CALIBRATION OF ANTENNA FACTOR AT A GROUND SCREEN FIELD SITE
USING AN AUTOMATIC NETWORK ANALYZER

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Abstract

The technique now employed at the National Institute of Standards and Technology (NIST) for calibrating antenna factor at frequencies from 25 to 1000 MHz uses a standard "open-circuit" half-wave receiving dipole to measure the electric field strength. Unfortunately, the dipole responds to ambient fields over a large frequency range. This approach is compared with a three-antenna method which uses an accurate automatic network analyzer with 120 dB dynamic range to measure insertion loss between the transmitting and receiving antennas. A field site having a 30 m x 60 m ground screen which acts as a good reflector is used. Thus the effects of ground reflection can be calculated and compensated for. The new insertion loss technique permits faster measurements with greater repeatability and reduction in calibration uncertainty, especially at frequencies above 75 MHz.

Introduction

Much of this paper is a summary of known methods used in antenna work for years, but which are not well known or applied in the EMC community. The present NIST approach for calibrating EMI antennas, using an open-circuit dipole, is very labor intensive and highly susceptible to errors from ambient fields. Other techniques, such as the insertion loss approach of MIL-STD-461 and ARP 958, are also very time consuming since they require connecting and disconnecting both antenna paths at each frequency of interest. Two new approaches are described in this paper which permit automatic stepped-frequency data acquisition and rapid calculation of several antenna parameters. These include antenna factor, intrinsic gain, realized gain, antenna input impedance, VSWR, and site attenuation. The effects of antenna impedance on the meaning and accuracy of antenna measurements are emphasized throughout this paper.

Most calibrations of EMI antennas at NIST involve determining the antenna factor K or realized gain G_{re} . Either of these quantities permits a customer to use a 50 Ω receiver with the calibrated antenna to measure radiated emissions. That is,

$$E_{inc} = (K)(V_{50\Omega}) = \frac{(9.73)(V_{50\Omega})}{\lambda\sqrt{G_{re}}} \quad (1)$$

where E_{inc} = RMS magnitude of the incident field being measured, V/m,
 K = antenna factor of the receiving antenna at the given frequency, m^{-1} ,
 $V_{50\Omega}$ = antenna voltage across the 50 Ω receiver, after reduction in signal caused by mismatch loss between the antenna impedance and 50 Ω load, V,
 λ = wavelength, m,
 $G_{re} = (G)(M)$ = realized gain of the receiving antenna with respect to an isotropic antenna,

G = intrinsic gain of the receiving antenna,
 $M = 1 - (\rho_{ant})^2$ = mismatch factor of the antenna with respect to 50 Ω , and
 ρ_{ant} = reflection coefficient of the antenna.

Equation (1) can also be expressed in decibels as

$$E_{inc} \text{ in dB}\mu\text{V/m} = K \text{ in dB} + V_{50\Omega} \text{ in dB}\mu\text{V}. \quad (2)$$

The intrinsic gain G of an antenna does not take into account any losses caused by impedance or polarization mismatches. For example, for a $\lambda/2$ dipole in free space, $G \approx 1.64$ (2.15 dB). The realized gain G_{re} of an antenna includes mismatch loss between the antenna and 50 Ω load (coax cable plus receiver). For example, for a self-resonant dipole in free space, which has a length/diameter ratio of 1000, $G_{re} \approx 1.26$ (1.00 dB). These two gains are defined on pages 15 and 24 of reference [1]. A greater change in the commonly accepted gain of a $\lambda/2$ dipole may occur if the antenna is situated near the ground or other objects.

Description of measurement techniques

There are four common, independent techniques for calibrating an antenna to make field strength measurements. These are (a) standard (calculable) receiving antenna method; (b) standard radiated field, or standard transmitting antenna method; (c) insertion loss method; and (d) relative gain method. The first three techniques are "absolute" gain calibrations since the gain is determined without comparing against another antenna that has known gain from a previous calibration.

EMI antennas are now calibrated at an open field site at NIST using technique (a) above. This approach consists of generating a local field and measuring its strength in terms of the effective length of a standard dipole and the induced open-circuit rf voltage measured across the center gap of the dipole. The standard dipole is then replaced (in the same position) with the antenna under test (AUT) and its response is measured with a calibrated receiver or spectrum analyzer. A sketch of the instrumentation used at NIST is given in figure 1. The theoretical basis and test procedure are described in a paper presented at the 1988 IEEE International EMC Symposium [2].

Technique (b) involves the measurement of net power delivered to a transmitting antenna whose gain can be calculated theoretically or which has been calibrated previously. This approach requires the use of a good anechoic chamber at the frequency of interest, or a sound technique to compensate for the effects of all reflections -- such as from the walls of an anechoic chamber or from the ground at an open field site. This technique will not be discussed further, although it was used here at frequencies between 600 and 1200 MHz to verify data taken for technique (a) [2].

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The insertion loss technique (c) for calibrating antenna gain or antenna factor does not require either a standard antenna or a known field strength. The procedure, in its traditional form, requires only the insertion of a calibrated attenuator between the transmitting and receiving antenna terminals, in place of the "radiated" signal path. Instead of inserting a variable attenuator to measure this path loss, it has become more common to measure the voltage ratio with a calibrated 50 Ω spectrum analyzer, or the power ratio with an accurate power meter. The insertion loss technique is also useful for calibrating an antenna when a "good" field site or anechoic chamber is not available for determining the "free-space" gain. That is, this technique is used to measure the in-situ gain of the antenna at the location in which the "calibrated" antenna will then be used to measure rf emissions of electronic equipment.

The well known three-antenna method of measuring antenna gain, and the two-antenna method for "identical" antennas, are examples of the insertion loss technique. Figure 2 is a sketch of the instrumentation commonly employed for EMI antennas having a nominal input impedance of 50 Ω . The basic equation for calibrating antenna gain by the insertion loss technique is the Friis free-space transmission formula [3]. This expression comes from equating the power density established at a given distance from a transmitting antenna, with the power density at the same point measured by the pickup of a receiving antenna. When impedance mismatch losses are taken into account, the pertinent equation is given in reference [4] as

$$(G_T)(G_R) = \left[\frac{P_{rad}}{P_{dir}} \right] \left[\frac{4\pi d^2}{\lambda} \right] \left[\frac{|1 - \Gamma_R \Gamma_L|^2}{(1 - |\Gamma_R|^2)(1 - |\Gamma_T|^2)} \right] \left[\frac{|1 - \Gamma_G \Gamma_R|^2}{|1 - \Gamma_G \Gamma_L|^2} \right] \quad (3)$$

where

- G_T and G_R = intrinsic gains of the transmitting and receiving antennas,
- P_{dir} = power delivered to the 50 Ω load when the generator and load are directly coupled, W,
- P_{rad} = power delivered to the 50 Ω load when the radiated path is "inserted" between the generator and load, W,
- d = separation distance between the two antennas, m,
- Γ_G and Γ_L = complex reflection coefficients of the generator and load, and
- Γ_T and Γ_R = complex reflection coefficients of the transmitting and receiving antennas.

Equation (3) shows that gain is not a function of the load attached to the antenna but is an intrinsic property of the antenna. It is assumed that good 50 Ω cables, connectors and attenuator pads are used. Then, as figure 2 shows, Γ_G and Γ_L will be approximately 0. Also, $\Gamma_T = \rho_T$ and $\Gamma_R = \rho_R$, where ρ_T and ρ_R are the magnitudes of the reflection coefficients for the transmitting and receiving antennas with respect to 50 Ω . Voltage measurements with a receiver or spectrum analyzer may be made in lieu of power measurements. Also, if the two antennas are identical, so $G_T = G_R = G$ and $\rho_T = \rho_R = \rho_{ant}$, then

$$(G)(M) = G_{re} = \left(\frac{V_{rad}}{V_{dir}} \right) \left(\frac{4\pi d}{\lambda} \right), \quad (4)$$

where V_{rad} = voltage produced across the 50 Ω load when the radiated path is "inserted" between the generator and load, and V_{dir} = voltage produced across the 50 Ω load when the generator and load are directly coupled.

Equation (4) is the one most commonly seen in EMC literature for measuring the antenna gain of two identical antennas. It leads to the correct value of antenna factor but the intrinsic gain cannot be determined without also knowing the antenna reflection coefficient. It would be possible to measure the reflection coefficients of the antennas involved in the insertion loss measurements, at their locations on the ground screen, for each frequency of interest. However, the more pertinent gain figure to use in EMI antenna calibrations is G_{re} , since it can be converted mathematically to K. Yet, the values of G_{re} and K are influenced by the proximity of a ground screen, or by closely spaced antennas--as contrasted with intrinsic gain or free-space antenna factor.

Equation (3) can be rewritten in the form

$$(G_T M_T)(G_R M_R) = (G_T re)(G_R re) = \left(\frac{P_{rad}}{P_{dir}} \right) \left(\frac{4\pi d}{\lambda} \right)^2. \quad (5)$$

It can also be expressed in terms of the insertion loss (IL) measured with the instrumentation shown in figure 3, or by using an automatic network analyzer (ANA), rather than using separate measurements of power ratios or voltage ratios. In that case

$$(G_T re)(G_R re) = \left[\frac{1}{(IL)} \right] \left(\frac{4\pi d}{\lambda} \right)^2. \quad (6)$$

The three-antenna method of calibrating antenna gain involves measuring three different antennas in paired configurations to determine the gains of all three antennas. This requires three insertion loss measurements at each frequency. Each of these measurements represents a transmitting-receiving antenna pair as follows:

$$G_A + G_B = -[IL]_{AB} + 20 \log (4\pi d/\lambda), \quad (7)$$

$$G_A + G_C = -[IL]_{AC} + 20 \log (4\pi d/\lambda), \text{ and} \quad (8)$$

$$G_B + G_C = -[IL]_{BC} + 20 \log (4\pi d/\lambda). \quad (9)$$

In eqs. (7-9), G_A , G_B , and G_C are realized gains of antennas A, B, and C, in dB; $[IL]$ is the power difference in dB between the direct connection and radiated path in figure 2, or the difference between the incident transmitted power and received power in figure 3, or the insertion loss measured with a network analyzer.

The solutions of eqs. (7-9) for the individual gains of the three antennas are

$$G_A = \frac{1}{2} [(IL)_{BC} - (IL)_{AB} - (IL)_{AC}] + Q, \quad (10)$$

$$G_B = \frac{1}{2} [(IL)_{AC} - (IL)_{AB} - (IL)_{BC}] + Q, \text{ and} \quad (11)$$

$$G_C = \frac{1}{2} [(IL)_{AB} - (IL)_{AC} - (IL)_{BC}] + Q, \quad (12)$$

where $Q = 10 \log (4\pi d/\lambda)$.

If only two antennas are available, and if they are known to have identical gains, eqs. (10-12) reduce to the one equation

$$G_{re} \text{ in dB} = 10 \log \left(\frac{4\pi d}{\lambda} \right) - \left(\frac{1}{2} \right) (IL) . \quad (13)$$

Correction for ground screen reflection

The insertion loss technique can be used to calibrate antenna factor at an open field site, such as those used for FCC compliance testing of electronic equipment. "Site attenuation" is the measured insertion loss between a transmitting and receiving antenna, usually $\lambda/2$ dipoles, with the added feature that the receiving antenna height is scanned (usually from 1 to 4 m) to obtain the maximum receiver indication (minimum insertion loss). An in-phase reflection from the ground plane generally increases the maximum observed signal by 4 to 6 dB, as explained later.

The ray-path diagram between a transmitting and receiving antenna at an open test site is shown in figure 4. One method of averaging out the effect of ground reflections at a field site is given in reference [5]. At NIST the phase and amplitude of both the direct and ground-reflected rays are taken into account, for all the distances involved.

If the height of the receiving antenna is scanned to obtain a maximum response, the uncorrected or in-situ value of K measured by this method is lower than the free-space value. If E field emissions are measured with a receiving antenna at this position of maximum response, as required for FCC compliance testing, this lower value of K could be used to measure the field strength of emissions. However, K is then not a fixed and independent property of an antenna, but has a different value for each field site geometry (antenna heights and separation distance).

To correspond with the "true" antenna factor obtained from eq. (1), a correction factor should be applied to the insertion loss measurement of K to correct for the ground reflection. This correction can be determined if the reflection coefficient of the ground is measured, or if a good ground screen is used. In the latter case, $\Gamma = -1$ for a horizontally polarized E field and $\Gamma = +1$ for vertical polarization.

The E field strength of the direct ray in figure 4 is proportional to $(e^{-j\beta d})/d$ and the strength of the ground-reflected ray is proportional to $(\Gamma)(e^{-j\beta r})/r$. The vector sum of these two rays gives the "total" strength of the E field at the receiving point. That is,

$$E_{tot} = E_{dir} + E_{rf1} . \quad (14)$$

The ground - reflected ray changes the E field magnitude by the factor

$$\frac{|E_{tot}|}{|E_{dir}|} = \frac{|E_{dir} + E_{rf1}|}{|E_{dir}|} \quad (15)$$

$$= \left| e^{-j\beta d} + (\Gamma) \left(\frac{d}{r} \right) e^{-j\beta r} \right|$$

$$= \sqrt{1 + \left(\frac{rd}{r} \right)^2 + \left(\frac{2rd}{r} \right) \cos \phi} , \quad (16)$$

where $d = \sqrt{D^2 + (h_T - h_R)^2}$, m,

$$r = \sqrt{D^2 + (h_T + h_R)^2} , \text{ m,}$$

$\Gamma = -1$ for horizontal polarization, $\Gamma = +1$ for vertical polarization, for a good ground screen,

$\phi = (1.2 F)(r-d)$, degrees,

= phase angle between the direct and ground-reflected rays at the receiving point, and

F = frequency, MHz.

The required correction in dB to the measured value of insertion loss, to account for the ground reflection, is thus

$$(Corr) = 20 \log (|E_{tot}|/|E_{dir}|)$$

$$= 10 \log \left[1 + \left(\frac{rd}{r} \right)^2 + \left(\frac{2rd}{r} \right) \cos \phi \right] . \quad (17)$$

Equation (17) shows that the theoretical correction for ground reflection is a function of reflection coefficient, antenna heights and separation distance, and frequency. FCC Bulletin OST 55, reference [6], gives an approximate correction factor of $20 \log (1 + d/r)$, which assumes total reflection with a phase angle of -180° . The bulletin also gives an empirically determined correction of approximately 11 dB for all frequencies between 25 and 70 MHz.

Calculation of antenna gain and antenna factor

After the correction in eq. (17) has been calculated, eqs. (10-12) are revised to give the corrected values of realized gains, as follows:

$$G_A = \frac{1}{2} [(IL)_{BC} - (IL)_{AB} - (IL)_{AC} - (Corr)] + Q, \quad (18)$$

$$G_B = \frac{1}{2} [(IL)_{AC} - (IL)_{AB} - (IL)_{BC} - (Corr)] + Q, \text{ and} \quad (19)$$

$$G_C = \frac{1}{2} [(IL)_{AB} - (IL)_{AC} - (IL)_{BC} - (Corr)] + Q. \quad (20)$$

For the two-antenna method, assuming identical antennas, eqs. (18-20) reduce to

$$G_{re} \text{ in dB} = 10 \log \left(\frac{4\pi d}{\lambda} \right) - \frac{1}{2} [(IL) + (Corr)]. \quad (21)$$

Finally, after the realized gain has been measured, using eq. (21) or eqs. (18-20), the antenna factor is calculated. The relationship between G_{re} and K comes from the basic definition of K, combining eq. (1) with the expression for power delivered to a 50 Ω receiving antenna when it is immersed in an electric field having a strength E_{inc} . That is,

$$K = \frac{9.73}{\lambda \sqrt{G_{re}}} = \frac{F}{30.82 \sqrt{G_{re}}} ; \text{ or} \quad (22)$$

$$K \text{ in dB} = 20 \log F - G_{re} \text{ in dB} - 29.78 \quad (23)$$

$$= 10 \log (F/d) + \frac{1}{2} [(IL) + (Corr)] - 16.00. \quad (24)$$

Experimental data taken at NIST field site

Table 1 gives an example of measured and corrected data obtained at the NIST ground-screen field site. The numbers are the average values for two horizontal biconical dipoles. In each case the receiving antenna height was scanned from 1 to 4.5 m to obtain a minimum insertion loss (maximum signal). The insertion loss was measured for three antenna pairs, with data taken in both directions at the field site. Figure 5 is a graph of the corrected antenna factors, from the last column of Table 1.

The data given in this paper were obtained with an automatic network analyzer. The data using the directional coupler method of figure 3 were essentially identical to that in Table 1 and are not included here. Column 4 of the table shows that reflection from the ground screen, at the antenna height which produces a maximum signal, occurs when there is essentially a phase reversal of the signal. The measured values of G_{re} for the biconical antenna show a large variation with frequency. This is due mainly to the variation of antenna impedance with frequency.

Conclusions

The feasibility of using a three-antenna insertion-loss technique at a ground-screen field site to calibrate antenna factor has been demonstrated. An automatic network analyzer is being used to obtain sufficient data for evaluation of the procedure. If certain criteria are met regarding antenna heights and separation distance, the repeatability is better than ± 0.2 dB. For greatest signal strength and measurement reliability, the receiving antenna should be scanned in height from λ up to the maximum achievable height. At NIST this is 4.5 m, which limits the lowest frequency for which an in-phase ground reflection can be obtained to about 75 MHz.

Two criteria sometimes used for assuming negligible effect of mutual impedance between two dipoles, or between a dipole and its image, are that the distance between dipoles should be $\geq 2\lambda$ and the height above ground should be $\geq \lambda$. When using signal frequencies as low as 75 MHz ($\lambda = 4$ m), the minimum permissible antenna distance is then 8 m and the minimum permissible antenna height is 4 m. However, data taken here at a few lower frequency points indicate that the insertion loss technique can be used down to 30 MHz with a repeatability of ± 2 dB. Corrections to the measured insertion loss must be made for the ground-reflected ray. We plan to determine the absolute error more accurately, comparing the new insertion loss technique with the NIST open-circuit dipole approach [2].

References

- [1] IEEE Std 145-1983, "IEEE Standard Definitions of Terms for Antennas," Copyright 1983, The Institute of Electrical and Electronics Engineers, Inc.
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- [6] Federal Communications Commission Bulletin OST 55, "Characteristics of Open Field Test Sites," U.S. Government Printing Office, Washington, DC, August 1982.

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Table 1. Measurements of antenna factor and other parameters for horizontal biconical dipoles.
Data taken at the NIST ground-screen field site, with $\Gamma \approx -1$.

Frequency, MHz	Trans. antenna VSWR	h_R for maximum response, m	Cosine of phase angle	Measured insertion loss, dB	Insertion loss correction, dB	Corrected gain G_{T0} , dB	Antenna factor K, dB
50	18.6	4.06	-.9999	33.45	4.75	-6.85	11.05
60	5.9	3.31	-.9999	23.35	4.92	-1.10	6.88
70	1.4	2.61	-.9830	18.93	5.07	1.73	5.39
80	3.7	2.20	-.9656	23.60	5.15	-0.04	8.32
90	5.8	1.94	-.9636	26.72	5.23	-1.09	10.39
100	5.4	1.79	-.9823	26.69	5.32	-0.66	10.88
110	2.8	1.65	-.9903	24.71	5.38	0.73	10.32
120	2.0	1.51	-.9905	24.30	5.43	1.30	10.50
130	3.8	1.34	-.9702	27.57	5.45	0.04	12.46
140	7.5	1.25	-.9743	31.42	5.49	-1.57	14.71
150	9.6	1.19	-.9856	33.56	5.54	-2.36	16.10
160	8.3	1.15	-.9972	33.55	5.57	-2.09	16.39
170	5.8	1.09	-.9987	31.60	5.60	-0.86	15.69
180	2.5	1.05	-.9999	27.41	5.62	1.48	13.85
190	1.6	0.98	-.9994	26.24	5.64	2.31	13.49
200	5.3	0.91	-.9950	31.36	5.66	-0.03	16.27

Figure 1. Field site instrumentation for calibrating antenna factor at NIST using a $\lambda/2$ open-circuit receiving dipole, 25 to 100 MHz.

Figure 2. Instrumentation for the insertion loss technique of measuring antenna gain and antenna factor according to ARP 958 and MIL-STD-461.

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Figure 3. Instrumentation for the insertion loss technique of measuring antenna gain and antenna factor using a directional coupler.

Figure 4. Ray-path diagram of the ground-screen test site for measuring antenna gain and antenna factor.

Figure 5. Comparison of published antenna factors of biconical dipoles with data taken at the NIST ground-screen field site.