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B

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ELECTROMAGNETIC INTERFERENCE MEASUREMENT ANTENNAS; STANDARD CALIBRATION METHOD

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1. SCOPE:

1.1 Purpose:

This SAE Aerospace Recommended Practice (ARP) outlines a standard method for the checkout and calibration of electromagnetic interference measurement antennas. Its primary application is for use when measuring a source 1 m from the antenna in a shield room versus a source at a greater distance (far field). This is the typical distance used in performing military EMC testing. Thus, this is a method of calibration. Shield room characteristics are not considered. It does not address an unknown distributed source. Yet it is close to reality since it is based on another antenna that represents a distributed source. This document presents a technique to determine antenna factors for antennas used primarily in performing measurements in accordance with 2.1 and 2.2. The purpose of Revision B is to include the calibration of other antennas, such as small loop antennas that are also specified for use in these same references.

1.2 Applicable Antennas:

The intent of Revisions A and B is to make this document applicable to passive and active antennas that may be used to measure signals from a source 1 m distant. Typical antennas being considered are the following:

- a. Biconical
- b. Resonant dipole
- c. Log periodic dipole
- d. Log spiral (200 MHz - 1 GHz)
- e. Log spiral (1 GHz - 10 GHz)
- f. Double ridged horn
- g. Log periodic
- h. Standard gain horns
- i. Loop antennas
- j. Vertical monopole
- k. "RE01/RE101" loop
- l. "RS01/RS101" loop

Most present day "104 cm" (41 in) rod antennas are of the active type and not calibratable per the previous issue of ARP958. The theoretical behavior of rod antennas is well understood. Therefore, the calibration really involves verifying the gain of the electronics in the antenna base. These antennas are calibrated by the use of a signal substitution source as defined in Revision B.

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1.3 General Background and Limitations:

This document originally was limited to determining antenna factors for conical logarithmic spiral antennas. It has been expanded to cover other antennas as indicated in 1.2. Antenna factors can be determined and calculated for the far field condition independent of ground reflections. The method, described in this document, of moving from the far field to a 1 m distance results in changes in antenna factors of a few decibels. The primary conditions which influence the antenna factors are the antenna separation, the height of the antenna above the ground plane, the orientation of the antenna relative to the ground plane, and the conductivity of the ground plane.

2. REFERENCES:

- 2.1 MIL-STD-461 Requirements for The Control of Electromagnetic Interference Emissions And Susceptibility
- 2.2 MIL-STD-462 Measurement Of Electromagnetic Interference Characteristics
- 2.3 Microwave Antenna Theory and Design by Silver, Vol. 12, Radiation Laboratory Series, McGraw - Hill, 1949, pp. 582-585
- 2.4 Antennas by Kraus, McGraw - Hill, 1950, pp. 455-457
- 2.5 Standard Site Method For Determining Antenna Factors, IEEE EMC Transactions, Vol. EMC-24, No. 3, August 1982, pp 316-322
- 2.6 ANSI C63.5 American National Standard for Electromagnetic Compatibility -- Radiated Emission Measurements in Electromagnetic Interference (EMI) Control -- Calibration of Antennas
- 2.7 IEEE Std 291 Standard Methods For Measuring Electromagnetic Field Strength of Sinusoidal Continuous Waves, 30 Hz to 30 GHz
- 2.8 IEEE Std 149 IEEE Standard Test Procedures For Antennas
- 2.9 SAE J551/5 Performance Levels and Methods of Measurement of Magnetic and Electric Field Strength from Electric Vehicles, Broadband, 9 kHz to 30 Mhz

3. RATIONALE FOR APPROACH:

3.1 Antenna Factor:

For an antenna to be useful in measuring EMI, an antenna factor (AF) must be specified which permits converting voltage at the input of a receiver (V) to field strength (E) in volts per meter (V/m) or into units suitable for comparison with radiated emission limits (dBμV/m) of reference 2.1. Thus,

$$E = AF \times V \quad (\text{Eq.1})$$

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3.1 (Continued):

where:

$$E = V/m$$

$$V = \text{volts}$$

where:

AF is the antenna factor based upon power gain of the antenna (it is derived from the square root of the power density (W/m^2)). Converting to dB:

$$E = 20 \log_{10} (AF \times V) \quad (\text{Eq.2})$$

where:

$$E = \text{dB}\mu\text{V}/\text{m}$$

$$V = \mu\text{V}$$

AF is the antenna factor based upon an antenna calibration similar to gain, henceforth referred to as 1 m gain, but performed under conditions characteristic of the actual use (1 m from the source) of the antenna for component-level EMC specification compliance testing. Numeric antenna gain (G) and wavelength (λ) (in meters) in a 50 Ω system express the antenna factor as follows:

$$AF = \frac{9.73}{\lambda} \cdot \frac{1}{\sqrt{G}} = \frac{9.73}{\lambda \sqrt{G}} \quad (\text{Eq.3})$$

Antenna gain is the ratio of the radiated power density in a certain direction to the average radiated power density.

The average radiated power density is the isotropic radiation intercepted by a surface area of a sphere of unit radius (see 2.3 and 2.4).

3.2 General Antenna Gain:

Antenna gain may be obtained by antenna pattern measurements which satisfy the following expression of antenna gain in integral form:

$$G = \frac{\Phi(\theta, \phi)}{\frac{1}{4\pi} \int_0^\pi \int_0^{2\pi} \Phi(\theta, \phi) d\phi \sin \theta d\theta} \quad (\text{Eq.4})$$

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3.2 (Continued):

where:

θ, ϕ = spherical coordinates in radians

Φ = power radiated per unit solid angle in a given direction

3.3 Using Two Identical Antennas:

The term "1 m gain" has been selected in lieu of "apparent gain," since "1 m" defines the conditions under which "apparent" applies. The 1 m gain determination can be calculated by the antenna gain equation. This method uses two identical antennas aligned on axis with polarization matched. The relationship for power received is:

$$P_R = \frac{P_T G_T}{4\pi r^2} \cdot \frac{\lambda^2}{4\pi} \cdot G_R \quad (\text{Eq.5})$$

where:

G_T and G_R = numeric power gain of the transmitting and receiving antennas respectively

P_R = power received in watts

P_T = power transmitted in watts

r = distance between antennas in meters

λ = wavelength in meters

$$\text{If } G_T = G_R, \text{ then } G^2 = \left(\frac{4\pi r}{\lambda} \right)^2 \frac{P_R}{P_T} \quad (\text{Eq.6})$$

If both receiving and transmitting systems are matched (50 Ω), voltage measurements may be made in lieu of power measurements so that:

$$G = \frac{4\pi r}{\lambda} \cdot \frac{V_R}{V_T} \quad (\text{Eq.7})$$

where:

V_R = voltage across the receive antenna terminals

V_T = voltage across the transmit antenna terminals

(It should be noted that G is the numeric power gain even though it is determined by two voltage measurements since these are used to form a ratio which is dimensionless.)

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3.4 Gain and 1 m Gain:

- 3.4.1 **Need for Gain and 1 m Gain:** Because the antenna may be used to make field strength measurements and specification compliance measurements, the gain, as well as the 1 m gain, is often needed. Accordingly, gain measurements are discussed in this document and a recommended measurement method is presented as an appendix to this document. However, the procedure specified in the document is only for determining the 1 m gain.
- 3.4.2 **Distance for Gain Measurements:** The gain is measured using the three identical antenna technique (see Appendix C). The distance between the antennas is 3 m. (See Figure 2 of this document.)
- 3.4.3 **Distance for 1 m Gain Measurements:** Measure the 1 m gain using the two identical antenna technique at a 1 m distance between the antennas. This is equal to that required between the antenna and the test sample for EMC specification compliance testing of components and subsystems. Some antennas have an "electrical" center that is used as the antenna position for theoretical calculations and measurements. Antennas, such as the log spiral, where the electrical center is not defined or is a function of frequency use the "nearest" point approach. (See Figure 2 of this document.)
- 3.4.4 **Necessary Number of Measurements:** Measurements should be made at a sufficient number of frequencies to describe their 1 m gain within the specified operating bandwidth of the antenna. A 1 m gain should be measured at frequencies as specified in 4.3(g). Such additional measurement frequencies should be chosen to precisely identify and define any anomalies in the 1 m gain characteristics.

3.5 Determining Antenna Factors:

- 3.5.1 **Antenna Factor For Gain (AF_1):** The AF for gain in the far field (referred to as gain and defined as AF_1) is calculated from Equation 3 where G was determined per 3.4.2.
- 3.5.2 **Antenna Factor for 1 m Gain (AF_2):** The antenna factor for 1 m measurements (defined as AF_2) is calculated from Equation 3 where G was determined per 3.4.3.
- 3.5.3 **Calculation:** The antenna factors AF_1 and AF_2 are calculated by the same method and by Equation 3 by using either the value G_1 or G_2 in the equation. To simplify the calculation it may be performed in logarithmic form. For this reason, Figure 1 was plotted which is a plot of $20 \log_{10} 9.73/\lambda$ as a function of frequency.

When the 1 m gain, G_2 , is a numeric, AF_2 in decibels may be found by the following expression:

$$AF \text{ (db)} = 20 \log_{10} \frac{9.73}{\lambda} - 10 \log_{10} G \quad (\text{Eq.8})$$

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3.5.3 (Continued):

where:

λ = meters

When the 1 m gain, G_2 , is in decibels, AF_2 may be found by:

$$AF \text{ (db)} = 20 \log_{10} \frac{9.73}{\lambda} - G$$

For example, at 200 MHz the 1 m gain was 10 dB. What is the antenna factor AF_2 ?

From Figure 1, $20 \log (9.73/\lambda) = 16$

Therefore, $AF_2 = 16 - 10 = 6 \text{ dB}$.

3.6 Use of Antenna Factor:

- 3.6.1 Correction of Signal Levels: The appropriate antenna factor is added to the voltage at the receiver input which is indicated in decibels above 1 μV , along with cable-loss factors to obtain field intensity in decibels above 1 $\mu\text{V/m}$.

$$E \text{ (dB}\mu\text{V/m)} = V \text{ (dB}\mu\text{V)} + AF \text{ (dB)} + \text{Cable Loss (dB)} \quad (\text{Eq.9})$$

- 3.6.2 Polarization Considerations: Section 4 outlines the procedure for obtaining gain of the antenna utilizing the two identical antenna technique. If the conical logarithmic spiral antenna is used, the gain so determined is that for a circularly polarized wave (see 3.3). When making field intensity measurements with linearly polarized received waves, the gain used to calculate the antenna correction factor, AF_1 , must be decreased by 3 dB (which means the antenna factor goes up by 3 dB. See Appendix B). The 1 m antenna factor, AF_2 , should also be based on the gain for linearly polarized signals.

4. PROCEDURE FOR TWO IDENTICAL ANTENNA 1 m GAIN MEASUREMENTS:

4.1 Apparatus:

- Signal generators with 50 Ω output impedance capable of generating test levels over the frequency range specified for the antenna type
- Two 6 dB, 50 Ω attenuators
- Calibrated receiver (or spectrum analyzer) tuning over the frequency range specified for the antenna type. The receiver input impedance should be 50 Ω and a VSWR ≤ 1.25 . An isolating attenuator can be used at the receiver input to achieve 1.25 VSWR.
- Coaxial cables of 50 Ω characteristic impedance and appropriate connectors for mating with antennas, 6 dB attenuator, signal generators, and receivers

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4.1 (Continued):

- e. Adapter for connecting two coaxial cables

4.2 Setup:

The basic setup is shown in Figure 3. The area in which the setup is situated should be clear of obstructions to achieve a free-space environment. A chamber permitting the 1 m spacing between antennas is acceptable if the chamber is anechoic, except for the floor, at all measurement frequencies. It also needs to maintain a ground plane to simulate open field sites. The antenna height above the ground influences the results and should be standard. A 3 m height for the center of the antenna is defined.

4.3 Measurement:

At each measurement frequency using the receiver as a transfer device the following operations shall be performed.

- a. Adjust signal generator output to obtain a receiver indication. Be sure the receiver is tuned for maximum response to the signal.
- b. Make fine adjustment of the alignment of the antennas for maximum indication and record the signal generator setting. (V_T)
- c. Disconnect the receiver and signal generator cables from their respective antennas and connect the signal generator and the receiver to each other using the same cables with the addition of a 50 Ω , calibrated coupling adapter.
- d. Reduce the signal generator output to obtain the same receiver output meter indication as obtained in step (b). Record the signal generator setting. (V_R)
- e. Solve for gain with 1 m spacing between antennas utilizing Equation 7 in which V_R and V_T are equivalent to the signal generator readings recorded in steps (d) and (b), respectively.
- f. Compute the antenna factor using the equation of 3.5.3 (Equation 8) or Equation A7 of Appendix A.
- g. Measurements should be taken as a minimum at frequency increments as follows:
 - (1) 20 kHz - 200 kHz: 10 kHz
 - (2) 200 kHz - 2 MHz: 100 kHz
 - (3) 2 MHz - 20 MHz: 1 MHz
 - (4) 20 MHz - 200 MHz: 10 MHz
 - (5) 200 MHz - 1.0 GHz: 100 MHz
 - (6) 1.0 GHz - 40 GHz: 1.0 GHz

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5. THE ROD ANTENNA:

5.1 Rod Antenna Theory:

The most significant characteristic of a rod antenna is its effective height (h_e). This is usually given in meters. With the rod antenna vertically oriented, it is perpendicular to a ground plane of infinite length ($h_e = \ell/2$). (ℓ = physical length of antenna.) With the antenna oriented vertically, h_e expresses the relationship between the voltage induced in the antenna and the vertical components of the incident field E . The effective height expression of $\ell/2$ applies exactly for most practical situations, within the limits of experimental measurements. Thus, the rod is mounted above a counterpoise that simulates this ground plane.

The factor 2 appears in $h_e = \ell/2$ and exists because of the effect of the proximity of a perfect ground and may be explained by the theory of images. The vertical rod and ground behave electrically as though a mirror image of the actual rod were located below the surface of the ground, and the ground removed. The antenna as a transmitter develops a field strength (E) having a peak value double that of the isolated rod, for the same voltage input to the antenna. By reciprocity, the incident field on the antenna as a receiver induces a voltage E_a equal to one-half that for the isolated rod. From the definition h_e for effective height, the value for the rod in the presence of ground is, therefore, $\ell/2$. Thus, for example, a rod 1 m in length has an effective height in the presence of ground of 0.5 m.

The value of $h_e = \ell/2$ for effective height is valid so long as $\ell < \lambda/8$ where λ is the wavelength. Thus, for 1 m physical length the frequency is 37.5 MHz. Therefore, the 1 m rod antenna is usually calibrated to 30 MHz. The rod has an internal impedance (Z_a).

$$Z_a = [R_a + 1/j\omega C_a] \quad (\text{Eq.10})$$

where:

R_a = radiation resistance

C_a = electrostatic capacitance of the rod and ground plane

Typical values of capacitance are 10 pF for a 1 m rod. Thus, for example, the maximum frequency for a 1 m rod (37.5 MHz) the capacitive reactance is 425 Ω , and it increases with decreasing frequency. Since the impedance of the rod antenna is quite high, most rod antennas have a coupling network or an amplifier to match the high impedance to the 50 Ω input impedance of the EMI meter. This coupling network or amplifier requires calibration.

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5.2 Rod Antenna Calibration:

The antenna factor for the rod antenna shall be determined by measuring the signal transfer characteristics of the matching device and assuming that the antenna is a short monopole with an infinite ground plane. The Thevenin equivalent of the rod element becomes an ideal voltage source equal to the electric field strength multiplied by the 0.5 m effective height of the antenna in series with a capacitor (typically 10 pF) representing the rod impedance. Figure 4 presents the general test setup and procedure for determining the antenna factor. Since some antenna assemblies include items such as the 10 pF capacitor or bandswitching mechanisms, details on the implementation of this technique for a particular antenna should be obtained from the manufacturer. Additional details can be found in reference 2.9.

6. LOOP ANTENNAS:

6.1 Operating Theory:

This test method is not meant to experimentally determine the magnetic fields. In most cases, for a controlled situation like this, they can be more accurately calculated than measured. This method is to set up a standard by which it can be determined that the antennas are functioning correctly. Thus, a failure such as a cold solder joint, broken wire, etc. can be detected.

6.1.1 Calculation for RE01/RE101 Loop:

6.1.1.1 The RS01 loop generates a field at 12 cm for 1 A of current as follows:

$$\begin{aligned}\beta &= \mu H = \mu I N R^2 / 2 (R^2 + Z^2)^{3/2} \\ &= 4\pi \times 10^{-7} \times [1 \times 10 \times (.06)^2] / 2[(.06)^2 + (.12)^2]^{3/2} \\ &= 9.366 \times 10^{-6} \text{ Tesla} = 139.4 \text{ dBpT}\end{aligned}$$

The RE01/RE101 loop reading of this field at 300 Hz is:

$$\begin{aligned}V &= 2\pi f N A \beta \\ V &= 2\pi \times 300 \times 36 \times \pi (6.65 \times 10^{-2})^2 \times 9.366 \times 10^{-6} \\ V &= 8.83 \times 10^{-3} \text{ V} = 78.9 \text{ dB}\mu\text{V}\end{aligned}$$

At 12 cm the RS01 field is 139.4 dBpT. The RE01 loop reads 78.9 dBμV. The difference is the factor that needs to be added to the RE01 loop reading to indicate the correct dBpT reading.

i.e., $139.4 - 78.9 - 60.5 \text{ dB} = \text{antenna factor for (unloaded) RE01 loop}$