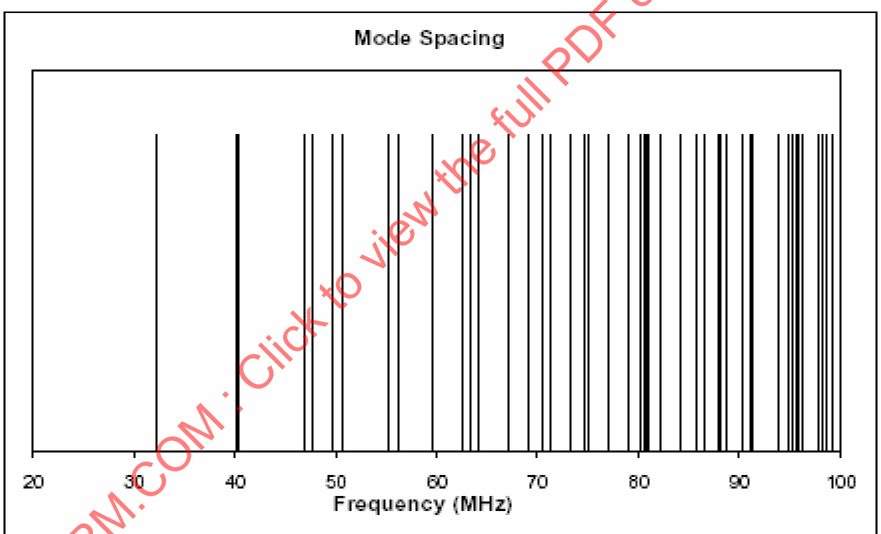

FIGURE A2—THEORETICAL MODAL STRUCTURE FOR A 10.8m x 5.2m x 3.9m CHAMBER (VERTICAL AXIS HAS NO MEANING OTHER THAN TO REPRESENT MODE FREQUENCY)

A.2.1 The cavity quality factor bandwidth, BW_Q, is defined as $F_{l,m,n}/Q$ at the 3 dB points of a Gaussian distribution[5,7]. A representative BW_Q is shown at $F_{4,2,2}$ (the 60th mode) in Figure A3. In this case, only a few modes are excited when the cavity is driven at $F_{4,2,2}$.

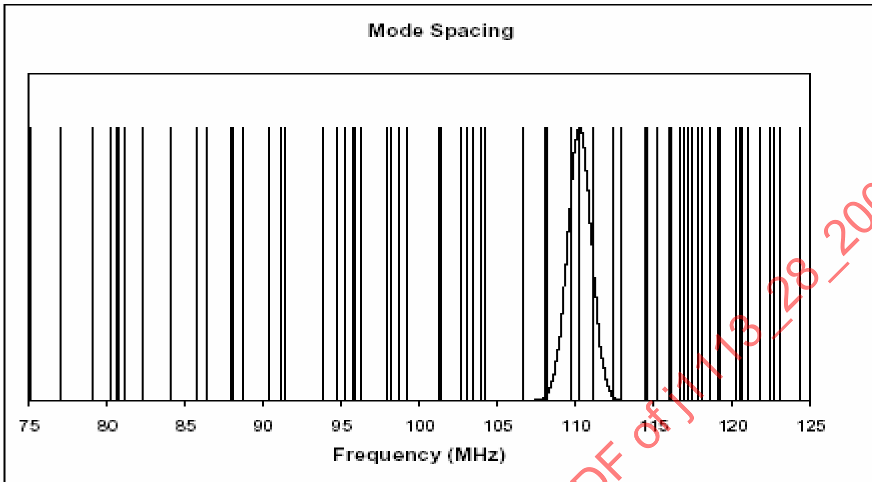

FIGURE A3—THEORETICAL MODAL STRUCTURE WITH QUALITY FACTOR BANDWIDTH SUPERIMPOSED ON 60th MODE

A.2.2 Figure A4 shows the effects of decreasing the Q of the cavity. In this case, additional modes can be excited when the cavity is driven at the frequency of the 60th mode. The effective modal structure would be the vector sum of the excited modes with different amplitudes. The spatial field variation will be different than that obtained with the higher Q cavity. Thus varying the cavity Q can change the “effective” modal structure. Note that if the frequency were increased, more modes would be available within a given BW_Q. Again, the effective modal structure would be the vector sum of the modes.

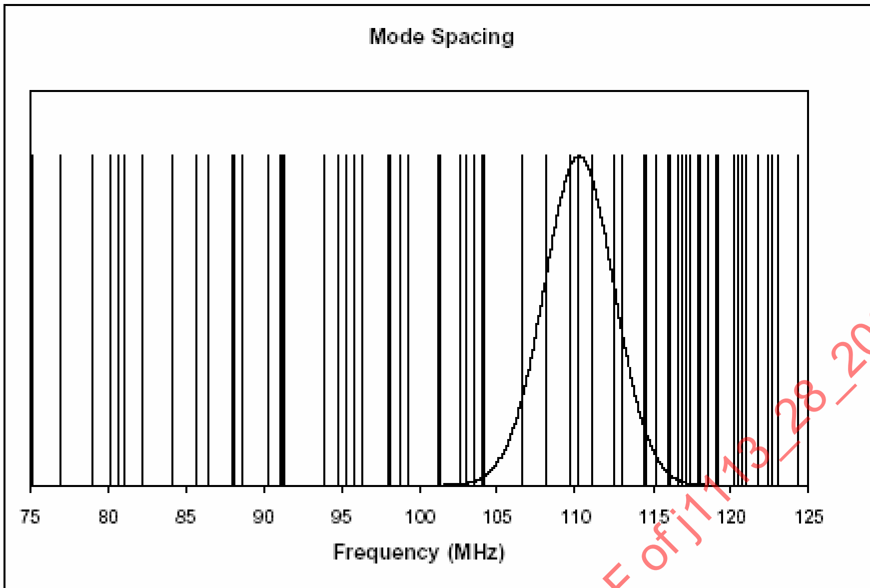

FIGURE A4—THEORETICAL MODAL STRUCTURE WITH GREATER QUALITY FACTOR BANDWIDTH (LOWER Q) SUPERIMPOSED ON 60th MODE

A.2.3 Figures A3 and A4 show that at the lower frequencies the modal population of a chamber is sparse. The figures also show that as frequency is increased the number and density of the modes increases.

A.2.4 The effective modal structure combined with the ability of the tuner to change the boundary conditions of the chamber determines how well a chamber will perform.

A.2.5 The effective modal structure depends on both the theoretical mode density and the quality factor bandwidth at the frequency of interest. The number of modes M excited in a BW_Q can be estimated by

$$M = \frac{8\pi V f^3}{c^3 Q} \quad \text{(Eq. A3)}$$

which is independent of the shape of the cavity[1].

A.2.6 Theories at present suggest that an “overmoded” condition exists when a sufficient number of modes are excited. In the overmoded condition, the power distribution has been shown to fit a Chi Squared distribution[14]. At lower mode densities, the distributions of received power do not fit the Chi Squared distribution.

A.2.7 It is not practical to define a minimum size test chamber and it is outside the scope of this standard to provide detailed design guidance. The critical factor is that if a chamber fulfills the calibration procedure (B.1.1) then this demonstrates that it will provide the required electromagnetic environment at the desired level of statistical confidence.

A.3 Tuner Efficiency

In order to apply statistics to data obtained from a reverberation chamber, the number of independent samples must be known. For a given frequency, a tuner (or tuners) must alter the boundary conditions sufficiently to effect a statistically significant change in the field pattern of the chamber. Once such a change has occurred in the field structure, any samples obtained from the fields resulting from the new tuner position are said to be statistically independent from those of the previous tuner position. Tuner performance data must be obtained in order to determine the number of statistically independent samples a given tuner (or tuners) can provide at a desired frequency. Tuner performance data is obtained by monitoring the received power at evenly spaced intervals over one tuner rotation. The tuner performance can be estimated by calculating the correlation coefficient between tuner steps[6]. A typical correlation coefficient calculation involves consecutively shifting the data file by one sample for each tuner step as shown below, assuming a total set of 450 samples.

D1, D2, D3, D4, D5,D6,··D450

D450,D1,D2,D3,D4,D5,D6,··D449

D449,D450,D1,D2,D3,D4,D5,D6, ···D448

D448,D449,D450,D1,D2,D3,D4,D5,D6 ···D447

The correlation coefficient r can be calculated using the following formula:

$$r = \frac{\frac{1}{N}\sum_{i}^{N}(x_i - u_x)(y_i - u_y)}{\sqrt{\left(\underbrace{\frac{\sum_{i}^{N}(x_i - u_x)^2}{N-1}}_{\sigma_x^2}\right)\left(\underbrace{\frac{\sum_{i}^{N}(y_i - u_y)^2}{N-1}}_{\sigma_y^2}\right)}} \qquad \text{(Eq. A4)}$$

where:

y_i is the same distribution as x_i but shifted by one sample for each tuner step.
u_i is the mean of the original received power vs tuner position data set

NOTE—x_i and y_i are received power values

since the y distribution is the same as the x distribution (there is only one data set, the distribution of the shifted data is the same as the original data set)

$$U_y = U_x \text{ and } \sigma_x = \sigma_y \qquad \text{(Eq. A5)}$$

The correlation coefficient r can be obtained using the correlation function built into most spreadsheets by comparing the original data set to the shifted data sets. The data becomes uncorrelated when the magnitude of the correlation coefficient is less than 0.36. Dividing the total number of samples (e.g. 450 above) by the number of steps necessary to reduce the correlation coefficient to less than 0.36 yields an estimate of the number of independent samples the tuner can provide at a particular frequency.

EXAMPLE—Carry out the above procedure on a chamber rotating the mechanical tuner 360 degrees in 450 evenly spaced steps at 80, 100 and 500 MHz. If the correlation coefficient became less than 0.36 after 25, 15, and 5 steps of the tuner respectively, then the tuner could be expected to deliver 18 independent samples at 80MHz, 30 independent samples at 100 MHz, and 90 independent samples at 500 MHz. As shown in the next section, the number of tuner steps required may exceed the ability of a single tuner to provide. In such cases a second tuner will be necessary.

A.4 Reverberation Chamber Statistics, Number of Samples Required, Tuner Effect on the Mean Chamber Field, Tuner Effect on the Maximum Chamber Field

The calibration procedure for this standard is based on the statistical nature of complex cavities[14,3]. It has been experimentally validated that the fields in a reverberation chamber can be theoretically predicted using the appropriate statistical models[4,5,7,8]. These models define distribution functions for 1) the received power by an antenna which is related to the chamber scalar power density and the electric field squared, 2) the maximum received power or the maximum electric field squared, 3) a rectangular component of the electric field, and 4) the maximum of a rectangular component of the electric field. These four distributions are different but relatable. There will be no attempt to cover reverberation chambers statistics in detail in this Appendix although some specific properties of some of the distributions will be discussed below. The function of a reverberation chamber is to generate a statistically uniform (i.e. statistically isotropic) test environment within acceptable uncertainty and confidence limits. This is accomplished by introducing a mechanical tuner into a shielded room, which is used to redistribute the field energy. The tuner changes the boundary conditions within the chamber when it is moved or rotated. Once the tuner has been moved to a sufficient number of new positions, the field variations resulting from rotating the tuner provide a set of fields covering all directions and polarizations. This implies that the magnitude and directionality of the fields was the same, within bounded uncertainty limits, for all points within the chamber. The term "isotropic" is often used to refer to the environment generated by a reverberation chamber. This term is somewhat misleading since the environment did not arrive with equal magnitude from all directions and polarizations simultaneously. For this reason the term should be used with caution when referring to reverberation chambers.

For the following discussion, it is assumed that the chamber dimensions are large compared to the excitation wavelength (the chamber is overmoded[4]) and that the chamber has a complex configuration. The introduction of antennas and tuners assure the required complexity in an otherwise regular cavity. In addition, we will restrict our discussion to the fields within the working volume of the chamber. The working volume is defined as being a distance of $\lambda/4$ from the chamber walls and from any antenna, tuner, or other object at the lowest frequency of operation. For a chamber operating above 100 MHz this would be 0.75 meter. A typical reverberation chamber facility is shown in Figure A5.

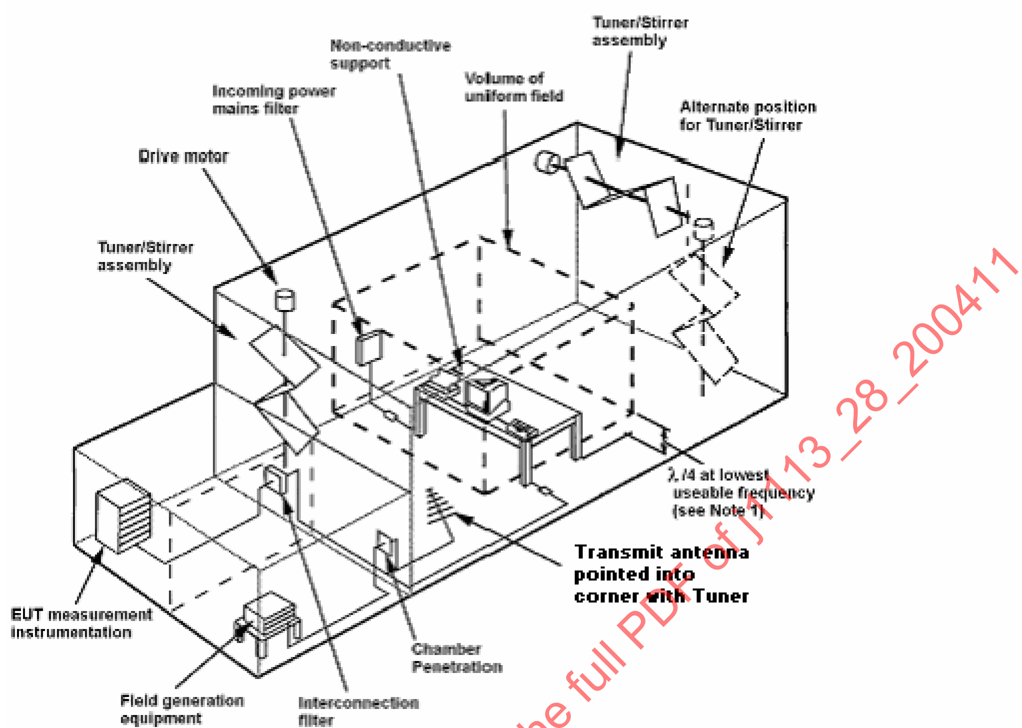

FIGURE A5—TYPICAL REVERBERATION CHAMBER FACILITY

A.4.1 Number of Samples Required

Given the distribution of the fields within a cavity, the number of samples that would have to be taken in order to determine the field level to within a given uncertainty can be determined. Figure A6 shows a theoretical prediction for the number of independent samples (boundary condition changes or steps of the mechanical tuners) required to obtain a 6 dB field uncertainty at a 95% level of confidence for a given cavity. As Figure A6 shows, at lower mode densities, as defined by Equation A3, the number of samples required increases rapidly. If the confidence level is lowered, then the number of samples required to obtain the same uncertainty is reduced. As shown in Figure A7, the number of samples can be reduced if the field uncertainty is lowered moderately. As noted above the number of samples depicted in Figures A6 and A7 are based on statistical theory[14,7]. In practice, the mechanical tuner may not be capable of providing the number of independent samples required to give the desired performance. For this reason, tuner performance should be evaluated as detailed in A.3 to determine the number of samples, which can be provided by a given tuner at a given frequency.

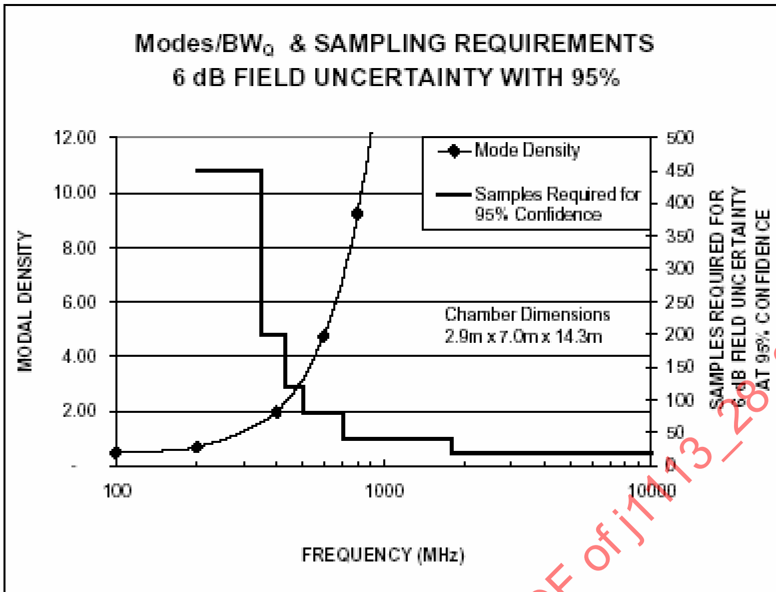

FIGURE A6—THEORETICAL SAMPLING REQUIREMENTS FOR 95% CONFIDENCE

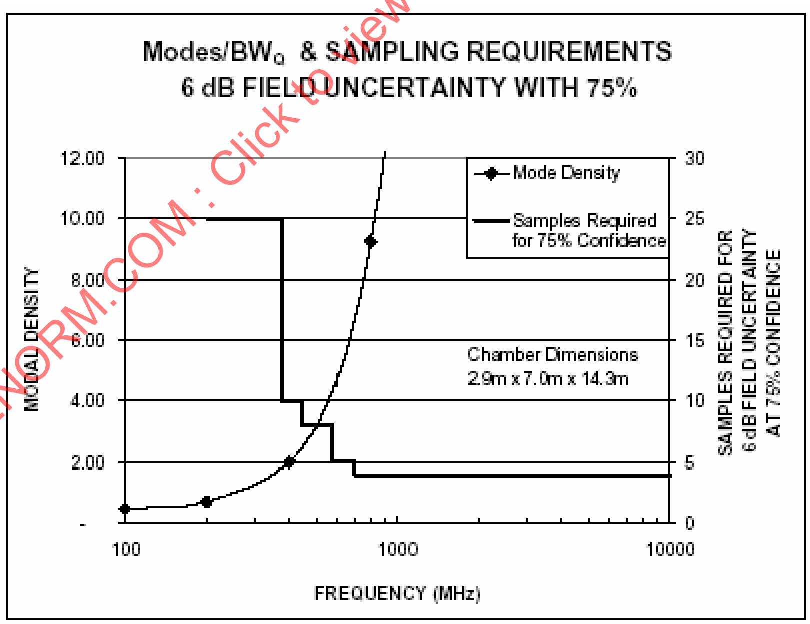

FIGURE A7—THEORETICAL SAMPLING REQUIREMENTS FOR REDUCED CONFIDENCE

A.4.2 Tuner Effect on the Mean Chamber Field

For an ideal reverberation chamber, the volume (spatial) mean value of the field for a fixed boundary condition and an “ensemble” average are equivalent[14,7]. An ensemble average is the average of the field at a fixed location for multiple boundary conditions. In reverberation chambers, boundary condition changes are typically achieved by rotating a mechanical tuner. However, boundary conditions changes also occur for any change in the configuration of performing objects such as antennas, test articles, and supporting instrumentation and equipment. Figure A8 is the probability density function (PDF) of the field at a location within an ideal reverberation chamber normalized by the “true” volume or ensemble average. As shown in Figure A8, the field in the chamber at an arbitrary location and a single boundary condition or at a single location and an arbitrary boundary condition can vary more than 30 dB. Figure A8 also shows that about 98% of the data for a single sample (N=1) would be between +10 dB and –20 dB. Figure A9 shows that, as the number of boundary condition samples (tuner steps) is increased, the Measured mean of the chamber field at any given location in the chamber converges toward the “true” mean value. The measured mean value is the “expected value” of multiple samples. The width of each curve is a measure of the uncertainty that would be expected in the mean at an arbitrary location in the working volume for N samples. Note that the improvement in the uncertainty of the mean field is very rapid as the number of tuner steps is first increased and then slows as N gets larger. Figure A9 also shows that for 12 tuner steps the uncertainty of the mean field is about 5 dB at the 95% confidence interval and about 2.4 dB for 100 tuner steps. This would correspond to an eight-fold increase in test time for a 2.3 dB reduction in measurement uncertainty in the mean field level.

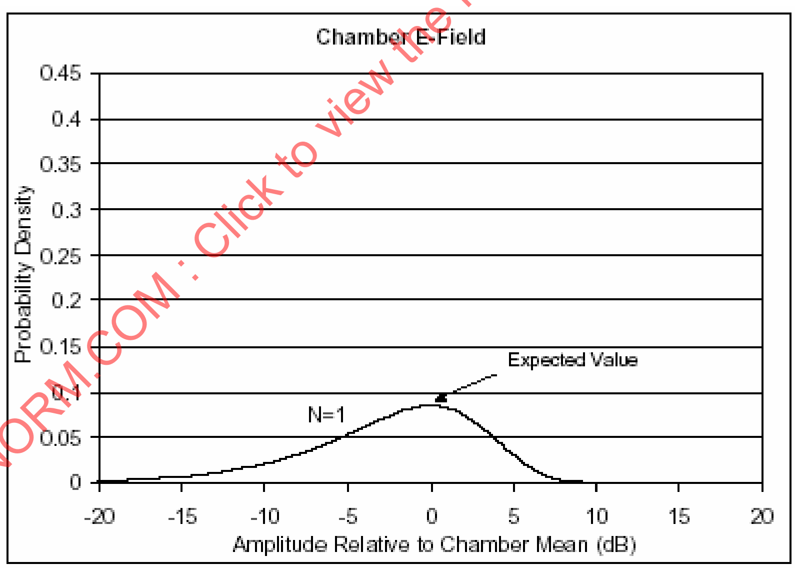

FIGURE A8—NORMALIZED PDF OF AN ELECTRIC FIELD COMPONENT AT A FIXED LOCATION FOR A MEASUREMENT WITH A SINGLE SAMPLE

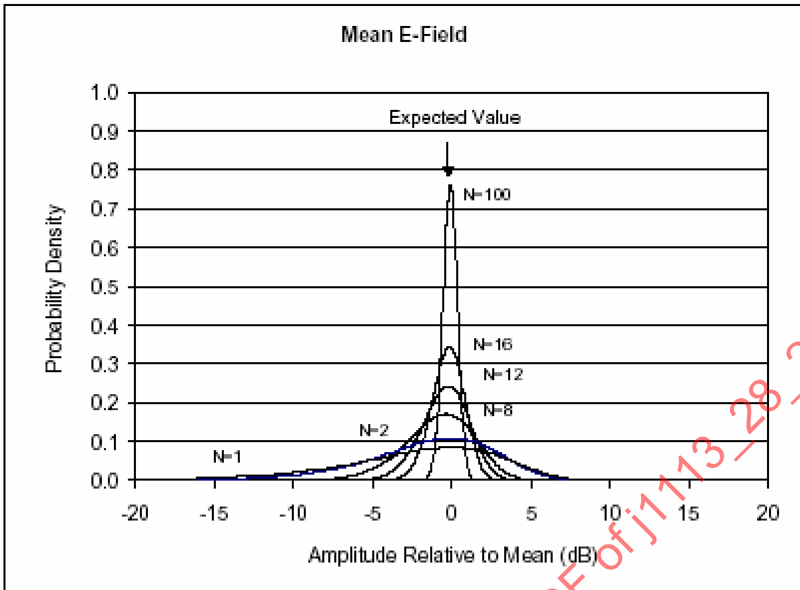

FIGURE A9—NORMALIZED PDF OF THE MEAN OF AN ELECTRIC FIELD COMPONENT AT A FIXED LOCATION FOR A MEASUREMENT WITH N SAMPLES

A.4.3 Tuner Effect on the Maximum Chamber Field

The distribution for N=1 shown in Figure A8 is valid for both mean and maximum fields, because the maximum, minimum, and mean measured at a location are all the same value, for a fixed position of the tuner. The PDF for the maximum field at an arbitrary location within a chamber is shown in Figure A10. As N increases, the distribution moves to the right and gets narrower (improved uncertainty). Also, like the mean field level, the improvement in uncertainty for the maximum field level is very rapid as the number of tuner steps is first increased and then slows as N gets larger. Figure A10 shows that for 12 tuner steps the uncertainty of the maximum field is about 7.2 dB at the 95% confidence interval and about 4.8 dB for 100 tuner steps. This would correspond to an eight-fold increase in test time for a 2.4 dB reduction in measurement uncertainty in the maximum field level. Also, note that increasing the number of tuner steps from 12 to 100 steps increases the expected value of the maximum field by about 3 dB.

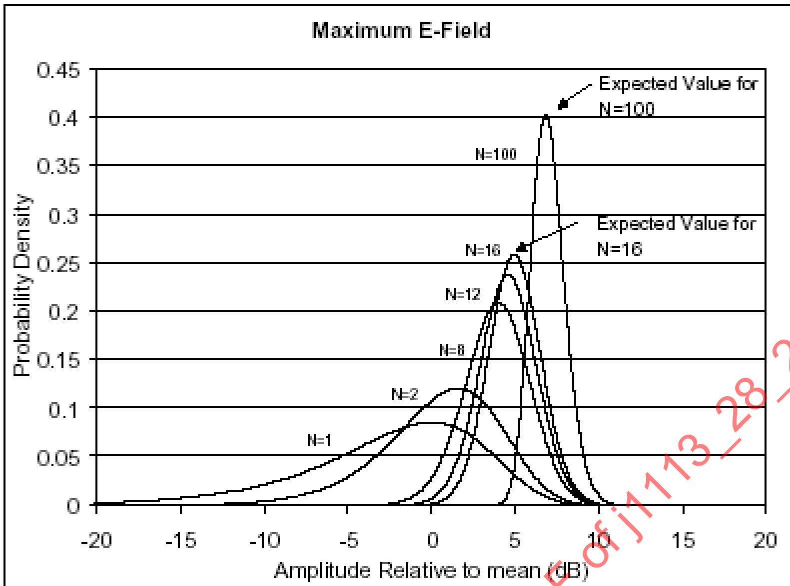

FIGURE A10—NORMALIZED PDF OF THE MAXIMUM OF AN ELECTRIC FIELD COMPONENT AT A FIXED LOCATION FOR A MEASUREMENT WITH N SAMPLES

Since the PDF for the maximum field applies at any arbitrary location, as it does with the mean field, the PDF is also a measure of the spatial uniformity for N samples of the maximum field over the working volume of the chamber.

A.5 Chamber Calibration, Calibration Procedure, Field Uniformity, E-Field, Loading Effects, Generating a Test Environment, Other Concerns

For this standard, the purpose of the calibration is to verify that the fields generated have the same magnitude, within defined uncertainty limits, for all polarizations (i.e. for all directions of arrival at all locations within the working volume) for a given number of tuner steps. In order to meet this requirement the use of an Isotropic E-field probe, which allows access to each axis of the probe, is required in order to perform the calibration. The calibration procedure should be performed once in the life of the chamber and after major modifications.

The empty chamber calibration procedure is based on a comparison of the peak fields measured by Isotropic E-field probes to the mean received power of a reference antenna. To enhance accuracy the reference antenna mean data is obtained for nine locations within the working volume. The number of samples recommended for calibration is based on a “theoretical” chamber of approximately 3 x 7 x 15 meters size and typical Q for a chamber constructed of welded steel. The number of samples required was rounded up to account for variations from this “theoretical” chamber in order to ensure a conservative test. It is possible that a larger chamber or one with a lower Q than the “theoretical” chamber could meet this calibration requirement using less than the recommended number of steps.

A.5.1 Calibration Procedure

The calibration procedure collects Isotropic E-field probe data (maximum data only) as well as chamber input power and the maximum and mean received power from a reference antenna placed within the working volume. The probe data are used to determine field uniformity. The probe data and chamber input power is used to determine the chamber calibration factor. The mean received power from the reference antenna and chamber input power is used to calculate an Antenna Calibration Factor (ACF). The ACF is used as a reference value when determining if the chamber has been "loaded" by a DUT. The maximum received power from the reference antenna is used to verify the probe readings. Probe data are collected from the nine locations that form the corners of the "volume of uniform field" or "working volume" as shown in Figure A11. Each time the probe is moved to a new location, the reference antenna is moved to a new location within the working volume. The orientation of the reference antenna relative to the chamber axes is also changed at least 20 degrees relative to each axis at each position. This ensures that any bias in the field is detected (e.g. no dominate polarization exists within the chamber). A minimum of nine locations for both the probe and reference antenna is required. Note: Once a chamber has been shown to operate properly over a frequency span of 300 to 400 MHz at the minimum number of tuner steps (i.e. 12), the number of locations may be reduced to three. For the chamber used to collect the data presented in this Appendix, the reduction in the number of locations occurred at 1000 MHz. As previously shown, the uniformity of the field depends on the number of tuner positions (N) used to collect the data. Recall that for a relatively modest number of tuner steps (i.e., 12), a reasonably uniform field can be obtained. As previously stated this is true for overmoded cavities. Every chamber will have a frequency at which it is no longer overmoded[5], and hence, it can no longer be used as reverberation chamber. This frequency will mostly be dependent on chamber size, and the cutoff will be gradual rather than abrupt as frequency decreases. In some cases, it is possible to compensate for decreased modal density that results as the operational frequency approaches the "undermoded" condition. In general and with care, compensation can be achieved by increasing the number of tuner steps, but effects may be limited. Table A1 lists the number of tuner steps "recommended" for performing the calibration. The number of steps may need to be decreased or increased to optimize performance. The minimum number of tuner steps should not be less than twelve.

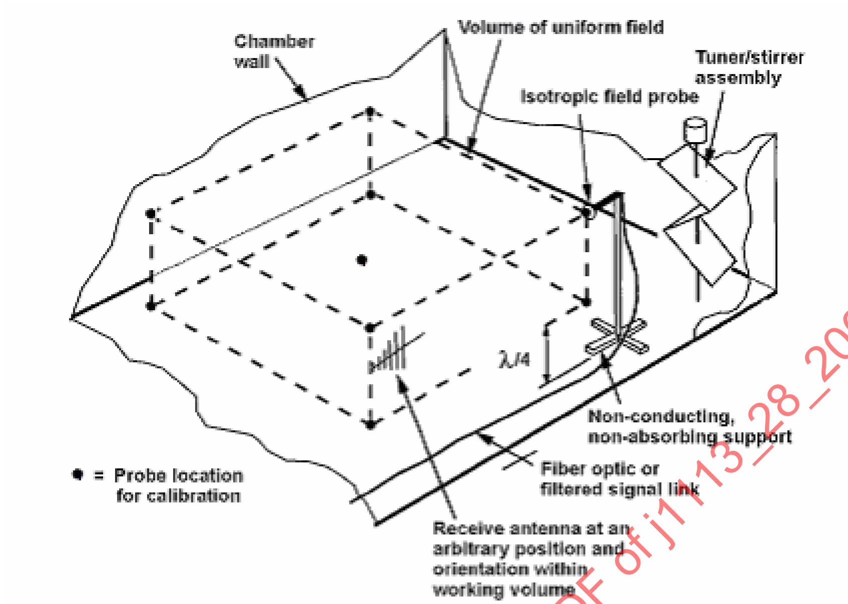

FIGURE A11—CHAMBER WORKING VOLUME

TABLE A1

Frequency Range	Number of Samples[1] Recommended for Calibration and Test	Number of Frequencies[2] Required for Calibration
f_s to 4 f_s	50	50/decade
4 f_s to 8 f_s	18	50/decade
Above 8 f_s	12	20/decade

1. (i.e. independent tuner positions or intervals)
2. logarithmically spaced

f_s = Start Frequency

A.5.2 Field Uniformity

The goal of a reverberation chamber is to generate a statistically uniform environment, within some bounded uncertainty, for all locations within the defined working volume. The procedure just described is designed to measure the expected magnitude and uniformity for a given chamber using a given number of tuner steps. A typical set of probe data obtained using the calibration procedure (x-axis only for clarity) is shown in Figure A12. Figure A13 shows the data of Figure A12 normalized to the mean of the eight maximum x-axis probe readings at each frequency (B.1.1.9(b)). The data show that the measured field uniformity is about ± 10 dB at 100 MHz and decreases as frequency increases. Also, note how the data at the higher frequencies show good uniformity even though the number of tuner steps is decreased.

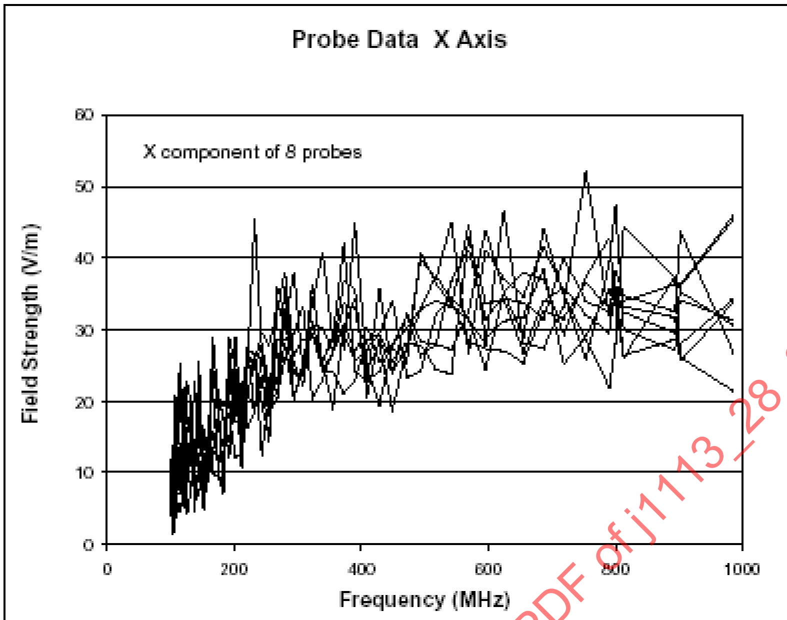

FIGURE A12—TYPICAL PROBE DATA

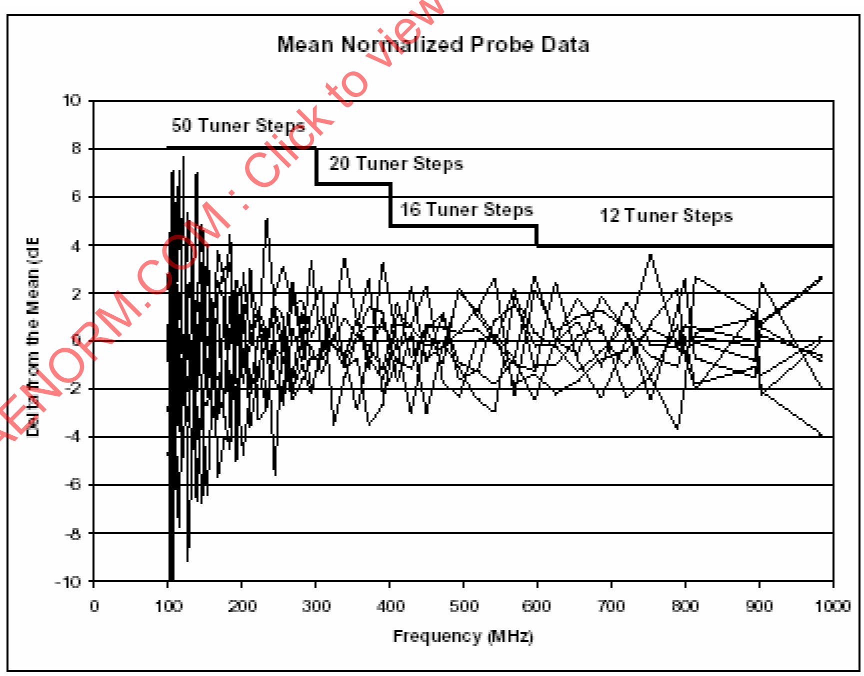

FIGURE A13—MEAN-NORMALIZED DATA FOR X COMPONENT OF E-FIELD OF PROBE DATA (8 PROBES)

NOTE—Due to the optimization of the number of tuner steps to fit the characteristics of the chamber used, the number of steps used to collect the data shown in Figure A13 does not match Table 1. So at what point is this chamber acceptable? At present, there are two schools of thought as to which is the best method to determine acceptable uniformity. For the first method[1], acceptable uniformity is decided by throwing away 25% of the data that have the most variation and then requiring the remaining data to be within a given limit. In the second method[10,11], acceptable uniformity is determined by calculating the standard deviation of the data and requiring that the standard deviation be within a given limit. The first method's major drawback is that there is no "weight" given to the data that are thrown away. This could result in the uncertainties being essentially an unknown. For the purposes of this standard it has been agreed to use the standard deviation method. The reason for adopting the standard deviation method is that all data is considered and given appropriate weight.

The standard deviation of the data shown in Figure A13 is shown in Figure A14. The data show the standard deviation exceeded 3 dB below about 200 MHz. For reference, the tolerance for the commercial aircraft avionics standard is shown as a heavy dashed line[10].

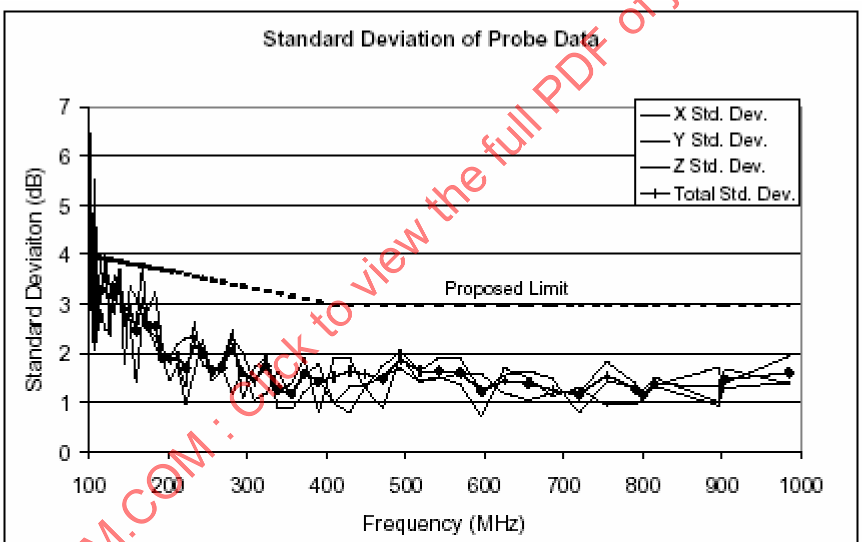

FIGURE A14—STANDARD DEVIATION OF DATA FOR E-FIELD COMPONENTS OF 8 PROBES

NOTE—The limit for this standard is the same as the proposed limit in[10] at frequencies common to both standards. The chamber is considered to pass the field uniformity requirements provided that the standard deviation for both the individual field components (E_x, E_y, and E_z) and the total data set (ETotal) are within the specified tolerance. The total data set consists of the 27 measurements made by combining the three individual field components (E_x, E_y, and E_z) from the nine probe locations. Note: The total data set is NOT the more commonly used ROOT SUM of the SQUARES (RSS) OF E_x, E_y, and E_z. The chamber used to collect this data could not be used below 130 MHz, according to the proposed limit, unless the field uniformity is improved[12]. The proposed limit was developed by a committee made up of representatives from both industry and government, and included both operators of reverberation chambers, as well as those not familiar with the method.

A.5.3 Chamber E-Field

The “expected” amplitude of the chamber E-field during the calibration is simply the average of the 27 maximum probe readings (the mean of the maximums). The “expected value” is the value to which the chamber is calibrated (see Figure A10). It is also possible to estimate the chamber E-field based on the reference antenna measurements. Equation A6, which was derived using methods similar to those used to derive expressions for the mean field in[13], gives an estimate of the chamber E-field based on the maximum readings from the reference antenna averaged over the number of antenna locations.

$$E_{Est} = \left\langle \frac{8\pi}{\lambda}\sqrt{5 * \frac{P_{MaxRec}}{\eta_{rx}}} \right\rangle_{\#\ AntennaLocations} \quad \text{(Eq. A6)}$$

where:

P_{MaxRec} = the maximum received power over the given number of tuner steps at an antenna location,
η_{rx} = the antenna efficiency factor for the receive antenna which can be assumed to be 0.75 for a log periodic antenna and 0.9 for a horn antenna[16].

For all measurements, it is assumed that the forward input power is the same for all data collected. If so, then the data can be normalized after taking the average of the probe readings. If not, then the probe readings need to be normalized to the input power, which corresponds to that probe reading. Normalizing the E-field to the chamber input power is done by dividing the probe reading by the square root of the input power. This can also be done for the estimated E-field based on the reference antenna.

It is recommended that a cross check be performed by comparing the expected E-field measured by the probes and the expected E-field estimate based on the nine antenna measurements. Any discrepancies greater than ± 3 dB between the probe and antenna based measurements should be resolved. Note that significant disagreement at the lower frequencies is expected. This is due to loading caused by the transmit and receive antennas. For this reason, the agreement between the two methods is not expected at frequencies where the difference between the chamber input power and the measured maximum received power from the reference antenna is 10 dB or less.

A.5.4 Loading Effects

When the DUT is placed into a reverberation chamber there is the possibility that the DUT will “load” the chamber. If the DUT loads the chamber, the energy absorbed by the DUT is no longer available to generate the desired environment. For this reason, the chamber input power needs to be increased to compensate for this loading.

NOTE—This is one of the more abstract aspects of reverberation chamber testing. The source of the fields is actually the reflection of RF energy from the walls. Although an antenna is used to inject RF energy into the chamber, that energy is not directed at the DUT. If the DUT absorbs energy then that energy is no longer available to contribute to the generation of the test environment. The following data will demonstrate the concept. Consider this when reviewing the data. If the field probes surrounding the “loaded” working volume measure the field: how could the items within the working volume be exposed to fields greater than measured by the probes?

Prior to performing any test, a check for loading effects must be made. This is done by measuring the mean power received by the reference antenna for the same number of tuner steps used to perform the calibration with the DUT in place. The data from this single measurement are then compared to the nine measurements from the calibration. If the mean received power measured with the DUT in place DOES NOT exceed the uniformity of the mean field measured during the calibration (i.e., it is not greater or less than the calibration data), then the chamber is considered to not have been loaded by the DUT. If the measurement exceeds the uniformity of the mean field measured during calibration, a correction factor will be required when calculating the input power necessary to generate the desired test field. This factor is referred to as the chamber loading factor (CLF). The CLF is obtained by taking the ratio between the measurement taken with the DUT in place and the mean or "expected value" from the nine measurements taken during the calibration[10].

To determine the limit to which a chamber may be loaded an evaluation must be performed to evaluate the field uniformity under severe loading conditions (B.1.5). An example of such an evaluation is shown in Figure A15. The working volume of this reverberation chamber was loaded with 27 pieces of 48-inch pyramidal absorber. Figure A16 shows the amount of loading induced into the chamber by the absorbers. The chamber loading or the amount of loading respectively, over the frequency range of 100 MHz to 18 GHz varied from a maximum of about 23 dB to a minimum of 10 dB with a mean loading of about 14 dB. Figure A17 shows the standard deviation of the fields in the loaded chamber. The standard deviation of the loaded chamber, while varying slightly from the empty chamber calibration shown in Figures A13 and A14, did not show significant degradation.

FIGURE A15—DISTRIBUTION OF ABSORBERS FOR LOADING EFFECTS TEST

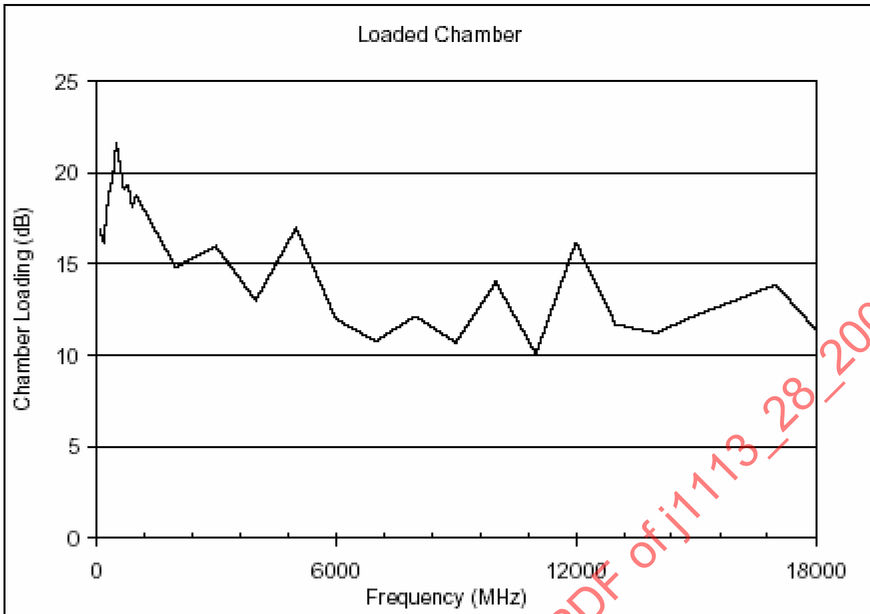

FIGURE A16—MAGNITUDE OF LOADING FROM LOADING EFFECTS TEST

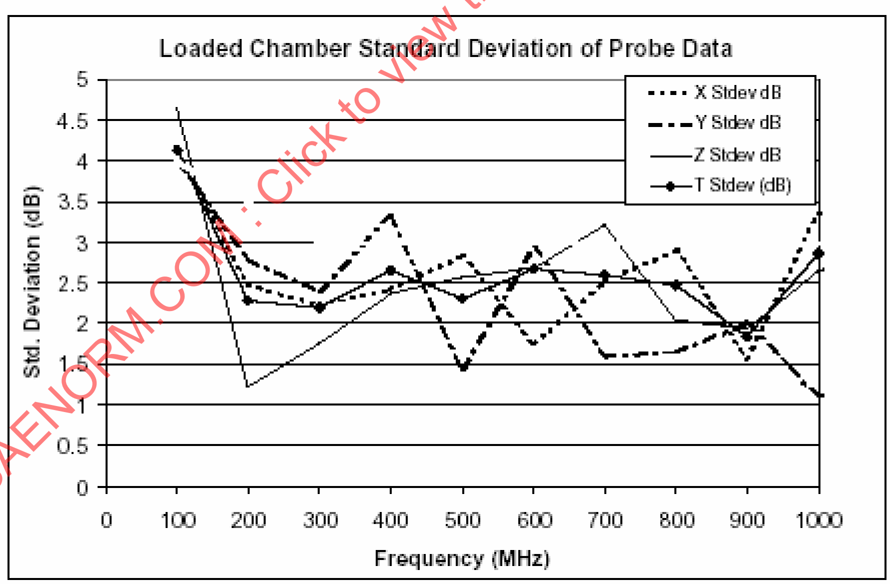

FIGURE A17—STANDARD DEVIATION DATA FOR ELECTRIC FIELD COMPONENTS OF 8 PROBES IN THE LOADED CHAMBER

NOTE—Standard deviation increased (instead of decreasing) by approximately ½ dB most probably due to probe proximity to absorber.

A.5.5 Generating a Test Environment

The desired test environment is generated by injecting the proper amount of power into the chamber.

The power necessary to generate the desired field strength can be calculated using Equation A7.

$$P_{Input} = \left[\frac{E_{Test}}{\overleftrightarrow{E} * \sqrt{CLF}} \right]^2 \qquad \text{(Eq. A7)}$$

where:

E_{test} is the required field strength (V/m),

CLF is the chamber loading factor (B.2.7),

$\overleftrightarrow{E}$ is the average of the maximum E-field measured by the probes normalized to the square root of the input power used during calibration (B.1.1.9(b)).

Note that the probe measurements used to determine the chamber E-field are the rectangular components of the probe, NOT the RSS. For the purposes of this standard, it has been agreed by committee members, including representatives of several national standards organizations, to establish field levels using individual rectangular components. The other main alternative is to calibrate using the RSS of the probe readings, as is often done in anechoic chamber methods. In the properly functioning plane-wave environment of an Anechoic Chamber, two of the rectangular components are zero. This results in the RSS and rectangular readings being equal, which is not the case in reverberation chambers.

A.5.6 Other Concerns

The calibration is based on using CW excitation. When using modulated waveforms consideration must be given to distortion caused by the chamber quality factor or "Q" (see Section B.3). The chamber Q can be calculated using Equation A8.

$$Q = \left(\frac{16\pi^2 V}{\eta_{Tx}\eta_{Rx}\lambda^3} \right) \left\langle \frac{P_{AvgRec}}{P_{Input}} \right\rangle_{\#\ AntennaLocations} \qquad \text{(Eq. A8)}$$

where

η_{Tx} and η_{Rx} are the antenna efficiency factors for the transmit and receive antenna respectively and can conservatively be assumed to be 0.75 for a log periodic antenna and 0.9 for a horn antenna

V is the chamber volume (m^3),

λ is the free space wavelength (m) at the specific frequency,

P_{AveRec} is the averaged received power from the reference antenna,

P_{Input} is the chamber input power[10]

Antenna Locations is the number of antenna locations used to collect the calibration data at the frequency being evaluated.

For pulse testing the chamber time constant , τ is given by Equation A9

$$\tau = \frac{Q}{2\pi f} \quad \text{(Eq. A9)}$$

where Q is the value calculated using Equation A7 above, and f is the test frequency (Hz)[10]. The chamber time constant should not be greater than 0.4 of any modulation test waveform pulse width. If it is, absorber must be added to the chamber or the pulse width increased. If absorber is used, add absorber until the time constant requirement is satisfied with the least possible absorber. A new CLF must be defined if absorber material is required. If the loading due to the absorber is greater than that obtained in the chamber loading verification (B.1.5) then the chamber calibration must be repeated.

A.6 Summary

The method used by this standard to calibrate a reverberation chamber has been presented. The statistical nature of the fields within a reverberation chamber, how to collect the data necessary to characterize a chamber, how to analyze the data to determine chamber performance, and how to determine the chamber input power necessary to generate a desired test environment have been reviewed.

The procedure described provides an accurate and economic methodology for calibrating reverberation chambers. The procedure is flexible in that it allows for an operator to adjust the number of tuner steps used to obtain the desired level uncertainty as well as maximize the ability of the chamber to generate higher fields by increasing the number of tuner steps. As previously stated, the mode density of a given cavity determines the number of samples required. Although a minimum sized chamber was estimated for calculating the mode densities at which the minimum requirements at 80 MHz are met, it is not practical to attempt to define a minimum sized chamber for this standard. A chamber's lowest useable frequency depends on it's dimensions, the tuner effectiveness, and on the Q of the chamber, which is heavily influenced by the construction materials, types of antennas used (antennas contribute significantly to chamber loading at lower frequencies), etc.

The calibration procedure does place a stringent requirement on the chamber being evaluated. The data required places the need for the time-averaged fields generated within the test volume to be uniform to within a given uncertainty. To ensure this requirement is met, three measurements are required at each of the 9 locations using three mutually perpendicular orientations. Each measurement is independent which results in a total of 27 measurements being taken. A chamber that passes the calibration procedure will have demonstrated its ability to generate the required field uniformity.

Further details can be found in IEC 61000-4-21.

APPENDIX B
(NORMATIVE)
MODE TUNING CHAMBER CALIBRATION

B.1 Calibration

As an initial guide to chamber performance and input power requirements, perform a "one-time" empty chamber calibration (no DUT) using the procedures of Section B.1.1. Prior to each test a calibration shall be performed using the procedures of Section B.2. The chamber field uniformity must be verified over the first decade of the operational frequency range. A chamber can be used to perform tests at and above the frequency at which the chamber meets the field uniformity requirements in Table B2.

B.1.1 Field Uniformity

B.1.1.1 Clear the working volume (i.e. remove test bench) and place the receive antenna at a location within the working volume of the chamber as outlined in the notes of Figure B1. Set the amplitude measurement instrument to monitor the receive antenna on the correct frequency.

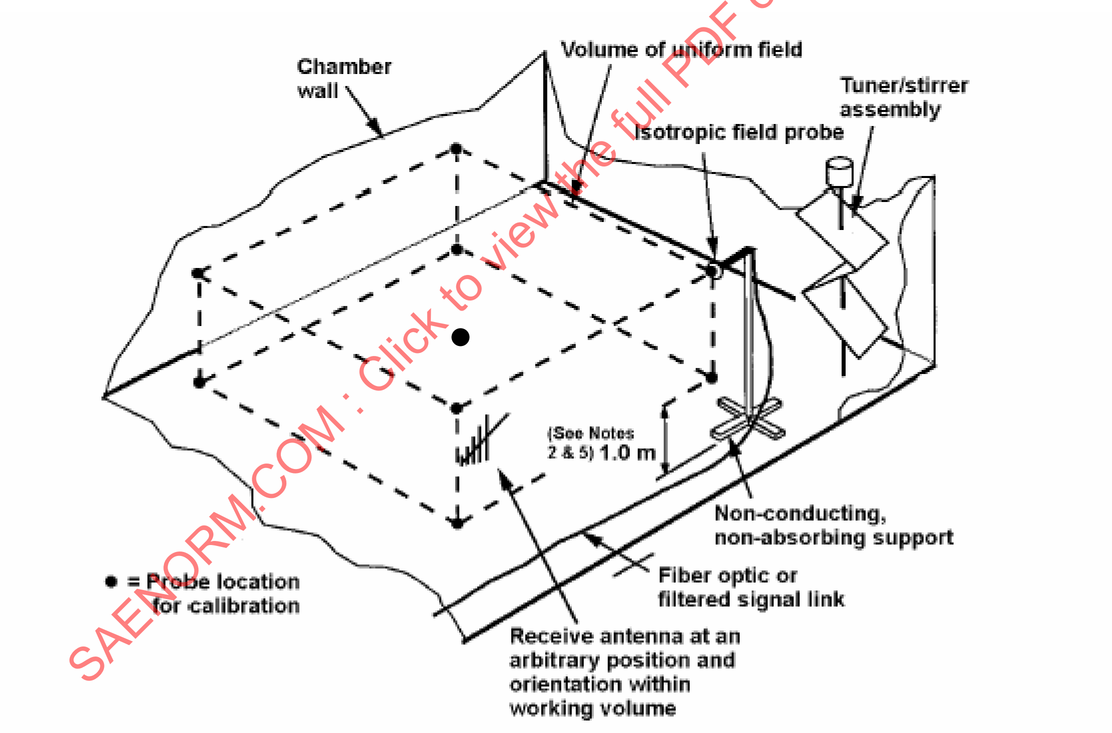

FIGURE B1—PROBE LOCATIONS FOR CHAMBER CALIBRATION

NOTE 1—Calibration of the fields inside the reverberation chamber shall consist of nine probe locations.

NOTE 2—The locations shall enclose a volume as shown above with the ninth location to be at the center of the working volume. This volume is the “working volume” of the chamber. It is recommended that the surfaces bounding the working volume not be located closer than 1 meter (see note 5) from any chamber surface, field generating antenna or tuner assembly. For calibration and monitoring purposes the receive antenna may be located at any location within the working volume. The transmit antenna should be directed into a corner of the chamber if possible (See Figure 1 for location of transmit antenna). Directing the antenna into the tuner is also acceptable. The location of the transmit antenna shall remain fixed during calibration and testing. The location of the transmit antenna shall be the same for both calibration and testing.

NOTE 3—The working volume may be sized to suit the maximum working volume of the chamber or sized to suit the items to be tested. It is recommended that the working volume be sized to suit the maximum working volume since a second calibration will be required if larger items are to be tested. The working volume need not be rectangular in shape. For some arbitrary shapes it may be necessary to add calibration points in order to properly define the working volume.

NOTE 4—An Isotropic E-field probe, which provides access to each of the three axes shall be used to perform calibrations. A calibrated electrically short dipole antenna (i.e. less than $\lambda/3$) may be substituted, provided that, the dipole antenna is positioned at three mutually perpendicular orientations for each measurement location. Care should be taken to ensure that the dipole is not influenced by its connecting cable. An optically isolated measurement system (Isotropic E-field probe or dipole) is recommended.

NOTE 5—The minimum separation distance may be reduced to less than 1 meter, provided that, the separation is greater than $\lambda/4$ for the lowest test frequency. Separation distances of less than $\lambda/4$ meter are not recommended in any case.

B.1.1.2 Place the Isotropic E-field probe at a location on the perimeter of the chamber working volume as shown in Figure B1.

B.1.1.3 Beginning at the lowest test frequency (f_s), adjust the RF source to inject an appropriate input power, P_{Input}, into the transmit antenna. The transmit antenna shall not directly illuminate the working volume or the receive antennas and probes. Directing the transmit antenna into one corner of the chamber is an optimum configuration. The frequency shall be in band for both transmit and receive antennas which shall be linearly polarized antennas. Care must be taken to ensure that the harmonics of the RF input to the chamber are at least 15 dB below the fundamental.

NOTE 6—For normal operation the lowest test frequency (f_s) is 80MHz, and field uniformity is demonstrated over the first decade of operation. If a start frequency other than 80MHz is chosen, for example a small chamber used to generate high field strengths, the chamber field uniformity must still be verified over the first decade of operation. The frequency at which a chamber can be used to conduct measurements is the frequency at which the chamber meets the field uniformity requirements in Table B2.

B.1.1.4 Step the tuner through 360° in discrete steps so that the amplitude measurement instrument and Isotropic E-field captures the minimum number of samples as outlined in Table B1 over one complete tuner rotation. Care must be taken to ensure that the dwell time is sufficiently long enough that the amplitude measurement instrumentation and Isotropic E-field have time to respond properly.

B.1.1.5 Record the maximum amplitude and average amplitude (linear average: i.e. watts, not dBm) of the receive signal (P_{MaxRec}, P_{AveRec}), the maximum field strength ($E_{Max\ x,y,z}$) for each axis of the Isotropic E-field, and the average value of the input power (P_{Input}) over the tuner rotation.

NOTE 7—The value for input power, P_{Input}, is the forward power averaged over the tuner rotation. The number of samples used to determine the average should be at least the same as the number of samples used for chamber calibration. Large variations in input power (i.e. 3 dB or more) are an indication of poor source/amplifier performance. All calibrations are antenna specific. Changing antennas may void calibrations. All power measurements are relative to the antenna terminals. The antennas are assumed to be high efficiency antennas (i.e. greater than 75% efficient).

B.1.1.6 Repeat the above procedure in log spaced frequency steps as outlined in Table B1 until frequency is at least 10 f_s.

B.1.1.7 Repeat for each of the nine probe locations (one of which must be at the center of the working volume) shown in Figure B1 and for nine receive antenna locations (one of which must be at the center of the working volume) until 10 f_s.

NOTE 8—Steps B.1.4 and B.1.6 may be interchanged if desired, i.e. step through the frequencies at each step of the tuner.

B.1.1.8 Above 10 f_s only three probe and receive antenna locations need to be evaluated. The probe and antenna should maintain the required clearance from each other and from chamber fixtures. One location for the probe and antenna shall be the center of the working volume. Repeat steps (B.1.4.) and (B.1.5) for the remainder of the calibration frequencies, as outlined in Table B1.

NOTE 9—The receive antenna should be moved to a new location within the working volume of the chamber for each change in probe location. The antenna should also be placed in a new orientation relative to the chamber axis at each location (at least 20° in each axis). For reference purposes x = chamber length (longest dimension), y = chamber width, and z = chamber height. The probe does not necessarily need to be oriented along the chamber axes during calibration.

Care should be taken to ensure that the proper separation distance between the antenna and probe are maintained. Each location should be at least 1 meter (or λ/4 at the lowest test frequency) from any previous location. If the receive antenna is to be mounted in a fixed position during routine testing, it is suggested that one of the locations should be the intended permanent location of the receive antenna.

B.1.1.9 Using the data from step (B.1.1.5), normalize each of the maximum Isotropic E-field measurements (i.e. each of the 27 rectangular components below 10 f_s and 9 rectangular components above 10 f_s) to the square-root of the average input power:

$$\overleftrightarrow{E}_{x,y,z} = \frac{E_{Maxx,y,z}}{\sqrt{P_{Input}}} \qquad \text{(Eq. B1)}$$

where

$E_{Maxx,y,z}$ = maximum measurement from each probe axis (i.e. 27 or 9 measurements),

$\overleftrightarrow{E}_{x,y,z}$ = normalized maximum measurement from each probe axis, and

P_{Input} = average input power to the chamber during the tuner rotation at which $E_{Maxx,y,z}$ was recorded.

B.1.1.10 For each calibration frequency calculate the average of the normalized maximum of each probe axis of the E-field probe measurements $\langle \overleftrightarrow{E}_{x,y,z} \rangle$.

(a) For each frequency below 10 f_s:

$$\langle \overleftrightarrow{E}_x \rangle_9 = \left(\Sigma \overleftrightarrow{E}_x\right)/9 \qquad \text{(Eq. B2)}$$

$$\langle \overleftrightarrow{E}_y \rangle_9 = \left(\Sigma \overleftrightarrow{E}_y\right)/9 \qquad \text{(Eq. B3)}$$

$$\langle \overleftrightarrow{E}_z \rangle_9 = \left(\Sigma \overleftrightarrow{E}_z\right)/9 \qquad \text{(Eq. B4)}$$

Also calculate the average of the normalized maximum of all the Isotropic E-field measurements giving equal weight to each axis (i.e. each rectangular component), $\langle \overleftrightarrow{E} \rangle_{27}$:

$$\langle \overleftrightarrow{E} \rangle_{27} = \left(\Sigma \overleftrightarrow{E}_{x,y,z}\right)/27 \qquad \text{(Eq. B5)}$$

NOTE 10—$\langle\ \rangle$ denotes arithmetic mean, i.e.

$$\langle \overleftrightarrow{E} \rangle_{27} = \left(\Sigma \overleftrightarrow{E}_{x,y,z}\right)/27 \qquad \text{(Eq. B6)}$$

represents the sum of the 27 rectangular E-field maximums (normalized) divided by the number of measurements.

(b) Repeat (a) for each frequency above 10 f_s replacing 9 with 3, and 27 with 9.

B.1.1.11 For each frequency below 10 f_s determine if the chamber meets the field uniformity requirements as follows:

(a) The field uniformity is specified as a standard deviation from the mean value of the maximum values obtained at each of the nine locations during one rotation of the tuner. The standard deviation is calculated using data from each probe axis independently and the total data set. The standard deviation is given by:

$$\sigma = \alpha * \sqrt{\frac{\Sigma\left(\overleftrightarrow{E}_i - \left\langle \overleftrightarrow{E} \right\rangle\right)^2}{n-1}} \qquad \text{(Eq. B7)}$$

where

n = number of measurements,

$\overleftrightarrow{E}_i$ = individual normalized E-field measurement,

$\left\langle \overleftrightarrow{E} \right\rangle$ = arithmetic mean of the normalized E-field measurements, and

α = 1.06 for $n \leq 20$ and 1 for $n > 20$.

For example, for the x vector:

$$\sigma_x = 1.06 * \sqrt{\frac{\Sigma\left(\overleftrightarrow{E}_{ix} - \left\langle \overleftrightarrow{E}_x \right\rangle_8\right)^2}{9-1}} \qquad \text{(Eq. B8)}$$

where

$\overleftrightarrow{E}_{ix}$ = individual measurement of x vector, and

$\left\langle \overleftrightarrow{E}_x \right\rangle$ = arithmetic mean of normalized $E_{Max\ x}$ vectors from all 9 measurement locations.

and for all vectors:

$$\sigma_{27} = \sqrt{\frac{\Sigma\left(\overleftrightarrow{E}_{ix,y\&z} - \left\langle \overleftrightarrow{E} \right\rangle_{27}\right)^2}{27-1}} \qquad \text{(Eq. B9)}$$

where

$\overleftrightarrow{E}_{ix,y\&z}$ = individual measurements of all vectors (x, y, and z),

$\left\langle \overleftrightarrow{E} \right\rangle_{27}$ = arithmetic mean of normalized $E_{Max\ x,y,\&\ z}$ vectors from all 27 measurements,

and

σ_{27} = standard deviation of all vectors (x, y, and z).