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# Evaluation of Uncertainty in Free-space Antenna Factor Calibration in CRL

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## Abstract

Conventional EMI antenna calibration in the VHF band has been performed by using the height-dependent antenna factor. For example CRL (Communications Research Laboratory) calibrates the height-dependent antenna factor by using the standard antenna method and the standard site method. Recently CISPR (International Special Committee on Radio Interference) decided to use the free-space value of the antenna factor in the radiated emission measurements, because it improves the measurement accuracy. Thus, we estimated the free-space antenna factor from the height-dependent value applying the method of least squares method. We also examined the influence of the calculation accuracy and measured the height-dependent antenna factor by the standard antenna method at a test site in an open area. A comparison of the measured and estimated results is shown.

**Keywords:** EMI antenna factor, uncertainty, free-space value, calibration, standard antenna method, dipole antenna

## 1. Introduction

Recently, the societal importance of EMI measurement has been greatly increasing and more accurate measurement method are required. In addition, testing laboratories and manufacturers will have to evaluate the uncertainty in their own measuring facilities [1]. So far, however, the error in these measurements has not been so small. The most serious cause of measurement error is the antenna factor of an EMI antenna. It is thus hoped that using the free-space value of the antenna factor will minimize the error.

To investigate this possibility, the height-dependent antenna factor is measured by the standard antenna method, with the goal of estimating a more accurate free-space value. The free-space antenna factor is usually estimated from an averaged value, from the value at a suitable antenna height, from an approximate value based on a model equation [2], or by various other methods. For this paper, we examined the simple estimation method with definite calibration accuracy.

We previously examined free-space antenna factor estimation by using the periodicity of the height-dependent antenna factor which uses the averaged value [3]. In this paper, we examined an estimation approach based on the method of least squares in order to improve accuracy. We tried approximation equations with various parameters and determined the optimum combination of parameters is based on the minimum residual sum of squares calculated by the least squares method.

## 2. Antenna factor

The antenna factor of an EMI antenna is usually defined as follows:

$$AF = E/V \quad [\mathrm{dB}(1/\mathrm{m})] \quad (1)$$

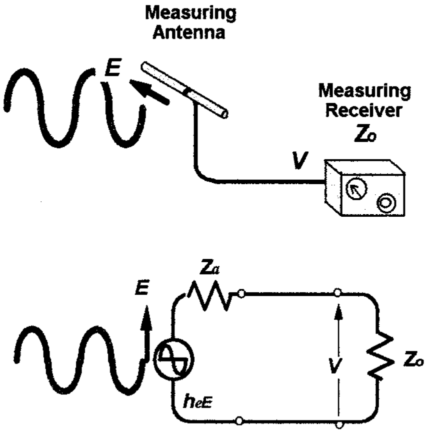
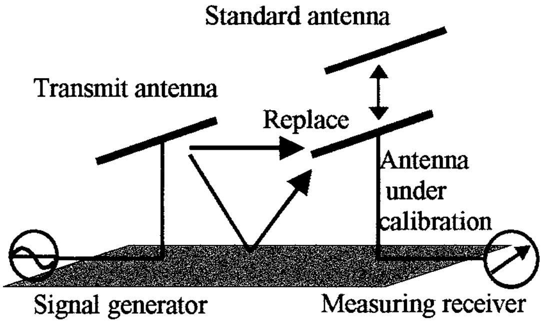


Figure 1 Antenna factor measurement and the equivalent circuit



Metal ground plane (45m×30m)

Figure 2 Standard antenna method

where E is the electrical field strength of a radio wave impinging on the antenna, and V is the voltage induced across the antenna terminals. Figure 1 illustrates the equivalent circuit of a receiving antenna. The induced voltage on the antenna can be substituted and Eq. (1) redefined as

$$AF = \frac{1}{h_e E} \cdot \frac{Z_a + Z_0}{Z_0} \quad (2)$$

where $Z_a$ is the radiation impedance of the antenna, $Z_0$ is the input impedance of the measuring receiver, and $h_e$ (=$\lambda/\pi$) is the effective length.

Due to the metal ground plane of the antenna, $Z_a$ is influenced by ground reflection and varies as follows:

$$Z_a = Z(\infty) + \alpha \cdot Z_r(h) \quad (3)$$

where h is the antenna height and α is the reflection coefficient. $Z_r(h)$ is the mutual impedance between the receiving antenna and its reflected image, which can be expressed approximately as

$$\begin{aligned} Z_r(h) &\propto h_e^{\,2} \frac{\exp(-jk \cdot 2h)}{2h} \\ &= \frac{\lambda}{\pi^2} \frac{\exp(-j \cdot 2\pi \cdot h/(\lambda/2))}{h/(\lambda/2)} \end{aligned} \quad (4)$$

where k (= $2\pi/\lambda$) is the wave number. The height is greater than the wavelength. Based on these equations, the height-dependent antenna factor can be expected to vary with a half-wavelength period.

## 3. Estimation method (averaging and least squares approximation)

The averaging method uses the height-dependence characteristics of the antenna factor. The height range of $\lambda/2$ is divided equally, and the free-space value is calculated from the mean of the height-dependent antenna factor. The half-wavelength value at a frequency of 30MHz is 5m. Only two height divisions are possible in the range of typical antenna heights (1m~4m). Therefore, we calculated the free-space antenna factor, AF(∞), with the following equation:

$$AF(\infty) = \frac{AF(4m) + AF\{(4 - \lambda/4)m\}}{2} \quad (5)$$

AF[4m]:antenna factor at a height of 4 m
AF[(4-λ/4)m]:antenna factor at a height of (4-λ/4) m

The method of least squares was applied to the approximation equations.

The height-dependent antenna factor, AF(h), could then be expressed with either of these equations:

$$AF(h; b_1, d\theta) = AF(\infty) + a\frac{\cos(k \cdot 2h + d\theta)}{\lambda \cdot b_1 + h} \quad (6)$$

$$AF(h; b_1, b_2, d\theta) = AF(\infty) + a\frac{\cos\left(k \cdot 2h + \frac{d\theta}{b_2 + h}\right)}{\lambda \cdot b_1 + h} \quad (7)$$

where a is an unknown quantity, and $b_1$ ($-1/\lambda < b_1 < 1-1/\lambda$), $b_2$ (=1,2,3,...), and $d\theta$ ($-\pi \le d\theta \le \pi$) are parameters. Unlike Eq. (6), Eq. (7) addresses the subtle variation of the characteristic period of the height dependence with respect to $\lambda/2$.

We varied each of the parameters, $b_1$, $b_2$, and dθ, in the equation and calculated the unknown quantities, AF(∞) and a, based on the least squares approximation. The method of least squares is based on calculating the residual sum of the squares of the differences between the approximated and the measured values. By minimizing the residual sum, the unknown quantities can be determined, together with the parameters.

We estimated the free space value under each of the following conditions, and the resulting errors ware compared.

(a) Eq.: (6), Scan height: 1-4 m
(b) Eq.: (6), Scan height: 1-6 m
(c) Eq.: (7), Scan height: 1-4 m
(d) Eq.: (7), Scan height: 1-6 m

The unknown quantities, AF(∞) and a, were calculated under each of these conditions by the least Squares method, as follows:

$$\sum_{i=1}^{n} \{AF_{data}(h) - AF(h; b1, b2, d\theta)\}^2 \to \text{min.} \quad (8)$$

Next, the combination of the most suitable parameters has to be determined. So we calculated the combination of the five parameters, (AF(∞), a, b1, b2 and dθ), by using the minimum residual sum of squares under the condition of (9). An equation was then determined from this combination of values:

$$\sum_{i=1}^{n} \{AF_{data}(h) - AF(h; AF(\infty), a, b1, b2, d\theta)\}^2 \to \text{min.} \quad (9)$$

## 4. Estimation results

A set of results estimated by these methods is shown in the Fig. 3. The interval between antenna scans was 10cm. Figure 4 shows another set of results for which the antenna scan height range exclusively from 1-6 m and the intervals between scans were 10, 50, and 100 cm.

We thus estimated the uncertainty of the free-space antenna factor to be less than 0.06dB under the following condition:

i) Approximation equation: (7)
ii) Scan range of antenna height: 1-6 m

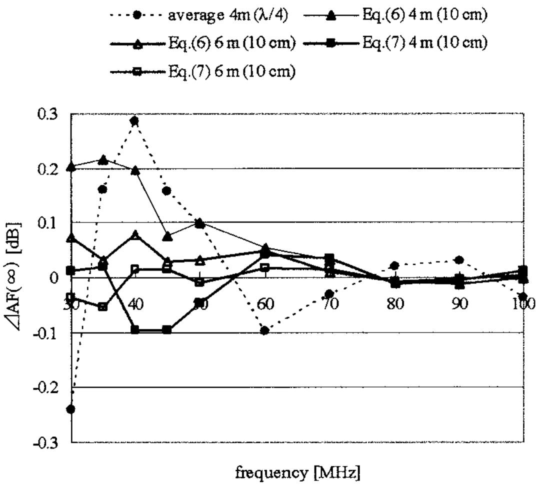


Figure 3 Differences between FA (∞) and the estimated results under various conditions

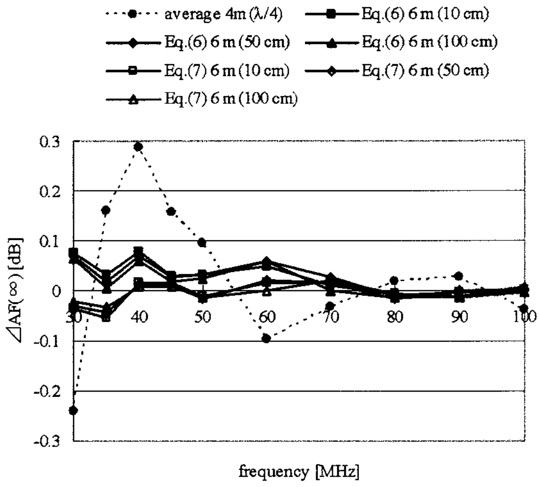


Figure 4 Differences between FA (∞) and the estimated results under various conditions

The correlation of the calculated values and the approximation equation seemed to require the following additional condition:

iii) Measurement interval: less than λ/8

For comparison, each figure also shows the results calculated by the averaging method. The main error factors appeared to be the height dependence of the mutual impedance and the idealized period of λ/2.

Table 1 Uncertainty of the standard antenna method at 30-1000MHz

| | Uncertainty | Distribution |
|---|---|---|
| Errors originating from the standard antenna | | |
| Antenna length (error = 3 mm at 30 MHz) | ±0.0 2dB | Uniform |
| Drifting impedance | ±0.2 dB | Uniform |
| Calculation program | ±0.1 dB | Uniform |
| Common mode | ±0.07 dB | Uniform |
| $\sigma 1 = \sqrt{\left(0.02^2 + 0.2^2 + 0.1^2 + 0.07^2\right)/3} = 0.14\,\mathrm{dB}$ | | |
| Errors originated from the measurement | | |
| Measuring receiver | | |
| Digital resolution (catalog specification) | ±0.01 dB | Uniform |
| Non-linearity | ±0.05 dB | Uniform |
| Receiver noise (S/N = 45 dB) | ±0.05 dB | Uniform |
| Repeatability | ±0.03 dB | Normal |
| Antenna arrangement | | |
| Rx. antenna height (error = 1 cm) | ±0.05 dB | Uniform |
| Antenna separation (error = 1 cm) | ±0.02 B | Uniform |
| Rx. antenna orientation (error = 2 °) | ±0.005 dB | Uniform |
| Antenna close coupling (R > 10 m) | <±0.1 dB | Uniform |
| $\sigma 2 = \sqrt{\left(0.01^2 + 3 \times 0.05^2 + 0.02^2 + 0.005^2 + 0.1^2\right)/3 + 0.03^2} = 0.08\,\mathrm{dB}$ | | |
| Errors originated from the mismatching | | |
| $\sigma 3 = \sqrt{0.19^2/2} = 0.13\,\mathrm{dB}$ | | U-type |

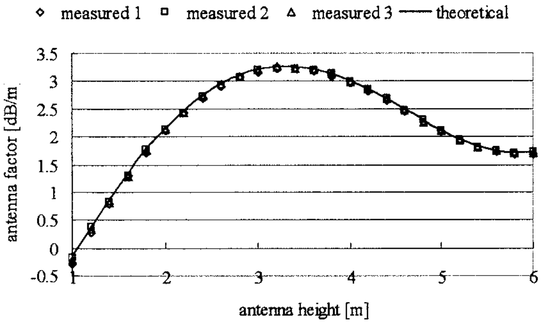


Figure 5 Height-dependent antenna factor at 30 MHz

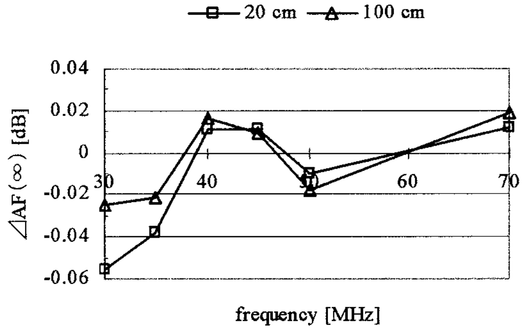


Figure 6 Differences between estimated FA (∞) and measured values under various conditions

## 5. Evaluation of uncertainty [4]

We then evaluated the uncertainty of height-dependent antenna factor calibration by the standard antenna method in the 30-1000 MHz band. Table 1 summarizes the results. The free-space antenna factor estimation performed at CRL can be achieved by including this error in the free-space value calculation.

The error was 0.08 dB or less. Therefore, if the error distribution is evaluated as a rectangle, the degree of accuracy becomes

$$\sigma(\mathrm{AF}(\infty)) < \sqrt{\left(0.08^2/3\right)} = 0.05\,\mathrm{dB}$$

The overall uncertainty is

$$\sigma(\mathrm{AF}) = \sqrt{\left(0.14^2 + 2\times 0.08^2 + 0.13^2 + 0.05^2\right)} = 0.23\,\mathrm{dB}$$

Therefore, the expanded uncertainty (k = 2) is 0.46 dB.

## 6. Results estimated from actual measurements

We checked the results calculated in this by comparing them with actual measurements obtained by the standard antenna method. Both the reference antenna and the measuring antenna were hybrid balun-type standard antennas which were in the market. Each antenna factor was calculated by the method of moment (NEC 2). Although the measurements were performed at various times for each frequency, the reproducibility was very good, as shown in Fig. 5. The free-space antenna factor was then estimated from the measured data. The measurement conditionswere as follows:

Measurement frequency: 30, 35, 40, 45, 50, 70 MHz
Scan range of antenna height: 1-6 m
Scan interval of antenna height: 20 cm, 100 cm
Approximation equation: (7)

The differences between the measured and estimated results are shown in Fig. 6. The estimation error was below ±0.06 dB.

## 7. Conclusions

We examined the estimation accuracy of the free-space antenna factor for the standard antenna method using a resonance dipole antenna. As the frequency decreases, the variation period of the ground height for the height-dependent antenna factor increases. Therefore, a greater scanning range is required for the measurement antenna height in the VHF band. Moreover, the indefinite nature of the antenna balun affects the period of each antenna. In this paper, the scanning range of the measuring antenna was set between 1 and 6 m to reduce the influence of the periodicity. This required us to obtain suitable parameters for an approximation equation by applying the least squares method. The free-space value estimation by this estimating method was simple and could easily be performed with sufficient accuracy. It increased to the calibration accuracy of the height-dependent antenna factor by only 0.02dB.

## 8. Acknowledgment

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