AEROSPACE RECOMMENDED PRACTICE

ARP958™ REV. E

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Superseding ARP958D

(R) Electromagnetic Interference Measurement Antennas; Calibration Method

RATIONALE

This document was fully revised to bring the content and formatting up-to-date. The following major improvements were also incorporated as part of this revision:

1. Defined how to calibrate hybrid biconical log antennas. Documented the measurement distance position on each antenna.

2. Incorporated the three-antenna method and compared with the two "identical" antenna method, particularly where the antenna is of the same type (e.g., biconical) but not the same manufacturer or model. At least two 1:1 (50 Ω) baluns should be paired, and two 4:1 (200 Ω) baluns.

3. Corrected errors in the ECSM equations.

4. Clarified the content in Appendix C and standardized globally.

5. Added near-field formulation to derive Antenna Factor (AF) from the site insertion loss between a pair of antennas as it relates to measurement uncertainty.

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1. SCOPE

1.1 Purpose

This SAE Aerospace Recommended Practice outlines a standardized and economical method for the checkout and calibration of electromagnetic interference measurement antennas. Its application is for use when measuring a source 1 m from the antenna in a shield room. This is the typical distance used in performing military EMC testing. The influence of the shield room on the measured field strength is not considered. This standard does not address the measurement of emissions from an unknown distributed source, yet it attempts to resemble reality by using another antenna, in the calibration method, that represents a distributed source. This document presents a technique to determine antenna factors for antennas used primarily in performing measurements in accordance with References 2.1 and 2.2. The purpose of Revision B was to include the calibration of other antennas, such as biconical, horn, monopole and 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. Revision E adds the inclusion of modern instrumentation, instruction on how to calibrate the hybrid antenna, and attempts to improve upon the clarity of this document for the user.

1.2 Applicable Antennas

Typical antennas being considered are the following:

a. Biconical

b. Resonant dipole

c. Log-periodic dipole array (LPDA)

d. Log spiral

e. Double ridged waveguide horns

f. Standard gain horns

g. Loop antennas

h. Monopole (i.e., rod)

i. Hybrid antenna (bilog/biconilog)

The use of such antenna, as listed, is limited by particular testing standards and the inclusion here should not be considered as endorsement for use universally. The standard measurement distance on the hybrid antenna shall be measured in the same way as that of the LPDA.

1.3 General Background and Limitations

The original 1968 version of ARP958 was limited to determining antenna factors for conical logarithmic spiral antennas over the frequency range 200 MHz to 1 GHz. The standard 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 methods, described in this document, of moving from the far field to a 1 m distance results in changes in antenna factors of typically zero to four dB, but in the case of log-periodic antennas these changes intentionally correct the field strength from the position of the phase center on the antenna at each frequency to the position of the tip of the antenna, being 1 m away from the source. 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 size, flatness and conductivity of the ground plane. However for an antenna separation of 1 m the calibration methods found in Section 4 are intended to reduce the influence of the ground plane.

2. REFERENCES

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 MIL-STD-461 Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility

2.2 ANSI/IEEE Std 145-2013 IEEE Standard Definitions of Terms for Antennas

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 C63.5-2017 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, 150 kHz to 30 MHz

2.10 NPL Report DEM-EM 005, D A Knight, A Nothofer, M J Alexander, Comparison of calibration methods for monopole antennas, with analysis of the capacitance substitution method, October 2004 (www.npl.co.uk).

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,

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

Where *V* is measured in µV, the E-field, *E*, can be expressed in units of dBµV/m by converting to decibels as in Equation 2:

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

AF is the antenna factor based upon a measurement of the antenna gain, but performed under conditions characteristic of the actual use (1 m from the source) of the antenna for EMI compliance testing, henceforth referred to as “1 m gain.” This gain is referenced as the apparent gain in most text and includes mismatch loss, and therefore differs from true antenna gain. In reference 2.2 AF is related to apparent gain in a 50 Ω system by Equation 3, where G is the numeric antenna gain and λ is the wavelength in meters (see the derivation in Appendix A):

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

Antenna gain is the ratio of the radiated power density in a certain direction to the average radiated power density (see 2.3 and 2.4).

3.2 Using Two Identical Antennas

The term “1 m gain” has been selected to signify that the derived antenna factors are intended to determine the field strength at a distance 1 m from the source. This is particularly relevant for log-periodic (including log spiral and hybrid) antennas where the field pick-up point on the antenna is further than 1 m away from the source. Other influences that cause the “1 m gain” to differ from far-field gain are that for biconical and horn antennas there is significant mutual coupling between the pairs of identical antennas, and also 1 m distance is less than the distance required to be in the Fraunhofer far-field region of the antenna where a plane wave is established. 1 m gain can be calculated by Equation 4. This method uses two identical antennas aligned on axis with matched polarization (for antennas that are non-identical, use the three antenna calibration method in 3.3). The relationship for power received is:

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

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

$$If\, G_T = G_R, then\, G^2 = \left(\frac{4\pi r}{\lambda}\right)^2 \frac{P_R}{P_T} \quad \text{(Eq. 5)}$$

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

$$G = \frac{4\pi r}{\lambda} \cdot \frac{V_R}{V_T} \quad \text{(Eq. 6)}$$

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. See 3.5.2 for calculation of gain in the near-field.)

It is often the case that identical antennas are not available, in that case the three antenna method shall be used. Identical antenna are of the same manufacturer, model number, and design. Similar antennas, as considered below, do not meet the requirements of identical. If identical antenna are not available, the three-antenna method shall be used.

Most biconical antennas have similar enough wire cage dimensions, but it is also important that the two antennas have the same balun transformation, the most common being 50 Ω or 200 Ω. Most LPDA antennas are sufficiently similar if they fit inside a generic template, which is a triangle of 0.72 m base and 0.63 m height (this eliminates the less common high gain antennas which are almost twice as long and result in larger uncertainties).

An LPDA antenna designed to cover the frequency range 200 MHz to 1 GHz should almost fill this template. As a general rule, antenna with dimensions within 2% of each other are considered identical. The taper pattern on an LPDA antenna must be within the 2% dimensional criteria as well.

3.3 The Three Antenna Method

The use of the three antenna method is preferred over the two identical antenna method since it allows the calculation of individual antenna factors and therefore does not rely on the presence of identical antennas. The method is identical to the standard site method (SSM) of ANSI C63.5-2017 with the following exceptions:

a. No height scan required at a 1 m separation; the antennas are kept at a fixed height.

b. The calibration distance is fixed at 1 m.

c. The antenna calibration site requirements are not considered as both antennas are raised to a height where the ground plane influence is reduced or to a height of 3 m, whichever is less.

For this calibration setup, where the ground reflection is negligible or is not detected by the antenna under calibration (AUC), E_D^{max} is 16.9 dB for the fixed distance of 1 m (this is particularly the case for directional antennas above 1 GHz). The results are then applied to the equations of Equation C1.

The use of three antenna reduces the impact of one antenna on the calibration process.

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 compliance measurements, the 1 m gain, is needed. Accordingly, gain measurements are discussed in this document and the method presented will not provide the user of this document with a true, far-field, free space antenna gain because a sufficient far-field separation between the antennas is one wavelength (λ) for wire antennas and $2D^2/\lambda$ for horn antennas, where D^2 is the radiating aperture area. The procedures specified in Sections 3 and 4 of this document are only for determining the 1 m gain.

3.4.2 Antenna Separation Distance for Measurements

Measure the 1 m gain using the appropriate method at a 1 m distance between the antennas. This is equal to that required between the antenna and the test sample for EMC compliance testing. Some antennas have an "electrical" center that is used as the antenna position for theoretical calculations and measurements, such as the horn antenna. For the log-spiral antenna, where the electrical center is not defined or is a function of frequency, the "nearest" point approach is used (see Figure 2).

3.4.3 Necessary Number of Measurements

Measurements shall 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 shall be measured at frequencies as specified in 4.3(g). Any anomalies in the 1 m gain characteristics can be identified by a swept frequency measurement of the insertion loss between a pair of antennas: where there are sharp resonances, additional measurement frequencies should be chosen, to ensure that the gain/antenna-factor in the resonant regions are captured.

3.5 Determining Antenna Factors

3.5.1 Antenna Factor for Gain (AF_1)

The antenna factor for 1 m distance measurements (defined as AF_1) is calculated from Equation 3 where G was determined with a separation distance of 1 m per 3.2.

3.5.2 Calculation

The antenna factor AF_1 are calculated by Equation 3 by using the value G_1 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_1, is a numeric, AF_1 in decibels may be found by the following expression:

$$AF(dB) = 20\,log_{10}\frac{9.73}{\lambda} - 10\,log_{10}\ G \quad \text{(Eq. 7)}$$

where:

λ = meters

When the 1 m gain, G_1, is in decibels, AF_1 may be found by:

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

For example, at 200 MHz the 1 m gain (G_1) is 10 dB. What is the antenna factor AF_1?

From Figure 1, 20 log (9.73/λ) = 16

Therefore, AF_1 = 16 - 10 = 6 dB.

3.6 Use of the 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.

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

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. When making field intensity measurements with linearly polarized received waves, the 1 m gain used to calculate the conical antenna factor, AF_1, must be decreased by 3 dB (which means the antenna factor goes up by 3 dB; see Appendix B).

4. PROCEDURE FOR 1 M GAIN MEASUREMENTS

4.1 Two Identical Antenna Method

4.1.1 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.

f. Alternatively, network analyzers can be used, matching attenuators (6 dB) that provide a VSWR of 2:1 or less at the mating plane with the antennas shall be used.

The basic setup is shown in Figure 3. The area in which the setup is situated shall be clear of obstructions and reflections. Chambers or variations from the setup shown in Figure 3 are allowable if there is a demonstrated correlation of under 1dB from the reference setup of Figure 3 at an outdoor calibration site. The calibration site shall maintain a ground plane to simulate open field sites. A 3 m height for the center of the antenna is defined as the initial antenna calibration height. For dipole like antenna, antenna factor will vary with polarization; both polarizations should be considered during the calibration process and shall be provided unless otherwise specified. For aperture type (horn) antenna, the antenna factor found using the methods of this document should vary less than 1dB between polarizations if calibrated at a 3 m height.

4.2 Three Antenna Method

The procedure of the three antenna method requires the same apparatus and setup as the two identical antenna method. When the three antenna method is used, three antennas taken two at a time: Antennas 1 and 2, antennas 1 and 3, and antennas 2 and 3. The equations for this are found in Appendix C as referenced in 3.3.

4.2.1 Measurement

The measurement process below describes using a signal generator and receiver, as an alternative, a network analyzer can be used in place of the of the two separate instruments. 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 at least 10 dB above the indicated noise floor. 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 6 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 C.1 of Appendix C.

g. Measurements shall 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: 5 MHz

    (5) 200 MHz - 1.0 GHz: 50 MHz

    (6) 1.0 GHz - 40 GHz: 100 MHz

5. THE ROD (OR MONOPOLE) ANTENNA

5.1 Rod Antenna Theory

The most significant characteristic of a rod (or monopole) antenna is its effective height (h_e). Assuming the rod antenna is vertically oriented and placed on a horizontal ground plane of infinite extent, h_e (the physical length of the element, h, divided by 2) expresses the relationship between the RF voltage induced in the antenna and the vertical component of the incident electric field (E). This voltage becomes the input to the amplifier or impedance matching stages in the base of most common rod antennas. The precise relationship depends upon the impedance of the element and the input impedance of the amplifier. The output signal from the base may then be measured by a standard RF receiver. The element impedance may be represented as:

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

where:

R_a = radiation resistance

C_a = equivalent capacitance of the rod element and ground plane

The essential idea behind the equivalent capacitance method of calibration is that the rod element is always operating well below resonant frequency, so the real part of impedance (radiation resistance) is much smaller than the imaginary part (the capacitive part). These conditions hold true when the height of the element is less than λ/8. This allows the impedance of the element to be simulated with a capacitor, which is then mounted in a suitable adaptor block and attached to the input of the antenna base. The expression for the equivalent capacitance is given below:

$$C_a = \frac{55.6h}{ln\left(\frac{h}{a}\right)-1} \quad \frac{\tan\frac{2\pi h}{\lambda}}{\frac{2\pi h}{\lambda}} \text{ (pF)} \quad \text{(Eq. 10b)}$$

where:

h = element length (m)

a = average element radius (m)

Ln() = natural logarithm

For most 104 cm (or 41 inch) telescopic rod elements with an average radius in the region of 3 mm it is safe to assume a capacitance value of 12 pF. For those elements with significantly larger radii the capacitance will increase so the correct value shall be calculated. Additional details can be found in references, 2.6, 2.8, and 2.10.

The theory presented above assumes an infinite ground plane. In normal use during emission measurements the rod is attached to a 'counterpoise' which may be a conducting plate of dimension 0.6 m by 0.6 m, which acts as a vestigial ground plane. The test configuration in the screened room varies from one test standard to another: the rod can either be placed on the floor, or free-standing with the counterpoise on a tripod, or alternatively the counterpoise may be bonded to the conducting bench which supports the DUT. Although these configurations do not equate to an infinite ground plane the test standards have each been designed for a specific purpose, and they should give self-consistent results against the limits set in those standards.

5.2 Rod Antenna Calibration

The antenna factor for the rod antenna shall be determined by measuring the signal transfer characteristics of the base amplifier and/or matching stage, using a capacitor of nominal tolerance of 20% to substitute the rod element. In the case of a 41 inch element, a capacitor of nominal value between 9.6 pF to 14.4 pF shall be substituted (see discussion above). The general test setup is shown in Figure 4.

5.2.1 ECSM Method

1. At selected frequencies (4.3(g)) adjust the signal generator to a level which is sufficient for an accurate reading on the RF receiver, but low enough to avoid over-loading the rod element input connection.

2. Record the Input level (V_D), and the Output level (V_R). When measuring V_D a 50 Ω load should be placed on the rod antenna output, and when measuring V_R the load should be placed on the coaxial T-piece output.

3. Calculate the antenna factor:AF = 20*Log_{10} (Input level / Output level) + 5.6(see notes below).

4. Repeat at the next frequency (4.3(g)).

NOTE: Saturation of the rod element input connection may be tested by reducing the input signal level and checking to see if the output falls by the same amount (in dB). If this is not the case then the input signal should be reduced until the ratio of (Input/Output) remains constant.

NOTE: The 50 Ω load is used to provide a constant match on all the outputs. A good quality RF receiver will present a 50 Ω match to the measured connector.

NOTE: The correction term +5.6 is actually: –20*Log_{10} (h_e). For a 41 inch element at frequencies below 30 MHz the effective height (h_e) is approximately half the physical height (i.e., $l/2$). For elements exactly 1 m high this correction becomes +6.0.

NOTE: All cables, except for power and band control, are 50 Ω coaxial.

Manufacturers should be consulted on implementation of this technique for a particular antenna due to variations between different model types. The adaptor casing is usually metallic with a ground strap which may be attached to a suitable ground point on the rod antenna. Note that the capacitor itself should be supported by some non-conducting material which extends away from the support casing so that, when the adaptor is connected to the antenna input, there is no direct ground connection to the same input. When constructing the adaptor care should be taken to minimize stray capacitive coupling between exposed wires and the casing; this is usually achieved by keeping wire length as short as possible.

6. LOOP ANTENNAS

6.1 Operating Theory

This method is not meant to experimentally determine the magnetic fields. In most cases, for a controlled situation, 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:

β = μH = μINR^2 / 2 (R^2 + s Z^2)$^{3/2}$
= 4π x 10^{-7} x [1 x 20 x (.06)^2] / 2[(.06)^2 + (.12)^2]$^{3/2}$
= 18.332 x 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:

β = μH = μINR^2 / 2 (R^2 + Z^2)$^{3/2}$
= 4π x 10^{-7} x [1 x 20 x (.06)^2] / 2[(.06)^2 + (.05)^2]$^{3/2}$
= 9.4955 x 10^{-5} Tesla = 9.4955 x 10^7 pT = 159.6 dBpT

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

V = 2πfNAβ
V = 2π x 300 x 51 x π (2 x 10^{-2})^2 x 9.4955 x 10^{-5}
V = 1.1471 x 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:

$$V = 2\pi f N A \beta / [(1 + R_w/R_L)^2 + (2\pi f L_w/R_L)^2]^{1/2} \quad \text{(Eq. 11)}$$

For the RE01/RE101 loop

V = 2π36π(6.65x10^{-2})^{2}x9.366x10^{-6}f/
[(1+10/50)^2+(2πf340x10^{-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
1000	51.6
3000	42.1
6000	36.2
10000	32.1
20000	27.4
30000	25.4
50000	23.8
100000	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
1000	68.6
3000	59.1
6000	53.1
10000	48.6
20000	42.6
30000	39.1
50000	34.6
100000	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.

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.

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:

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

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

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

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

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

8.1 Revision Indicator

A change bar (l) 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, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

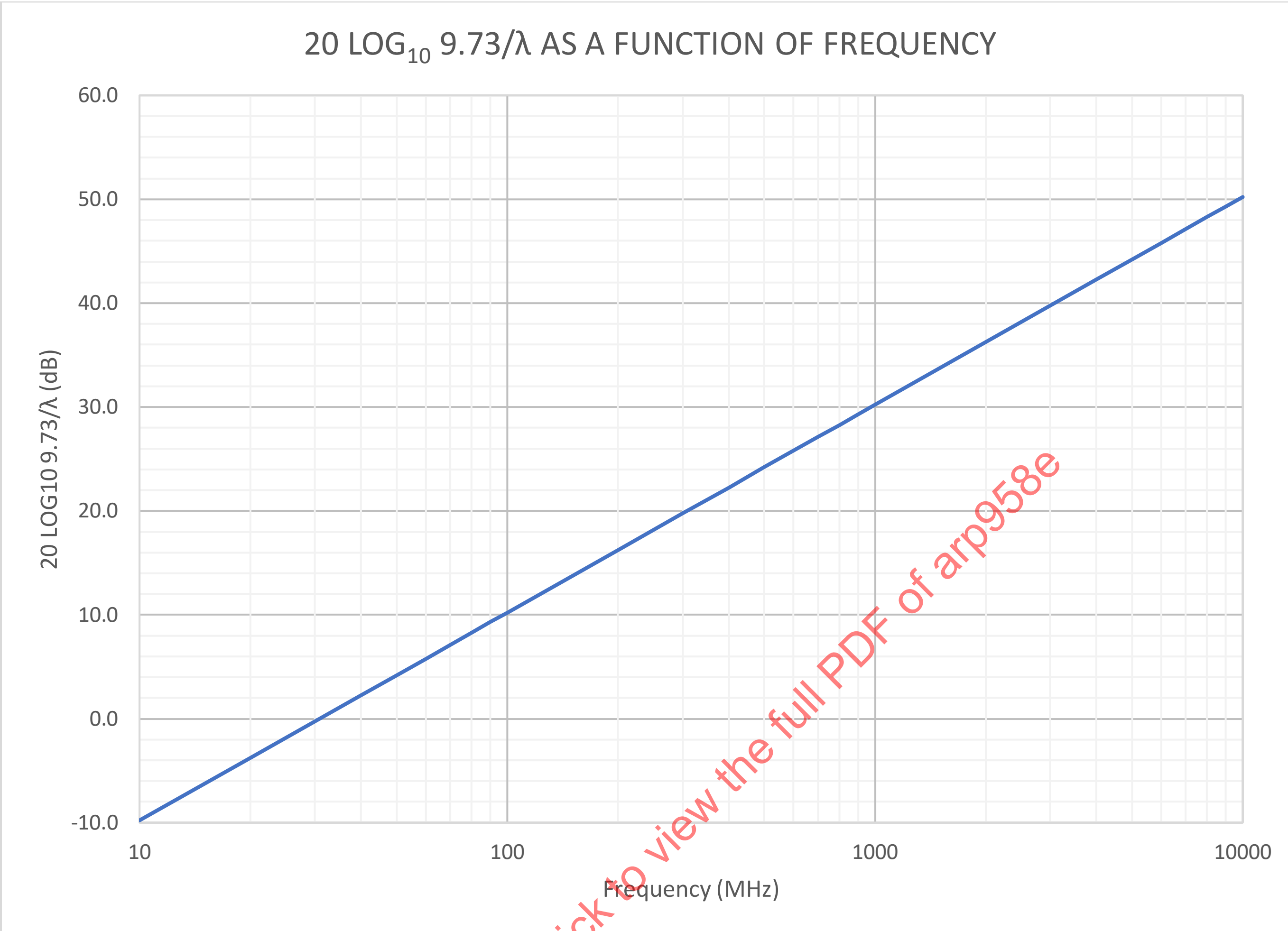

Figure 1 - Plot of 20 LOG_{10} 9.73/λ as a function of frequency use for calculating antenna factors AF_1 AND AF_2

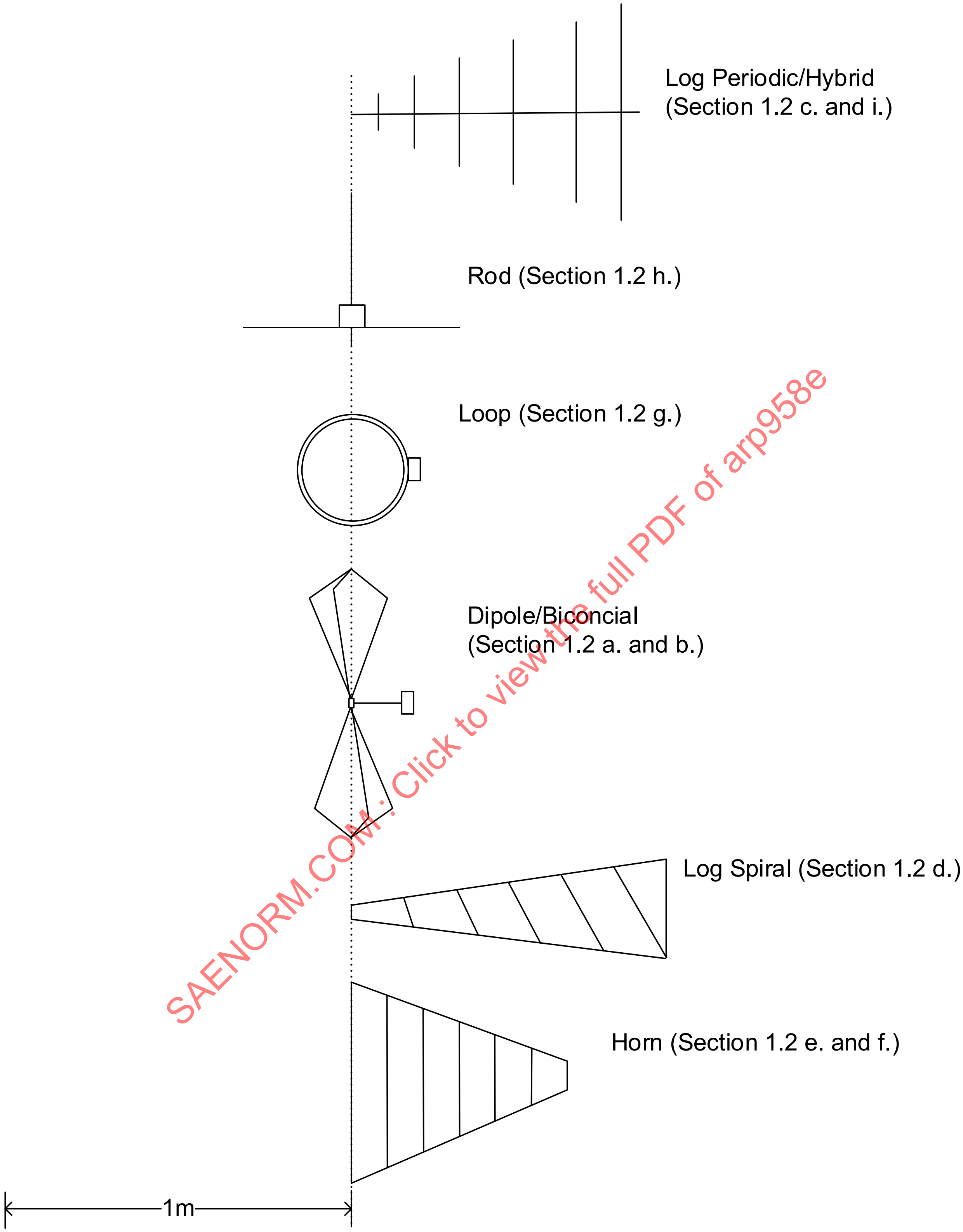

Figure 2 - Reference plane for antenna distance

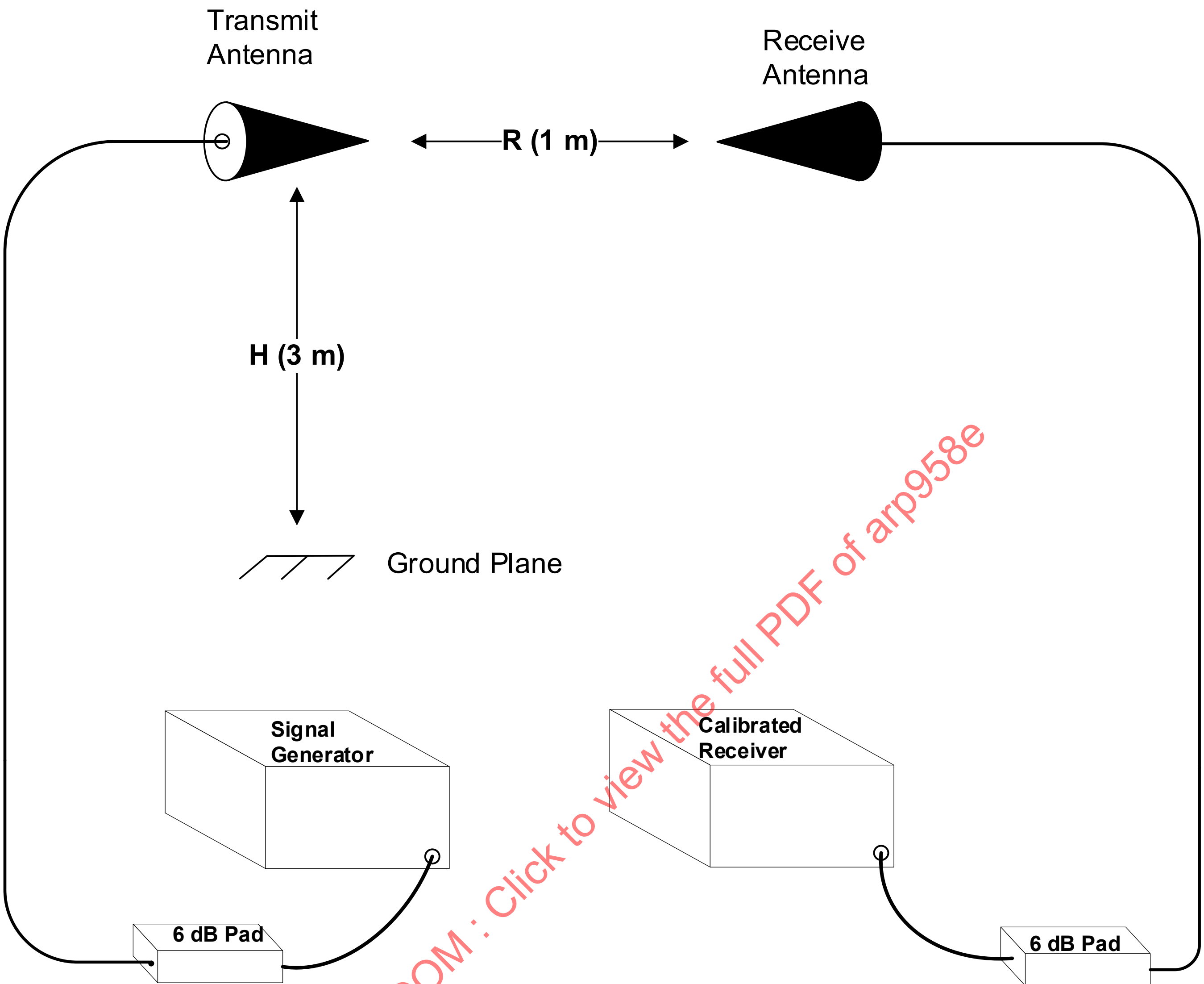

Figure 3 - Test set-up for determining 1 m gain utilizing two identical-antenna technique

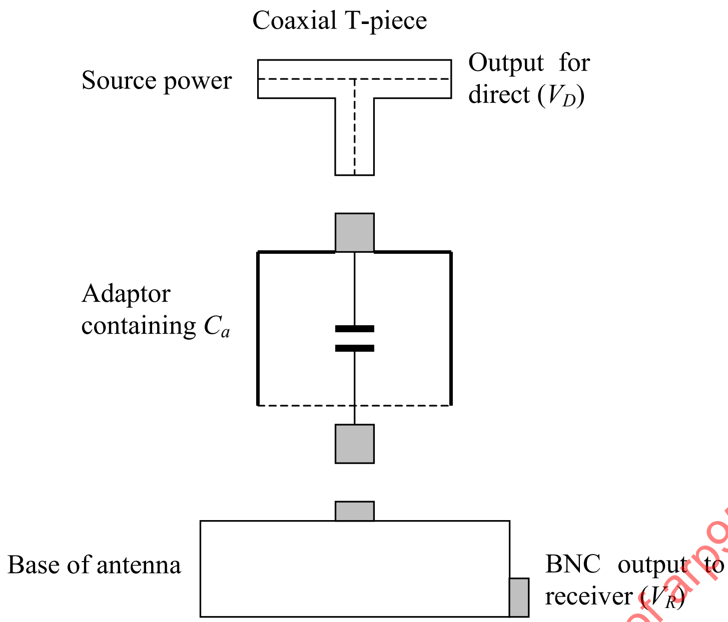

Figure 4 - Rod antenna calibration setup

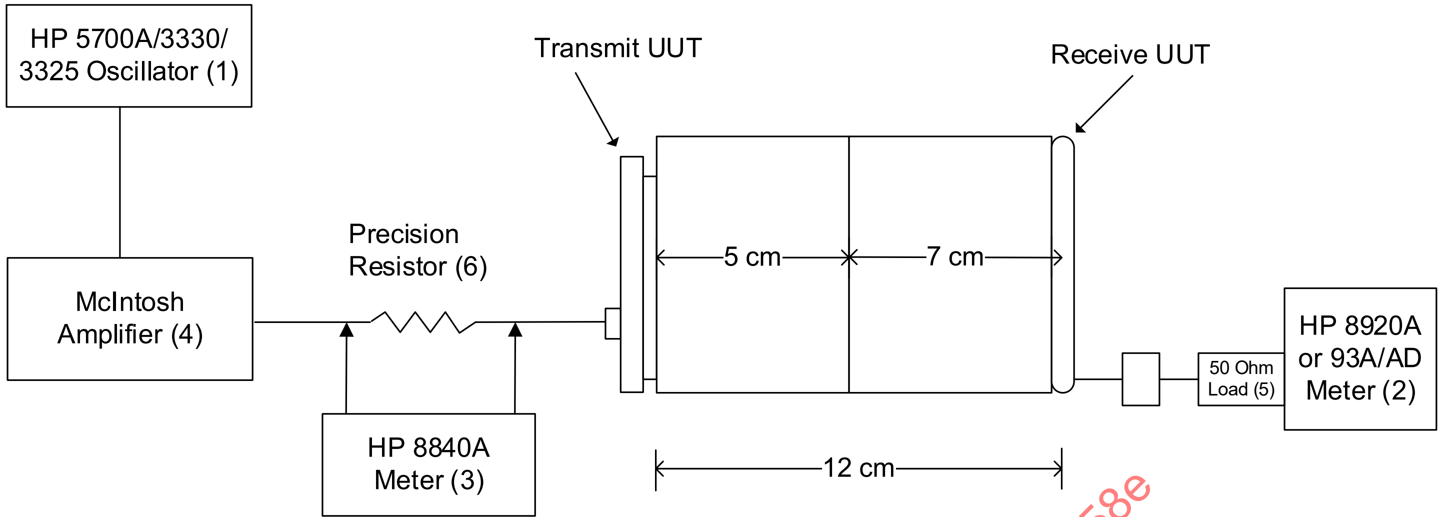

Figure 5 - Test setup for small loop calibration

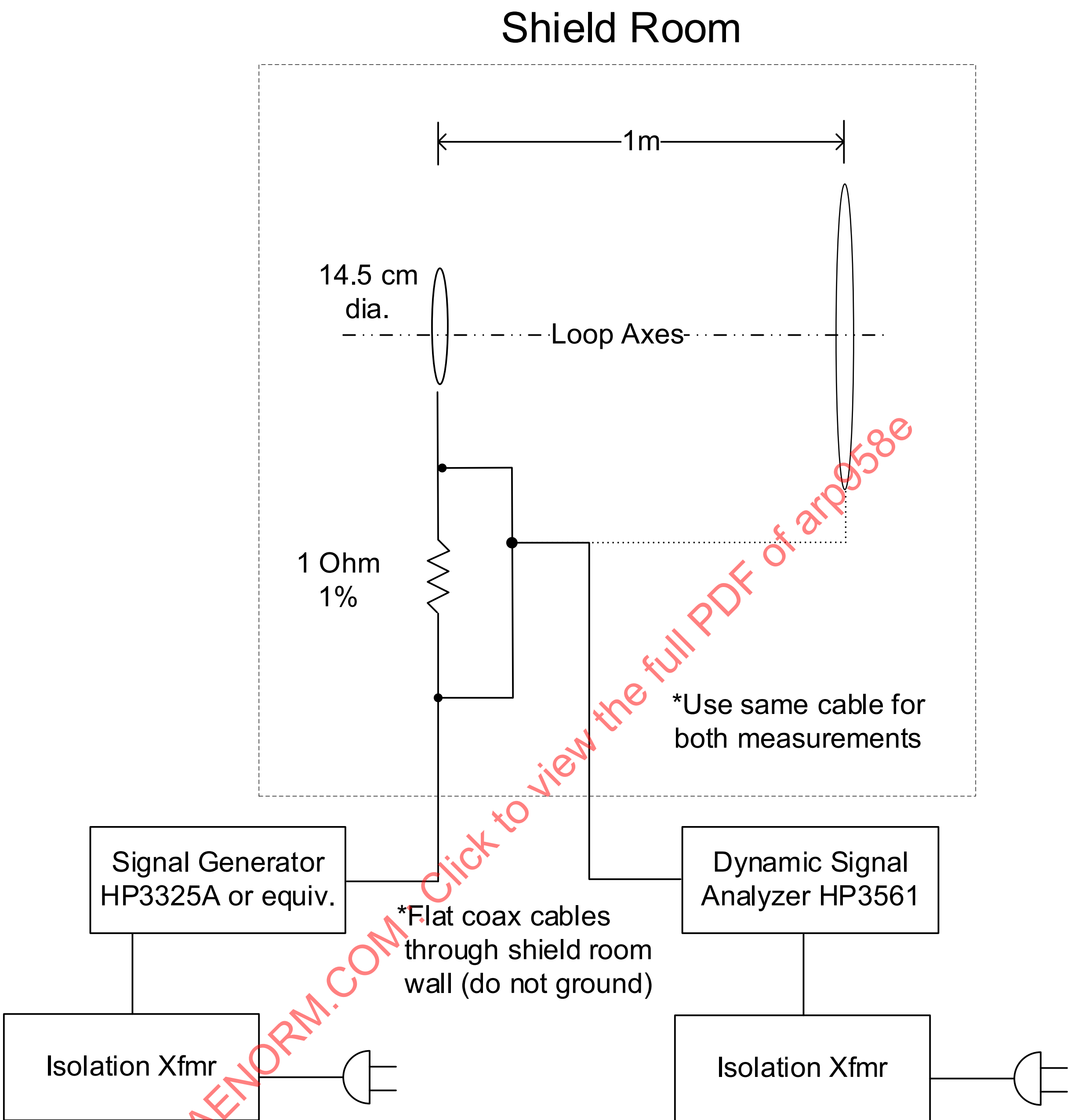

Figure 6 - Test setup for f <= 10 kHz

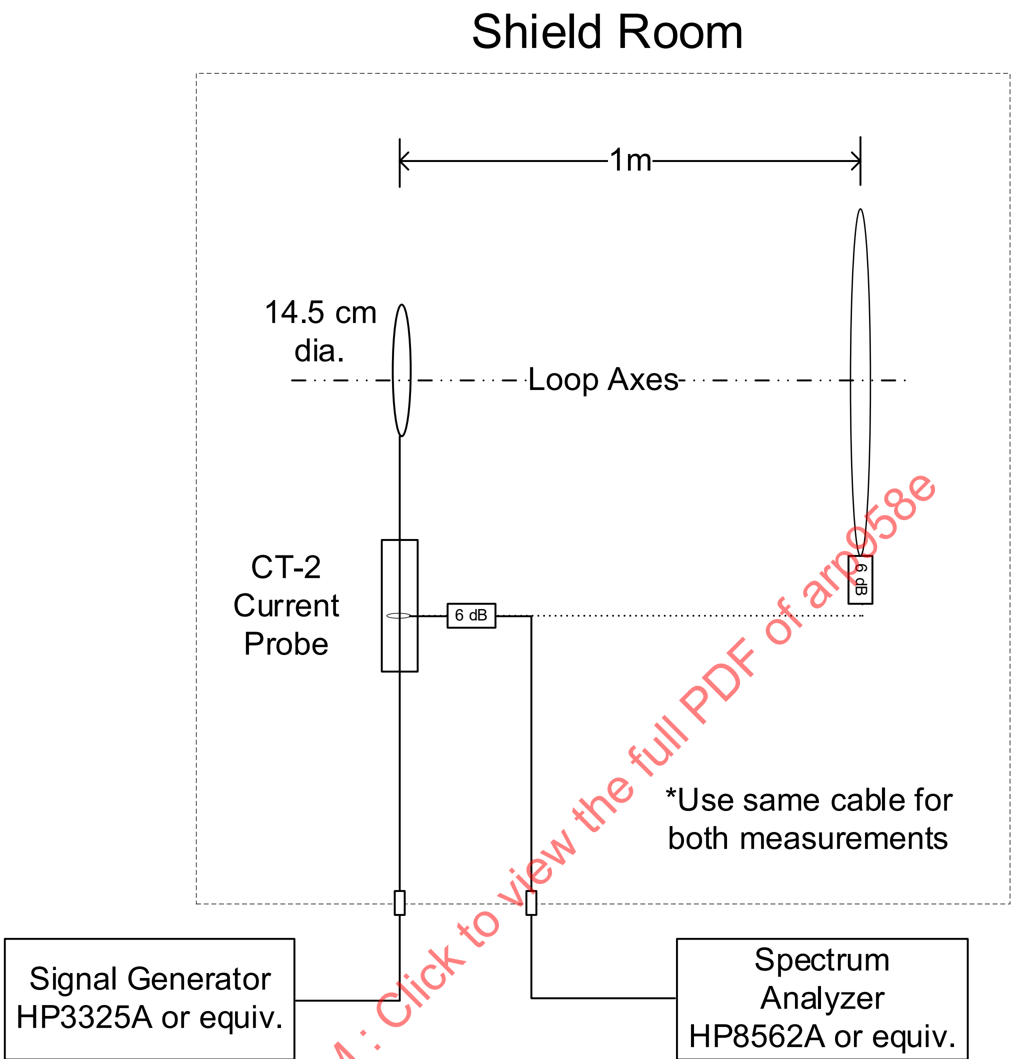

Figure 7 - Test setup for 10 kHz < f <= 10 MHz

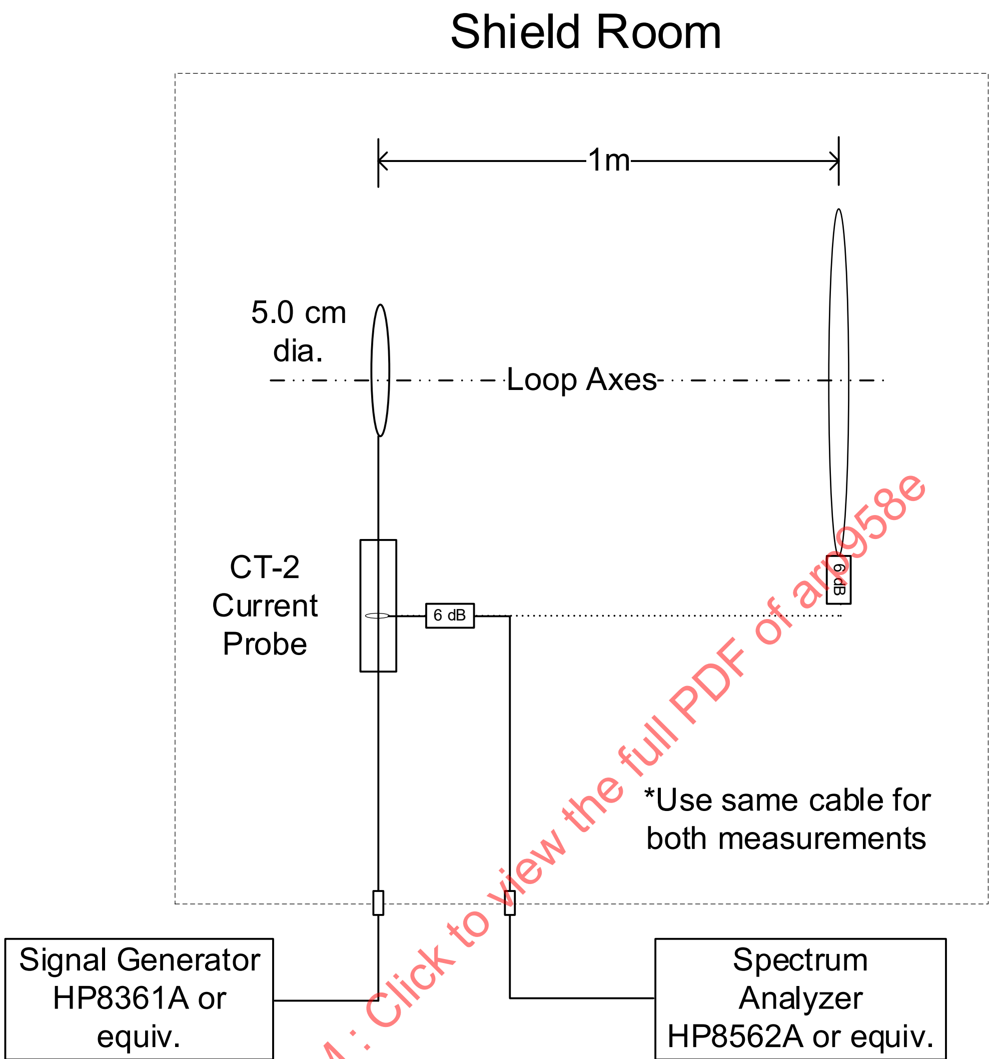

Figure 8 - Test setup for f >10 MHz

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