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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. Revision D includes a specific procedure for loop antennas that are separated by 1 m from the device under test.

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 to 1 GHz)
e. Log spiral (1 GHz to 10 GHz)
f. Double ridged horn
g. Log periodic
h. Standard gain horns
i. Loop antennas
j. Vertical monopole

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.

A separate section is included to cover the “RE01/RE101” loop and “RS01/RS101” loop even though they are used much closer than 1 m from the equipment under test.

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 refections. 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

2.10 NBS Circular 517, Calibration of Commercial Radio Field-Strength Meters

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,

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

where:

E = V/m
V = 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:

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

where:

E = dBμV/m
V = μV

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 (see Appendix A) as follows:

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

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:

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

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 (see Appendix C when there are significant differences) 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

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

3.3 (Continued):

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

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

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.)

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:

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

where:

λ = meters

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

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

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, $AF_2 = 16 - 10 = 6$ 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 μV/m.

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

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:

a. Signal generators with 50 Ω output impedance capable of generating test levels over the frequency range specified for the antenna type

b. Two 6 dB, 50 Ω attenuators

c. 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.

d. Coaxial cables of 50 Ω characteristic impedance and appropriate connectors for mating with antennas, 6 dB attenuator, signal generators, and receivers

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

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).

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

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.

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:

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

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

$$V = 2\pi fNA\beta$$
$$V = 2\pi \times 300 \times 36 \times \pi\,(6.65 \times 10^{-2})^2 \times 9.366 \times 10^{-6}$$
$$V = 8.83 \times 10^{-3}\ \text{V} = 78.9\ \text{dB}\mu\text{V}$$

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 dB = antenna factor for (unloaded) RE01 loop

6.1.1.2 The RS101 loop (with 20 turns) generates a field at 12 cm as follows:

$\beta = \mu H = \mu INR^2 / 2\,(R^2 + s\,Z^2)^{3/2}$
$= 4\pi \times 10^{-7} \times [1 \times 20 \times (.06)^2] / 2[(.06)^2 + (.12)^2]^{3/2}$
$= 18.332 \times 10^{-6}$ Tesla = 145.4 dBpT

The field generated by the RS101 loop is higher than for the RS01 loop, and the reading by the RE01/101 loop increases accordingly to 84.9 dBμV. Therefore, 145.4 - 84.9 = 60.5 dB = antenna factor for (unloaded) RE01 loop.

6.1.2 Calculation for 4 cm Calibration Loop: The 4 cm loop is used to measure the level generated by the RS101 loop.

The RS101 loop generates a field at 5 cm as follows:

$\beta = \mu H = \mu INR^2 / 2\,(R^2 + Z^2)^{3/2}$
$= 4\pi \times 10^{-7} \times [1 \times 20 \times (.06)^2] / 2[(.06)^2 + (.05)^2]^{3/2}$
$= 9.4955 \times 10^{-5}$ Tesla = 9.4955×10^{7} pT = 159.6 dBpT

The 4 cm loop reading of this field at 300 Hz is:

$V = 2\pi fNA\beta$
$V = 2\pi \times 300 \times 51 \times \pi\,(2 \times 10^{-2})^2 \times 9.4955 \times 10^{-5}$
$V = 1.1471 \times 10^{-2}$ V = 81.2 dBμV

At 5 cm the RS01 field is 159.6 dBpT. The 4 cm loop reads 81.2 dBμV. The difference is the factor that needs to be added to the 4 cm loop reading to indicate the correct dBpT reading.

i.e., 159.6 - 81.2 = 78.4 dB = antenna factor for (unloaded) 4 cm loop

6.1.3 Loading Effect on the Loops: The calculations of 6.1.1 and 6.1.2 (for simplicity) are for the condition in which the loop is open circuited or sees a high impedance, such as 100 kΩ. When a 50 Ω receiver is used, the loading of the loop must be considered. Tables 1 and 2 have been developed using the 50 Ω load. The equation in general is:

$$V = 2\pi fNA\beta/[(1+R_w/R_L)^2 + (2\pi fL_w/R_L)^2]^{1/2} \qquad \text{(Eq. 11)}$$

For the RE01/RE101 loop

$V = 2\pi 36\pi(6.65\times10^{-2})^2 \times 9.366\times10^{-6} f/$
$[(1+10/50)^2+(2\pi f 340\times10^{-6}/50)^2]^{1.2}$
@ 300 Hz: V = 77.3 dB
and the antenna factor is 139.4 - 77.3 = 62.1 dB

TABLE 1 - Antenna Factor[1] for RE01/RE101 Loop

Frequency (Hz)	Reading (±2 dB tolerance)
30	82.1
60	76.0
100	71.6
300	62.1
600	56.0
1 000	51.6
3 000	42.1
6 000	36.2
10 000	32.1
20 000	27.4
30 000	25.4
50 000	23.8
100 000	23.0

[1] To be added to loop reading in dBμV to yield magnetic field level in dBpT. Factors are for the loops when loaded by a 50 Ω system.

TABLE 2 - Antenna Factor[1] for 4 cm Calibrating Loop

Frequency (Hz)	Reading (±2 dB tolerance)
30	99.1
60	93.1
100	88.6
300	79.1
600	73.1
1 000	68.6
3 000	59.1
6 000	53.1
10 000	48.6
20 000	42.6
30 000	39.1
50 000	34.6
100 000	28.6

[1] To be added to loop reading in dBμV to yield magnetic field level in dBpT. Factors are for the loops when loaded by a 50 Ω system.

6.1.3 (Continued):

For the 4 cm calibrating loop

$$V = 2\pi 51\pi(2x10^{-2})^2 x9.496x10^{-5} f / [(1+4/50)^2+(2\pi f2x10^{-6}/50)^2]^{1/2}$$

@ 300 Hz: V = 80.5 dB
and the antenna factor is 159.6 - 80.5 = 79.1 dB

6.2 Calibration:

6.2.1 Test Equipment Specification:

Equipment and critical specifications
Calibrator/Oscillator (1)
parameter: AC flatness
ranges: 30 Hz to 50 kHz
resolution: .01%
acceptable uncertainty: ±0.4%
Meter (2)
parameter: rms voltage/dBm
range: dBm, 30 Hz to 50 kHz
resolution: NA
uncertainty of standard: ±5% of full scale
acceptable uncertainty: ±0.5 dB
Meter (3)
parameter: rms voltage
range: 1 V, 30 Hz to 50 kHz
resolution: NA
uncertainty of standard: ±5% of full scale
acceptable uncertainty: ±0.5 dB

Audio Amplifier (4)
Load: 50 Ω (5)
Precision Resistor: 1 Ω ± 1% (6)

The RS01/RS101 and RE01/RE101 loop antennas are calibrated at a distance of 12 cm as a pair. Both transmit and receive loop antennas must have structures on or attached to them to allow them to be placed against each other and still have the required 12 cm loop separation.

The dBμV calculations obtained from the receive loop antenna shall be subtracted from 139.4 dBpT (pico Tesla), which was calculated for the 12 cm distance and is the constant used to determine the antenna factor.

The loop antenna shall be considered calibrated when the levels have been compared to the values of Table 1 and found to be within ±2 dB of those values.

6.2.1 (Continued):

If the transmit loop has a series resistor on the input (approximately 10 Ω), measure its value and include this information on the data sheet. Bypass the resistor for this calibration.

6.2.2 RS101 (4 cm) Calibration Loop: The 4 cm loop antenna is mounted at 5 cm from the RS101 loop. The dBμV calculations obtained from the receive (4 cm) loop antenna shall be subtracted from 159.6 dBpT, which was calculated for the 5 cm distance and is the constant used to determine the antenna factor. (Note that this calibration loop is calibrated at 5 cm to match the drawing for Reference 2.2 Revision D versus 12 cm for other loops.)

The loop antennas shall be considered calibrated when the levels have been compared to the values of Table 2 and found to be within ±2 dB of those values.

6.2.3 Procedure: See Figure 5 for the test arrangement:

a. Using the meter (3), verify the value of the 1 Ω precision resistor. (6)

b. Set up the equipment as shown in Figure 5.

c. Using meter (3), establish a 1 V rms, 30 Hz signal across the 1 Ω series resistor.

d. Record the level measured by the meter. (2)

e. Calculate the antenna factor.

Example if the reading is in dBm

meter (2) reading	-30 dBm
107 + (-30) =	77 dBμV
139.4 (from 6.1) - 77 dBμV =	62.4 antenna factor

Example if the reading is in mV

meter (2) reading	7.3 mV
20 log 7.3 mV/1 μV =	77.3 dBμV
139.4 - 77.3 =	62.1 antenna factor

f. The results should be within the limits as shown in Table 1.

g. Repeat steps c through f for the remaining frequencies in Table 1.

h. If the calibration fails, replace the receive antenna with another and repeat the procedure.

i. If the calibration fails again, the transmit loop is at fault. Replace the defective loop and repeat the calibration procedure.

7. LOOP ANTENNAS AT 1 m SEPARATION:

7.1 Theory:

The general approach using two antennas described in Section 4 does not apply to loop antennas measuring the magnetic field. Accordingly a test approach was developed based on the procedures of Reference 2.7. Reference 2.10 was used. In addition, in order to get a more uniform current in the transmit loop, and therefore, the H field, it is suggested that the relationship of $\pi d_{xmt} < \lambda/8$ (from 2.10) be changed to $\pi d_{xmt} < \lambda/64$.

7.2 Test Method:

The following procedure is used to perform the loop antenna calibration method. First, assume two loop antennas labeled xmt and rcv (for transmit and receive), and the objective is to determine the antenna factor for the receive antenna. In order to obtain the antenna factor, the magnetic field strength averaged over the area of the receive loop must be calculated. This equation is as follows:

$$H = \frac{1}{2 \cdot \pi} \cdot \pi \cdot \frac{d_{xmt}^{2}}{4} \cdot I \cdot n_{xmt} \cdot \frac{\sqrt{1 + \left(\frac{2 \cdot \pi \cdot f}{c}\right)^2 \cdot \left[L^2 + \left(\frac{d_{xmt}}{2}\right)^2 + \left(\frac{d_{rcv}}{2}\right)^2\right]}}{\left[L^2 + \left(\frac{d_{xmt}}{2}\right)^2 + \left(\frac{d_{rcv}}{2}\right)^2\right]^{\frac{3}{2}}} \quad \text{(Eq. 12)}$$

where:

H = magnetic field strength (A/m)
d_{xmt} = diameter of transmit loop (m)
d_{rcv} = diameter of receive loop (m)
L = distance between loops, center-to-center (m)
I = injected current into transmit loop (A)
n_{xmt} = number of turns in transmit loop
n_{rcv} = number of turns in receive loop
f = test frequency (Hz)
c = speed of light (m/s)
π = 3.14159

7.2 (Continued):

Once the H-field has been determined, the antenna factor, in units of dBS/m, can be calculated using Equation 13:

$$AF = 20\log\left(\frac{H}{V}\right) \quad \text{(Eq. 13)}$$

where:

H = magnetic field strength (A/m)
V = voltage induced into receiving loop (V)

Two quantities must be measured in the test setup:

1. the injected current into the coaxial port of the transmit antenna in amperes, A, and
2. the received voltage at the coaxial port of the receive loop in volts, V, into 50 Ω.

In order to measure these quantities it is necessary to account for cable losses. To do this, either use the same cable to measure transmitted current and received voltage, or use the exact same length and type of cable for each measurement. The antennas are to be separated by 1 m since this is the distance that is specified for MIL-STD-461 testing. (Note: This antenna spacing is not used for MIL-STD-461D testing.) The antennas must be mounted using dielectric materials and they should be oriented with their axes collinear (see Figures 6 to 8).

In order to measure the injected current into the transmit loop for frequencies below 10 kHz, it is necessary to place a precision 1 Ω resistor in series with the antenna. The voltage measured differentially across this resistor is the current going through the loop. For frequencies above 10 kHz, use a Tektronix CT-2 current probe to make this measurement. To make all measurements, use the same analyzer for both transmit current and receive voltage. Use the dynamic signal analyzer (HP3561) for 10 kHz and below and a spectrum analyzer (HP8562) for 10 kHz and above. (This equipment has been used, but equivalent instrumentation is acceptable.) Above 10 MHz use the 5 cm diameter transmit loop instead of the normal 14.5 cm diameter transmit loop. Sample calculations are provided in 7.3.

7.3 Sample Calculations:

TABLE 3 - Inputs

d_{xmt}	0.145	Diameter of transmit loop (m)
d_{rcv}	0.61	Diameter of receive loop (m)
L	1	Distance between loops (center-to-center) (m)
n_{xmt}	1	Number of turns in transmit loop
n_{rcv}	17	Number of turns in receive loop
u_o	1.26E-06	Permeability of free space (H/m)
c	3.00E+08	Speed of light (m/s)
I		Injected current (A)[1]
V		Received voltage (V)[1]
f		Test frequency (Hz)

[1] Include any attenuation factors in these levels.

TABLE 4 - Calculations

f (Hz)	I (A)[1]	V (V)[1]	H (A/m)	AF_{meas} dB(S/m)	AF_{man} dB(S/m)	Delta
1.00E+02	9.34E-02	8.00E-07	2.13E-04	48.51	48	0.51
1.00E+03	9.95E-02	8.40E-06	2.27E-04	28.65	28	0.65
1.00E+04	1.01E-01	7.83E-05	2.31E-04	9.38	9	0.38
2.00E+04	1.01E-01	1.41E-04	2.30E-04	4.26	5	0.74
3.00E+04	9.99E-02	1.80E-04	2.28E-04	2.05	3	0.95
4.00E+04	9.99E-02	2.03E-04	2.28E-04	1.01	2.5	1.49
5.00E+04	1.00E-01	2.19E-04	2.29E-04	0.39	2	1.61

where:

AF_{meas} = measured antenna factor
AF_{man} = manufacturer's antenna factor

[1] Include any attenuation factors in these levels.

8. NOTES:

The change bar (I) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document.

PREPARED BY SAE COMMITTEE AE-4, ELECTROMAGNETIC COMPATIBILITY

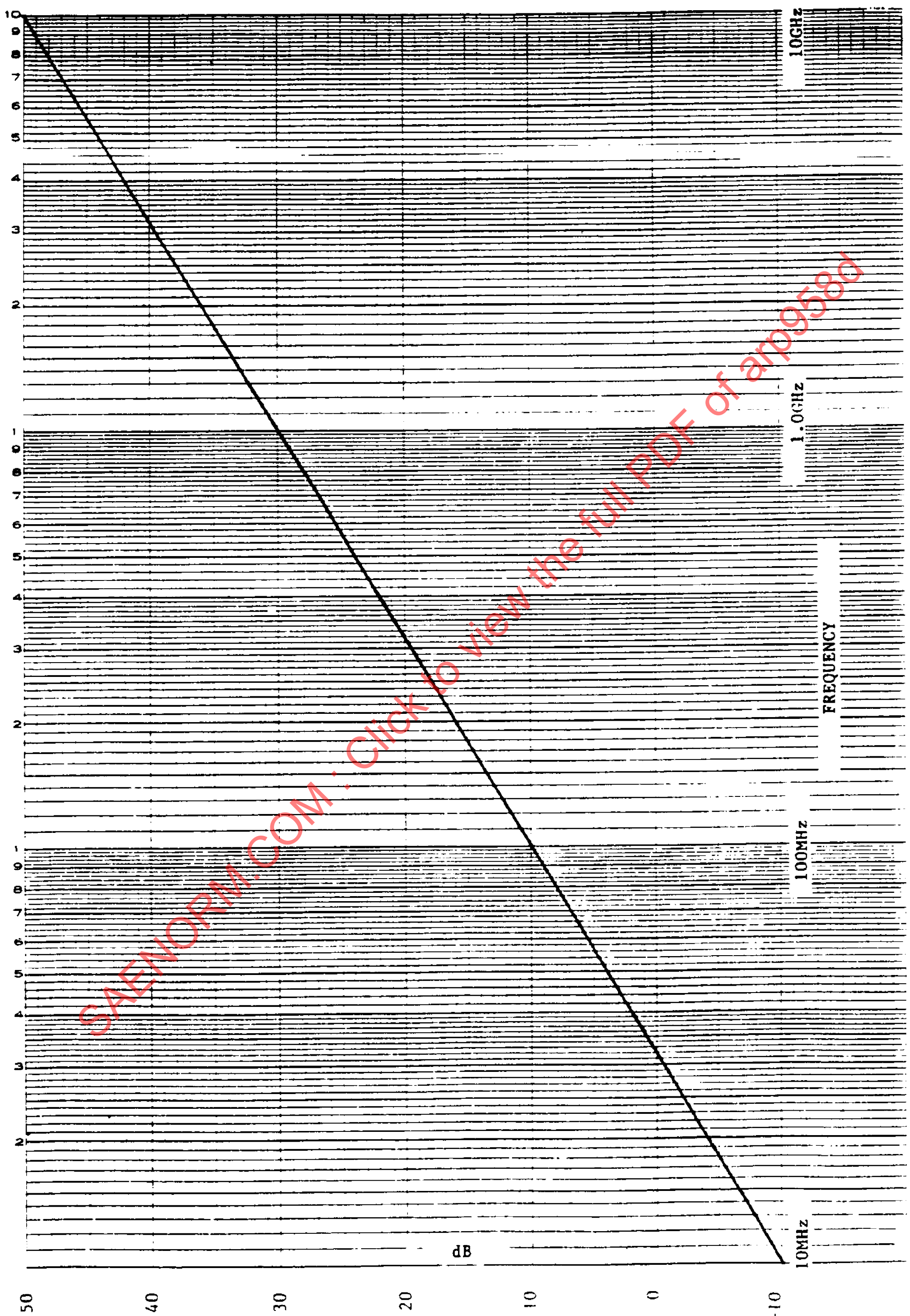


FIGURE 1 - Plot of 20 $\log_{10}$ 9.73/λ as a Function of Frequency Use for Calculating Antenna Factors AF_1 and AF_2

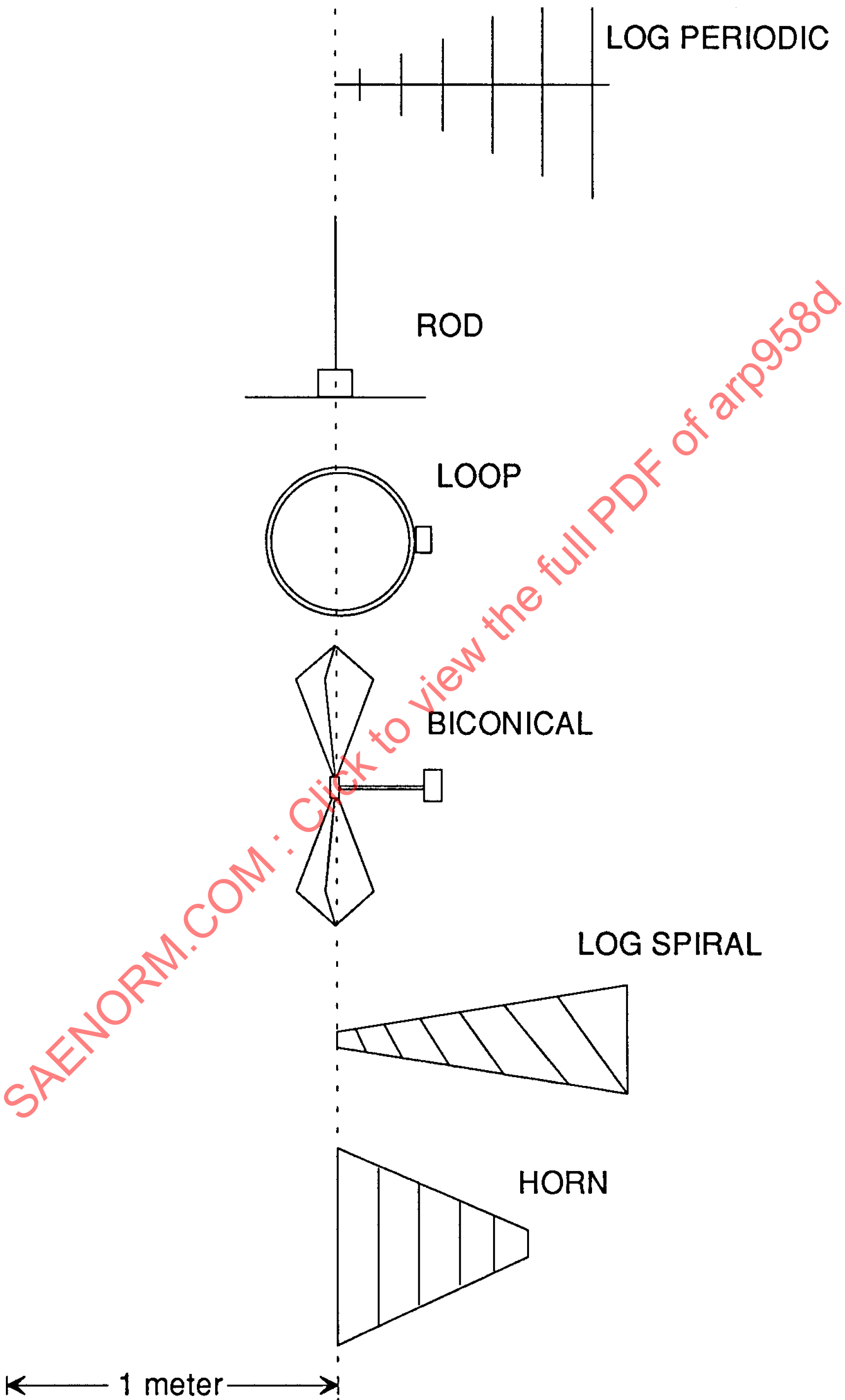


FIGURE 2 - Reference Plane for Antenna Distance

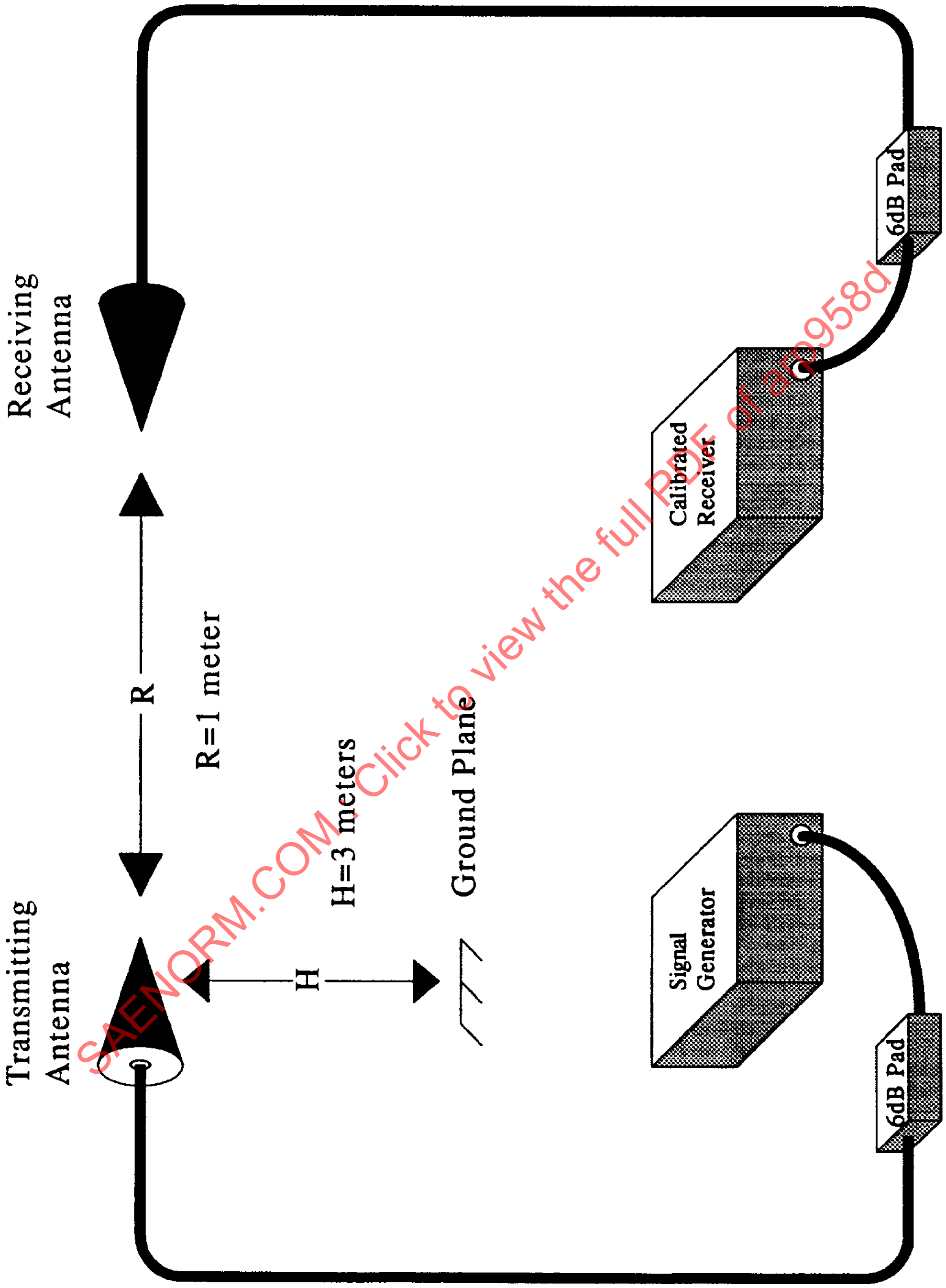
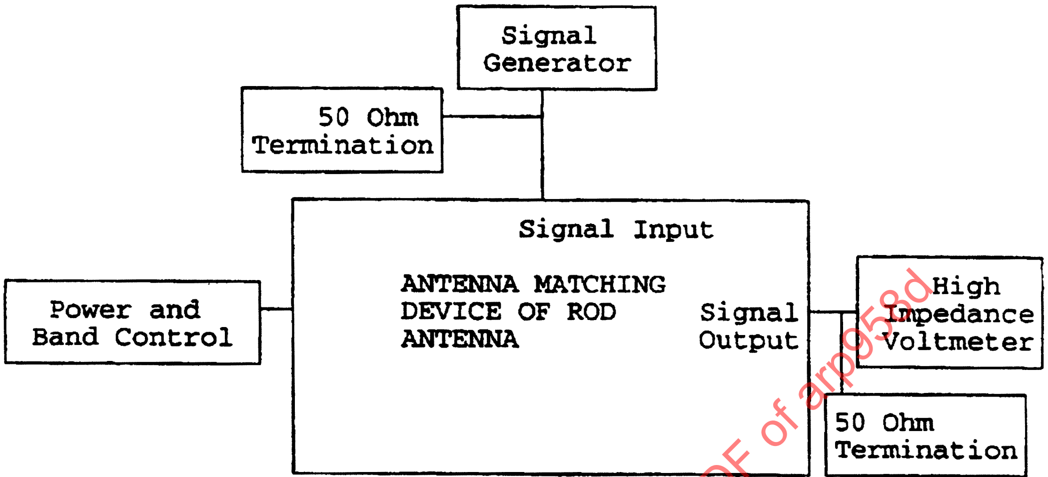


FIGURE 3 - Test Set-Up for Determining 1 m Gain
Utilizing Two Identical-Antenna Technique



NOTES:

1. At selected frequencies (4.3(g)) adjust the signal generator for a level which is sufficient for an accurate reading on the voltmeter. Insure that the level is below over-load.
2. Calculate the antenna factor (AF) where
   AF = 20 Log (Input Voltage / Output Voltage) + 6 dB
3. Repeat at the frequencies of 4.3(g).
4. Manufacturers should be consulted on implementation of this technique for a particular antenna due to variations between antennas.
5. All cables except for power and band control are 50 Ω coaxial cables.

FIGURE 4 - Rod Antenna Calibration Setup

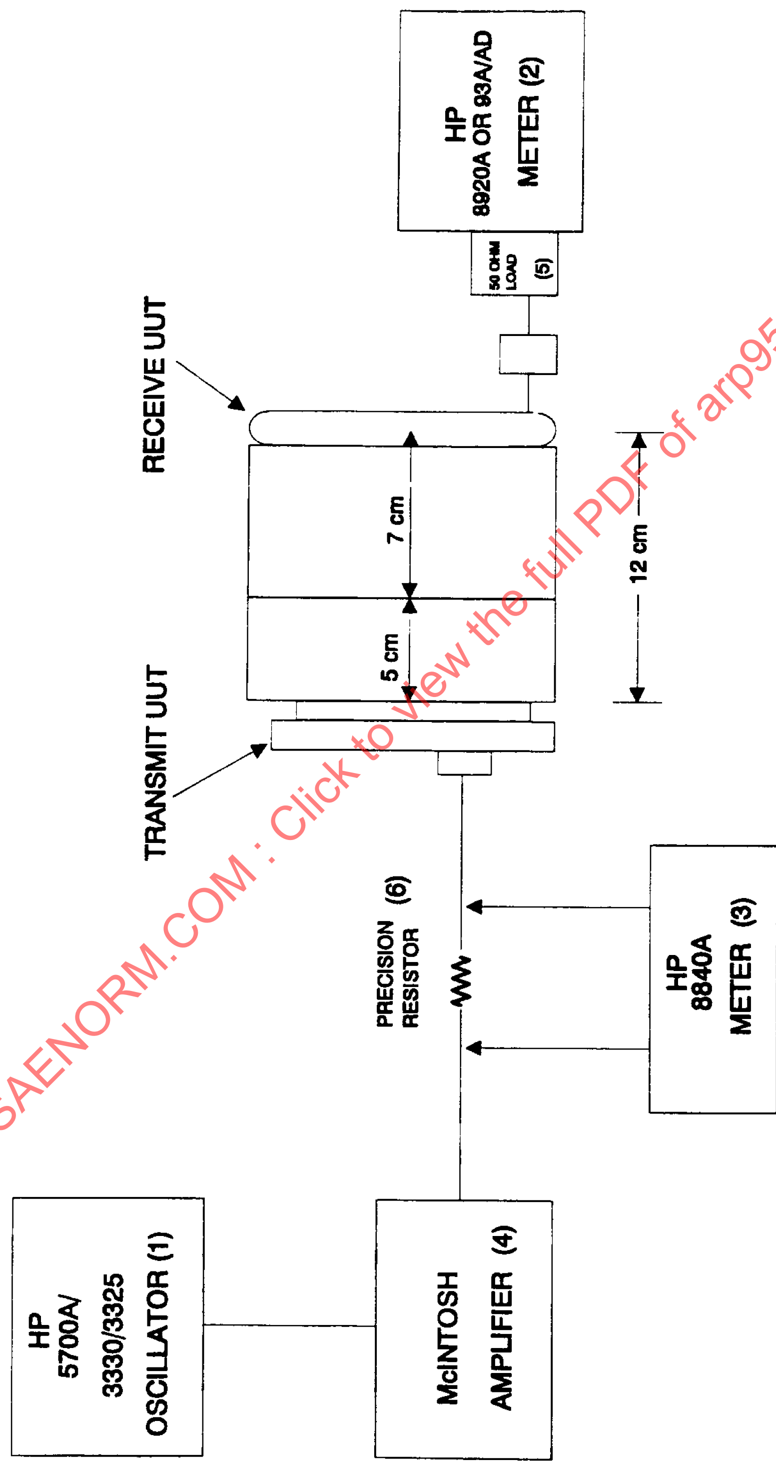


FIGURE 5 - Test Setup for Small Loop Calibration

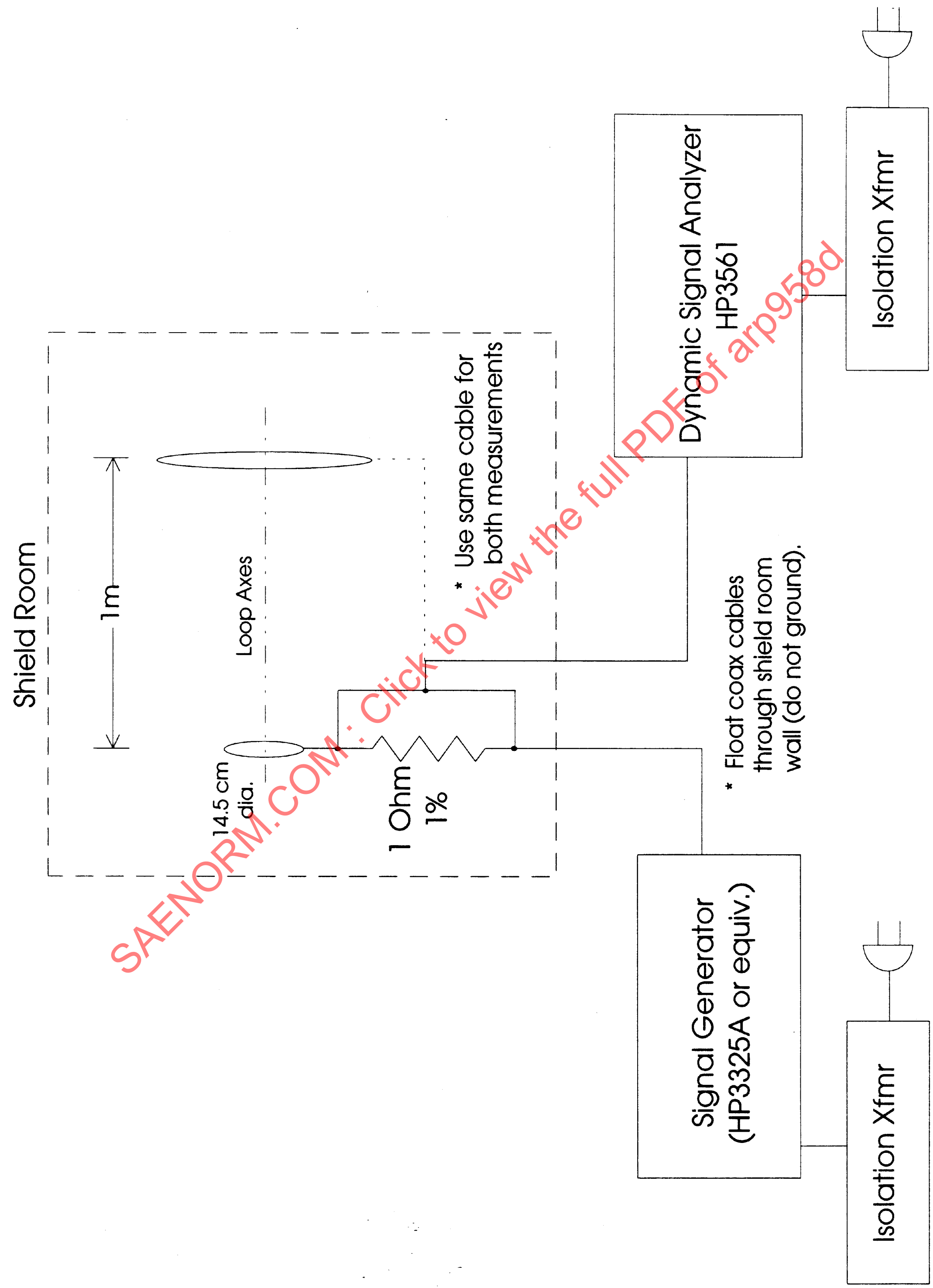


FIGURE 6 - Test Setup for f <= 10 kHz

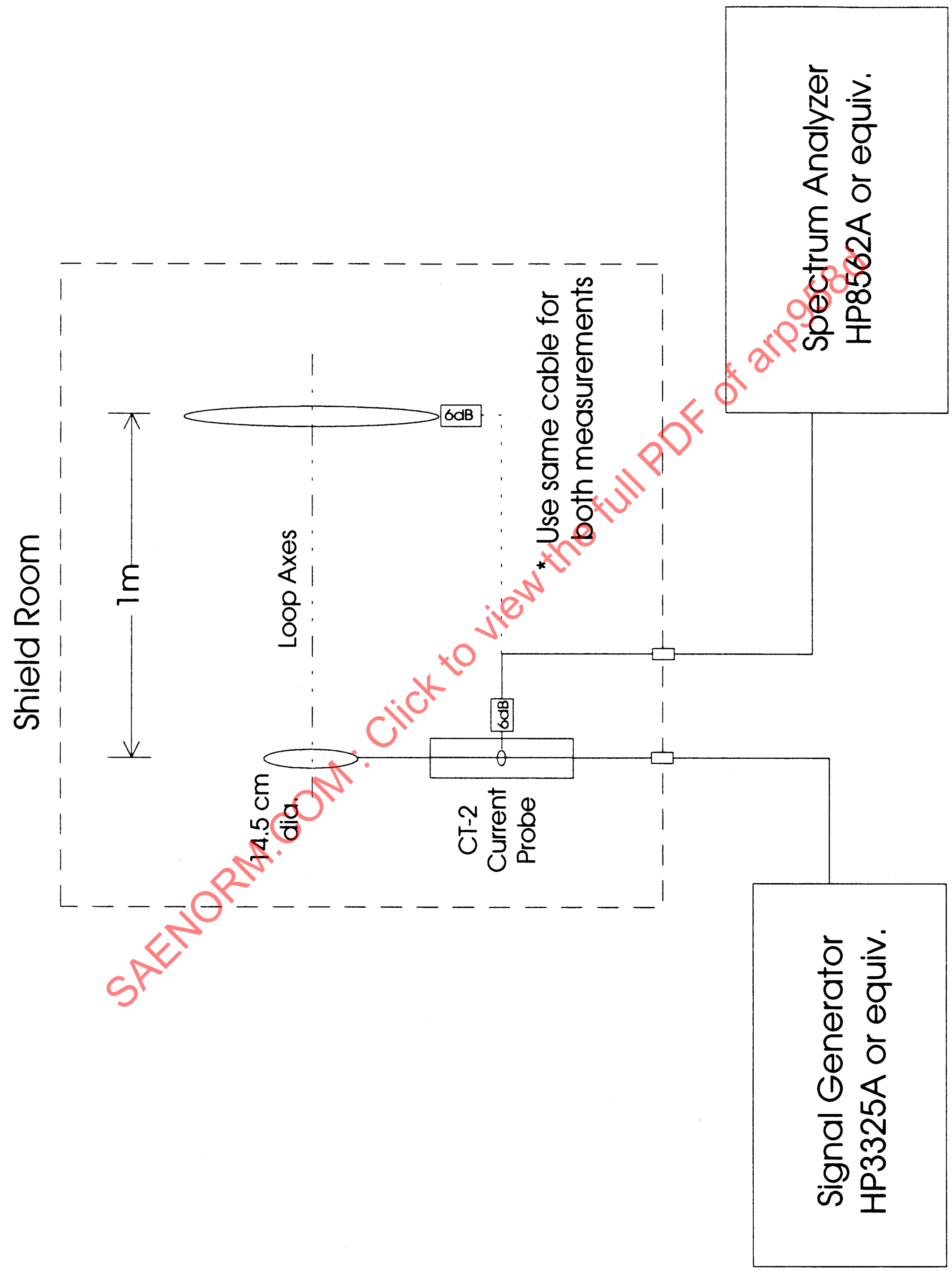


FIGURE 7 - Test Setup for 10 kHz < f <= 10 MHz

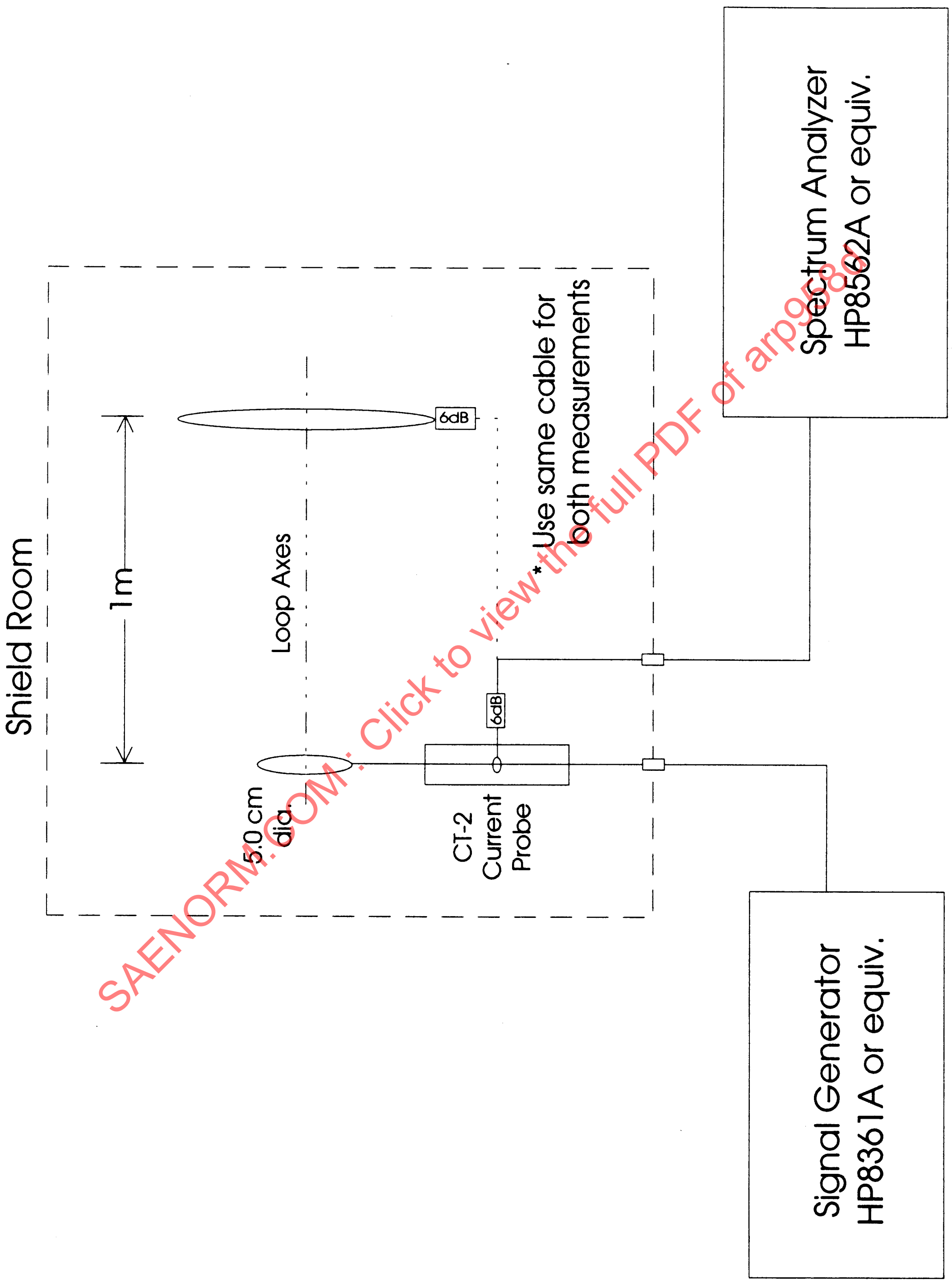


FIGURE 8 - Test Setup for f > 10 MHz

APPENDIX A
ANTENNA FACTOR DERIVATION

The factor associated with any antenna of a given gain can be calculated as follows:

$$V = h_{eff} E/2 \quad \text{(Eq. A1)}$$

where:

V = voltage at input to a 50 Ω receiver
E = field intensity in volts/meter
h_{eff} = effective height of antenna in meters

The factor of one half assumes that the voltage appearing at antenna terminals divides by one half when the 50 Ω receiver is placed across the antenna terminals.

$$h_{eff} = 2\,(A_{em}R_r/Z)^{1/2} \quad \text{(Eq. A2)}$$

$$A_{em} = \frac{D\lambda^2}{4\pi} \quad \text{(Eq. A3)}$$

where:

A_{em} = maximum effective aperture in square meters (aperture which would deliver maximum power to a matched load)
R_r = 50 Ω
Z = 120π = 377 Ω
D = directivity of the antenna

Substituting (Eq.A3) into (Eq.A2):

$$h_{eff} = \lambda(Dr_r/\pi Z)^{1/2} \quad \text{(Eq. A4)}$$

If a zero loss 50 Ω transmission line is assumed between the antenna and the receiver and a zero mismatch is assumed, D = G. Therefore:

$$V = \frac{E\lambda}{2}(G50/\pi 377)^{1/2} = E\,\frac{\lambda}{9.73}\sqrt{G} \quad \text{(Eq. A5)}$$

where:

G = numeric power gain
λ = wavelength in meters

If a conversion from V to E is now desired, it can be seen from Equation A5 that:

$$V \frac{9.73}{\lambda \sqrt{G}} = E \qquad \text{(Eq. A6)}$$

The antenna correction factor in going from a meter reading in volts to field intensity is then:

$$AF = \frac{9.73}{\lambda \sqrt{G}} \qquad \text{(Eq. A7)}$$

NOTE: If field intensity is derived from antenna induced voltage or a voltage across open circuit antenna terminals, the factors is $\frac{4.87}{\lambda \sqrt{G}}$.

APPENDIX B
CIRCULAR/LINEAR POLARIZATION

A circularly polarized wave can be represented as two E vectors in space quadrature and separated in time phase by 90° as shown below.

V is $1/\sqrt{2}$ and P is 1/2 for linear polarization relative to circular polarization. Therefore, if an antenna is calibrated with a circularly polarized source

TABLE B1

Signal Being Measured	Gain	Correction Factor
circular	G	X
linear	G/2	2X (or add a 3 dB factor)

If an antenna is calibrated with a linear source

TABLE B2

Signal Being Measured	Gain	Correction Factor
linear	G	Y
circular	2G	Y/2 (or subtract 3 dB from the correction factor since the antenna will be reading twice as high as it should)

NOTE: 2X = Y, so that final results are independent of the method of calibration.

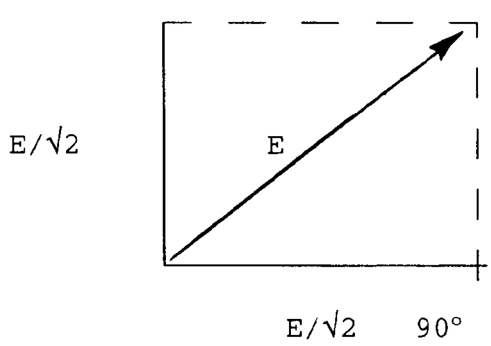


FIGURE B1

APPENDIX C
THREE ANTENNA DETERMINATION

The three antenna method is for calibrating antennas from site attenuation measurements made on an open field site. Reference 2.5 describes the method. Reference 2.8 also provides details on the method. This method uses three antennas taken two at a time: Antennas 1 and 2, antennas 1 and 3, and antennas 2 and 3. These are placed 1 m above the ground plane at a separation of 3 m. The receiving antenna is varied in height between 1 and 4 m to determine the maximum reception level. With the three antennas used, the results provide three equations and three unknowns. This removes source and reflection variations leaving a good far field antenna factor.

$$AF_1\ (dB) = 10 \log_{10} (f_M) - 24.46 + .5 \times (E_D^{max} + A_1 + A_2 - A_3)$$
$$AF_2\ (dB) = 10 \log_{10} (f_M) - 24.46 + .5 \times (E_D^{max} + A_1 + A_3 - A_2) \quad \text{(Eq. A1)}$$
$$AF_3\ (dB) = 10 \log_{10} (f_M) - 24.46 + .5 \times (E_D^{max} + A_2 + A_3 - A_1)$$

where:

A (dB) = 20 $\log_{10} (V_T/V_R)$ for each of the three tests
V_T = voltage applied to transmitting antenna
V_R = voltage out of receiving antenna
f_M = frequency in MHz
E_D^{max} (dBμV/m) = calculated maximum

E_D^{max} is tabulated in Table C1.

TABLE C1

F_M (MHz)	E_D^{max} (dBμV/m)	F_M (MHz)	E_D^{max} (dBμV/m)
25	2.3	150	12.1
30	3.5	160	12.2
35	4.6	175	12.3
40	5.6	175	12.3
45	6.4	180	12.4
50	7.1	200	12.5
60	8.3	250	12.6
70	9.2	300	12.1
80	10.0	400	11.7
90	10.5	500	12.2
100	10.9	600	12.4
120	11.6	700	12.6
125	11.7	900	12.3
140	11.9	1000	12.4

APPENDIX D
EXPECTED RESULTS

Appendix D contains a partial list of commercially manufactured antennas which include the frequency range and typical antenna factors. The value of the antenna factors were derived from manufacturer's data and these data are provided as typical calibration data and are not valid for all antennas. They can serve as "typical" results when using this ARP and indicate an approximate value that should be obtained when using this calibration method. They are included here to serve as a check that results obtained by this method are close to the expected results.

NOTE: Some of these antennas are no longer available and some newer ones may not be included.

TABLE OF CONTENTS

ANTENNA FACTORS (See Figure D1)

Fairchild PEF-10 Electric Field Probe
Fairchild ALP-10, 20 Hz to 50 kHz, Loop
Empire LG-105, 14 kHz to 150 kHz, Loop
Empire VR-3-105, 14 kHz to 150 kHz, Vertical
Empire VR-1-105, 14 kHz to 150 kHz, Vertical
Empire VX-105, 14 kHz to 150 kHz, 41" Vertical
Fairchild ALR-25, 14 kHz to 25 MHz, Magnetic Loop
Fairchild RVR-25, 14 kHz to 25 MHz, 41" Vertical
Empire LP-105, .15 MHz to 30 MHz, Loop
Empire VA-105, .150 MHz to 30 MHz, 41" Vertical
EMCO 3104, 20 MHz to 200 MHz, Biconical
(S/N 2139 and S/N 2140)
Fairchild BDA-25, 20 MHz to 55 MHz Broadband Dipole
Double Extension
Honeywell 7833, 20 MHz to 300 MHz Bi-Conical
Fairchild BIA-25, 20 MHz to 200 MHz
Bi-Conical
CDI B100 Bi-Conical, 20 MHz to 200 MHz
Fairchild BDA-25, 24 MHz to 210 MHz, Broadband
Dipole. No Extension
Empire DM-105-T1, 25 MHz to 200 MHz, Dipole
Honeywell 7826, 200 MHz to 1000 MHz Conical-Log Spiral
Fairchild BDA-25, 45 MHz to 120 MHz, Broadband Dipole, Single
Extension
Roberts Antenna TM Dipole, 30 MHz to 1.0 GHz
CDI B300 Bi-Conical, 400 MHz to 1.0 GHz
CDI B200 Bi-Conical, 175 MHz to 400 MHz
Empire DM-105-T2, 190 MHz to 400 MHz, Dipole
Fairchild LCA-25, 200 MHz to 1000 MHz
Conical Log Spiral

TABLE OF CONTENTS (Continued)

Honeywell 7828, 1 GHz to 10 GHz
Conical-Log Spiral
Stoddart 93490-1, 200 MHz to 1000 MHz
Conical Log Spiral
Empire DM-105-T3, 400 MHz to 1000 MHz, Dipole
EMCO CLP-1 B, 1 GHz to 10 GHz Conical Log Spiral
Singer EMA 910 Series, 1 GHz to 10.5 GHz, Horns
Polarad CA Series, 1 GHz to 10 GHz, Horns
EMCO 3105, 1 to 12.4 GHz
Stoddart 93491-1, 1 GHz to 10 GHz, Conical Log Spiral

The term “non-sensitized” is used for several antennas. This implies that the receiver will give the correct reading when using the antenna factors as long as it hasn’t been de-sensitized by another out-of-band high level signal.

FAIRCHILD PEF-10, ELECTRIC FIELD PROBE

Add 32dB to meter reading to obtain accurate volts/meter reading when E-Field measurements are made according to section 3.14.4 of the EMC-10 instrumentation manual.

FAIRCHILD ALP-10, 20 Hz to 50 kHz, LOOP

FREQUENCY (Hz)	AF (dB)	FREQUENCY (Hz)	AF (dB)
20	62	1000	26
30	56	1200	25
40	54	1400	24
50	52	1600	22
60	50	2000	21
70	49	2400	19
80	48	2800	18
90	47	3200	16
100	46	3600	15
120	45	4000	14
140	43	4800	13
170	42	5600	12
200	40	6200	11
230	39	7000	10
260	38	8000	9
300	37	9000	8
350	36	10,000	7
400	35	13,000	6
450	33	20,000	5
500	32	30,000	4
550	31	50,000	.3
600	30		
700	29		
800	28		
900	27		

Note 1: Meter reading (dBμV) + Antenna factor (dB) = Field Intensity (dBμA/m).

Note 2: To rad the E-field (Far Field), add 51.5 dB to the dBμA/m value to get dBμV/m.

EMPIRE LG-105, 14 kHz to 150 kHz, LOOP

NF-105 BAND	FREQUENCY (kHz)	AF (dB)
1	14	7
	16	6
	20	5
	24	4
	25	4
2	25	4
	30	3
	35	2
	40	1
	45	0
	50	1
	60	1
3	62	0
	70	-3
	80	-5
	120	-6
	140	-4
	150	-5

Note 1: These factors apply for a non-sensitized calibration of the receviers.

Note 2: Meter reading (dBμV) + Antenna factor (dB) = Field Intensity (dBμA/m).

Note 3: To read the E-field (Far Field), add 51.5 dB to the dBμA/m value to get dBμV/m.

EMPIRE VR-3-105, 14 kHz to 150 kHz, VERTICAL

FREQUENCY (kHz)	AF (dB)
14	44
20	44
25	42
35	41
60	41
100	41
150	41

Note 1: These values apply to a non-sensitized calibration of the NR-150 receiver.

Note 2: Meter reading (dBμV) + Antenna Factor (dB) = Field intensity (dBμV/m).

EMPIRE VR-1-105, 14 kHz to 150 kHz, VERTICAL

FREQUENCY (kHz)	AF (dB)
14	52
20	50
25	48
35	47
60	46
100	46
150	46

Note 1: These values apply to a non-sensitized calibration of the NF-150 receiver

Note 2: Meter reading (dBμV) + Antenna factor (dB) = Field intensity (dBμV/m).

FIGURE D1