2-5-2 Calibration of Dipole Antennas

Iwao NISHIYAMA, Kojiro SAKAI, Tsutomu SUGIYAMA, Kouichi SEBATA, and Katsumi FUJII

This paper describes a calibration method of the half-wave tuned dipole antenna for the frequency band from 30 to 1000 MHz. NICT performs the calibration of half-wave tuned antennas by the Standard Antenna Method with the special designed half-wave tuned dipole antenna which is called standard antenna, even though there are some calibration methods as known well. We introduce the Standard Antenna Method and show the experimental calibration results of half-wave tuned dipole antennas. In addition, we describe the detail of the calibration uncertainties.

1 Introduction

With regard to the issues of electromagnetic interference (EMI) emitted from electric / electronic equipment—its major instance being computers—and interfering with broadcasting or business radios, the establishment of technologies to secure electromagnetic environments—such as EMI measurement technologies for making correct measurements of interfering waves, or EMI countermeasure technologies for preventing interfering wave emission—have been discussed as the key technologies. In recent years, the criticality of such technologies has grown because a variety of types of apparatuses have built-in computers, and also mobile phone terminals are being used all around us.

Therefore, EMI measurement / prevention technologies are critically needed, particularly for the frequency range of 30 to 1,000 MHz; this frequency range has been used as well as for radio / TV broadcasting, for various types of communications for various purposes including mobile phones / terminals; the frequency range is also used for communications in transport operations such as air, sea, railroad and taxi; moreover, the frequency range is used for emergency communications for police, fire-fighting, rescue, or disaster prevention.

Internationally, as for the EMI measurement methods in that frequency range, the International Special Commission of Radio Interference (CISPR), which is a sub-commission of the International Electrotechnical Commission (IEC), has enacted CISPR Standards [1].

Locally in Japan, the VCCI Council has specified measurement methods in their standards [2]. The standards specify the EMI measurement scheme as shown in Fig. 1, for an equipment emitting EMI, where a equipment under test (hereinafter, referred to as an EUT) will be put on a large metal ground (hereinafter, referred to as a ground plane), and measurements will be executed on the electric field using a receiver at specified distances, such as 3 or 10 m, and at different heights from the ground plane. In such measurements, different types of wideband antennas are widely used; for the 30 to 300 MHz frequency range, biconical antennas; for the 300 to 1,000 MHz range, loga-

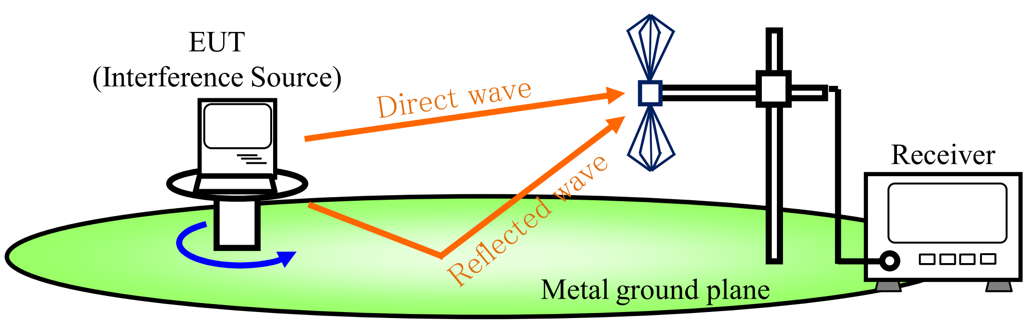


Fig. 1 EMI measurement (30 to 1,000 MHz)

rithm periodic dipole array antennas, called log periodic antennas or "LPDA," (hereinafter, referred to as LPDA). For accomplishing correct measurements, correctly calibrated antennas must be used. Therefore, NICT has been conducting calibration operations on a half-wavelength resonant dipole antenna, and has released the calibration results—the antenna is used as a reference in the calibrations of various wideband antennas.

In this paper, we will describe antenna calibration methods; in Section **2**, describing the antenna factor—the key characteristics in EMI measurements; in Section **3**, showing how to calibrate antennas, particularly concerning the "standard antenna method," where NICT has been using a standard antenna as a calibration reference and conducting calibrations of half-wavelength resonant dipole antennas; in Section **4**, introducing actual examples of calibrations; and in Section **5**, describing the uncertainty in the results of calibration.

2 Antenna factor

The antenna factor is the key parameter in EMI measurement. As shown in Fig. 2, when the planar electric field of strength E is received by an antenna placed in a free space and excites the receiver connected to the antenna to generate the output voltage of V, the antenna factor is defined as the ratio of E to the voltage V, as shown in Equation (1),

$$F_a = \frac{E}{V} \quad [1/\mathrm{m}] \tag{1}$$

where its unit is [1/m]. If we use an antenna of which the factor is already known by measurement, we can determine the strength E of the electric field by measuring V. Because these kinds of values are usually expressed in dB, we take the value of the common logarithm of Equation (1) and multiply by 20 as shown by Equation (2).

$$20\log_{10} F_a = 20\log_{10}\frac{E}{V} \quad [\mathrm{dB\ (1/m)}] \tag{2}$$

Then we can determine the electric field strength by simple additions as shown in Equation (3). However, in the actual measurements, we have to take into account the loss in the cable connecting the antenna to the receiver, or the impacts of standing waves generated in the cable.

$$E^{\mathrm{dB}}\ [\mathrm{dB}(\mu\mathrm{V/m})] = F_a^{\mathrm{dB}}\ [\mathrm{dB(1/m)}] + V^{\mathrm{dB}}\ [\mathrm{dB}_\mu] \tag{3}$$

On the other hand, while the CISPR Standards and others require that EMI measurements be executed on a perfectly conducting ground plane, the value of the antenna factor is known to vary due to the influence of the ground plane [3]. If considering the configuration as that shown in Fig. 3 (a) where a dipole antenna is placed at the height of h above a ground plane, when the elements of the antenna are set horizontal to the ground plane and the circuit attached to the element such as a bulan is expressed by S-parameters, we can express the equivalent circuit of the antenna factor as shown in Fig. 3 (b), and at the same time can express Equation (1) as shown in Equation (4)[4].

$$F_a(h) = \left| \frac{1}{l_e} \frac{Z_a(h) + Z'_0}{\sqrt{Z'_0 Z_0}} \frac{1 - S_{11}\Gamma_a(h)}{S_{21}} \right| \quad [1/\mathrm{m}] \tag{4}$$

where the S-parameters are defined as a "power wave" of which amplitude is equal to the square root of its power.

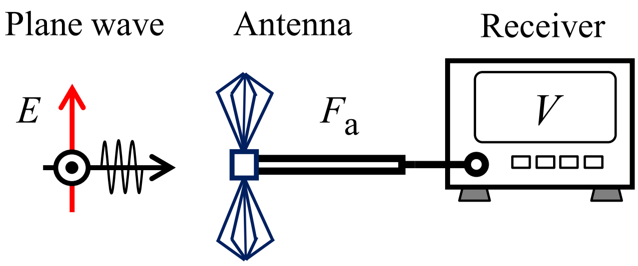


Fig. 2 Definition of antenna factor

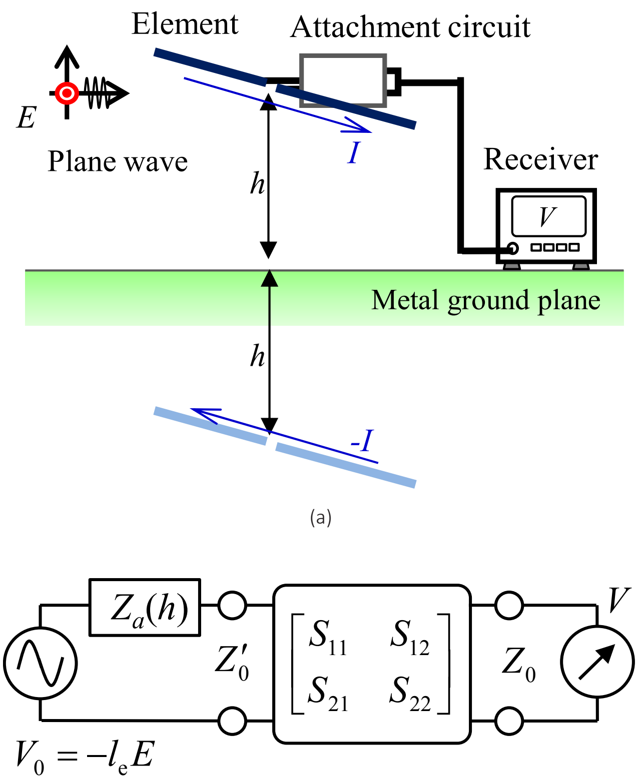


Fig. 3 Equivalent circuit representation of a dipole antenna
(a) Dipole antenna above ground plane (b) Equivalent circuit

l_e Effective length of dipole element

$Z_a(h)$ Input impedance of dipole element at the height of h

Z'_0 Characteristic impedance of Port 1

Z_0 Characteristic impedance of Port 2(50 Ω)

And $\Gamma_a(h)$, the reflection coefficient of the dipole element, is related to the impedances as shown below, where the receiver input impedance Z_0 matches the measurement system impedance.

$$\Gamma_a(h) = \frac{Z_a(h) - Z'_0}{Z_a(h) + Z'_0}$$

For a larger antenna height, the ground plane has smaller influence. Therefore, we can express the relation of the antenna factor at the height of *h*, $F_a(h)$, to the antenna factor when the antenna is in a free space, F_a, as shown in Equation (5).

$$F_a = \lim_{h\to\infty} F_a(h) = \left| \frac{1}{l_e} \frac{Z_a(\infty) + Z'_0}{\sqrt{Z'_0 Z_0}} \frac{1 - S_{11}\Gamma_a(\infty)}{S_{21}} \right| \quad [1/\text{m}] \qquad (5)$$

In Fig. 4, we show plots of the instances of antenna factor of a dipole antenna by height, where the antenna factor depends on the height. We obtained those plots by calculations using an electromagnetic field numerical simulation program, Numerical Electromagnetic Codec (NEC2)[5], where we assumed that the attachment circuit is not inserted, instead, the antenna element is directly loaded with Z_0 of 50 Ω. In other words, we calculated antenna factors using Equation (4), by plugging the values of Z_a and l_e obtained from NEC2 into the equation, and letting Z'_0 = Z_0 = 50 Ω, S_{11} = 0, and S_{21} = 1. The horizontal axis is *h*/*λ*, the height normalized by λ; the vertical axis is the difference between the antenna factor at the height of *h* and the antenna factor in a free space, which shows the influence of the ground plane. Figure 4 clearly indicates that the antenna factor converges with the free space antenna factor as the antenna moves away from the ground plane.

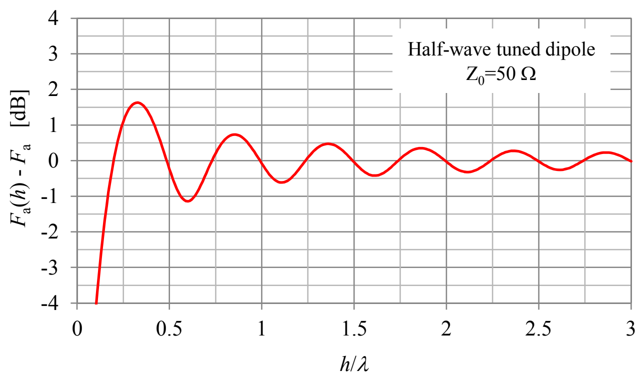


Fig. 4 Height dependency of antenna factor
Case of half-wavelength resonant dipole antenna

3 Antenna calibration method

3.1 Types of calibration method

Antenna calibrations are generally conducted, as shown in Fig. 5, through propagating waves from a transmitting antenna to a receiving antenna However, the calibration is conducted under the assumption that any one of the three components in the calibration—the measurement site (hereinafter referred to "site"), the transmitting antenna, or the receiving antenna—is ideal and its characteristics can be determined based on relevant theories.

First, we will explain a calibration method where it is assumed that "the site is ideal"; the ground plane is fully reflective, flat, and infinitely expands; in the site environment, there exist no objects reflecting / diffracting the waves that the transmitting antenna radiates; and, no

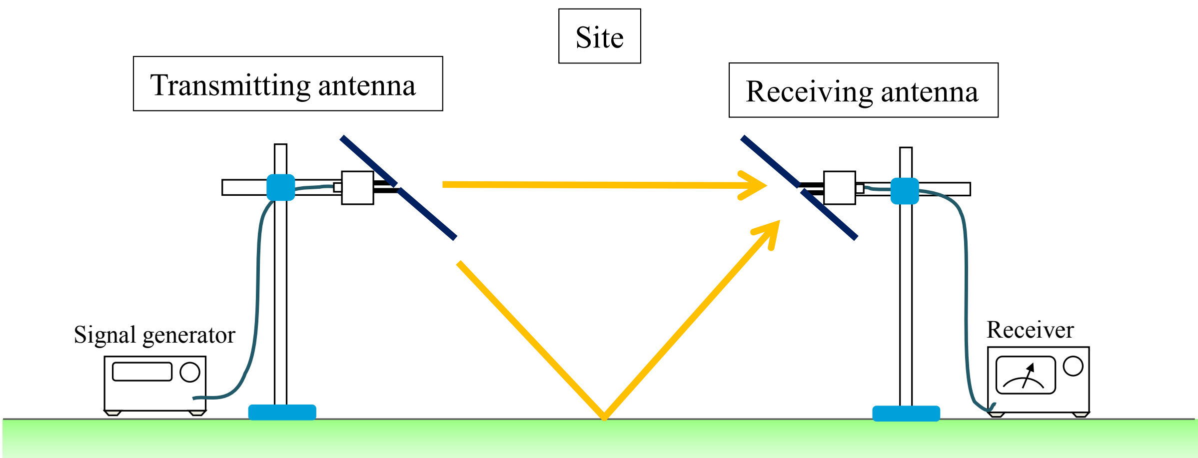


Fig. 5 Necessary conditions for antenna calibration

other waves such as broadcasting waves come into the site environment. Under those ideal conditions, waves from a transmitting antenna propagate to a receiving antenna exactly as propagation theory predicts; therefore, by making three measurements of the propagation losses on each combination of two antennas out of the three—antenna #1, antenna #2, and the antenna under calibration (hereinafter, referred to as "AUC")—setting up simultaneous equations and solving them, we can determine the required antenna factor. We call the method described above the "standard site method" because the site is used as the reference, or the "three-antenna method" because three antennas are used [6]. The significant feature of the method is that it can produce antenna factors even using antennas whose characteristics are completely unknown. Therefore, national institutes in charge of measurement standards have employed a calibration method to estimate antenna factors using other physical quantities—length, RF attenuation, RF impedance, and frequency. However, the method has the following drawback: the method requires more work compared to other methods because measurements have to be made three times—more measurements can lead to greater uncertainty in calibration.

Second, we will explain a calibration method where it is assumed that "the receiving antenna is ideal." By the method, we determine the antenna factor of AUC by making measurements of the electric field strength induced by an arbitrary transmitting antenna at the position of AUC using a receiving antenna whose antenna characteristics are identical to the theoretically estimated characteristics. Such an ideal antenna is called a calculable antenna or a standard antenna [7][8]. For conducting calibration by this method, we have to make measurements two times. Also, as a standard antenna, we usually use dipole antennas or standard gain horn antennas, because they have simple structures ensuring the easy determination of characteristics.

Third, we will explain a calibration method based on the assumption "the transmitting antenna is ideal." By the method, we determine the antenna factor of AUC by preparing an ideal transmitting antenna that radiates electric field strength as theoretically predicted, and measuring the electric field strength at the position where AUC is placed to receive the waves. The method is called "standard field method," because it uses a theoretically predicted electric field. The method, while having the advantage that it requires measurement just one time [9], is likely to produce errors when used in an unrealistic site for propagating waves, even if an ideal transmitting antenna is prepared—discrepancies in the field strength measured at the AUC position from the theoretical strength. Because the method requires that those two conditions are satisfied, we can't perform high accuracy calibrations by this method compared to others. We will summarize the discussions shown above in Table 1. NICT, with regard to the calibrations of half-wavelength resonant dipole antennas, have been employing the "standard antenna method"—assuming that the receiving antenna has ideal characteristics—among the three methods mentioned so far.

3.2 Standard antenna method

In the standard antenna method, the antenna factor of AUC is determined by comparing the strength measured by the standard antenna of the field radiated from an arbitrary transmitting antenna with that measured by AUC replacing the standard antenna [8].

In Figure 6, we show the simplified scheme of the

Table 1 Antenna calibration methods

Calibration method	Conditions	Features
Standard Site Method (Three-antenna method)	· Characteristic of the site is consistent with relevant theory.	· Calibration is conducted using three antennas whose antenna factors are unknown. · Antenna factors are determined using other physical quantities. · Measure three times.
Standard antenna method	· Characteristic of the receiving antenna is consistent with relevant theory.	· Electric field strength is measured using a standard antenna and an antenna under calibration is immersed in the field. · Measure twice.
Standard field method	· Characteristic of the transmitting antenna is consistent with relevant theory. · Characteristic of the site is consistent with relevant theory.	· An antenna under calibration is placed in an electric field obtained by a theoretical computation. · Characteristics of both the transmitting antenna and site must be consist with relevant theories. · Measure once.

standard antenna method; where a standard antenna with a known antenna factor is placed at a position sufficiently away from the transmitting antenna to treat the waves transmitted from the transmitting antenna as plane waves—the strength E of the field emitted from the transmitting antenna at the position of the standard antenna is determined by allying the antenna factor of the standard antenna F_a (STD) and the standard antenna receiving voltage V(STD) to Equation (1).

$$E = F_a(\mathrm{STD})\cdot V(\mathrm{STD}) \tag{6}$$

Then, a similar measurement is executed with AUC replacing the standard antenna; the antenna factor of AUC, F_a (AUC), is determined from Equation (7) obtained by putting Equation (6) into Equation (1).

$$F_a(\mathrm{AUC}) = F_a(\mathrm{STD})\cdot\frac{V(\mathrm{STD})}{V(\mathrm{AUC})} \tag{7}$$

Usually, we express an antenna factor in dB value; so, actually, addition or subtraction operations are used as shown in Equation (8).

$$F_a^{\mathrm{dB}}(\mathrm{AUC}) = F_a^{\mathrm{dB}}(\mathrm{STD}) + V^{\mathrm{dB}}(\mathrm{STD}) - V^{\mathrm{dB}}(\mathrm{AUC}) \tag{8}$$

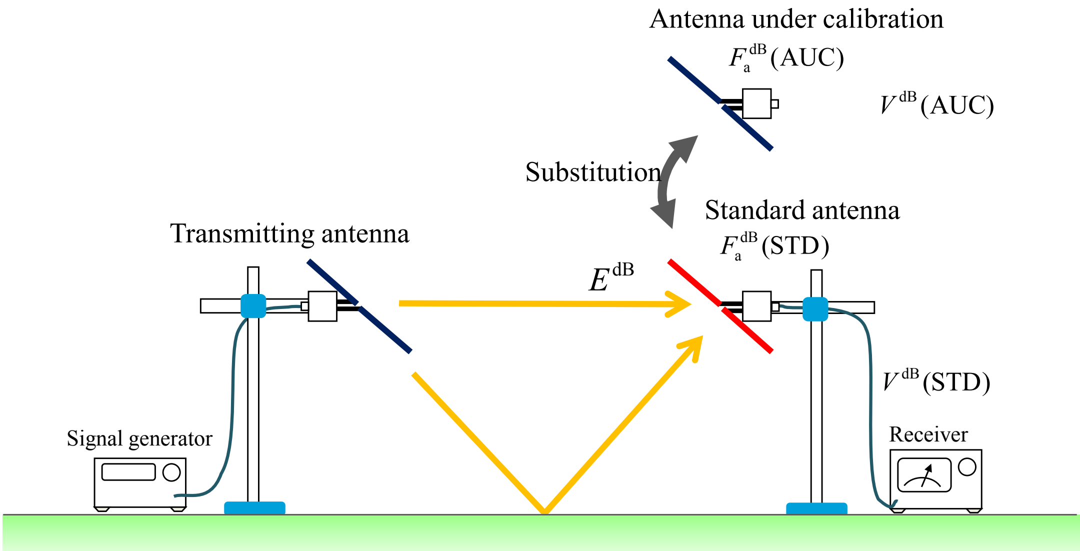
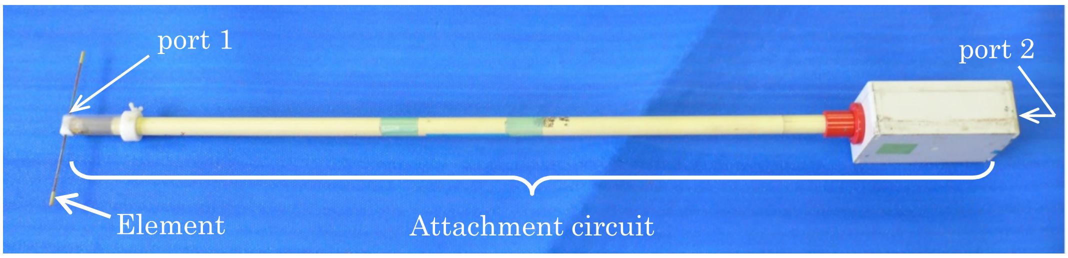
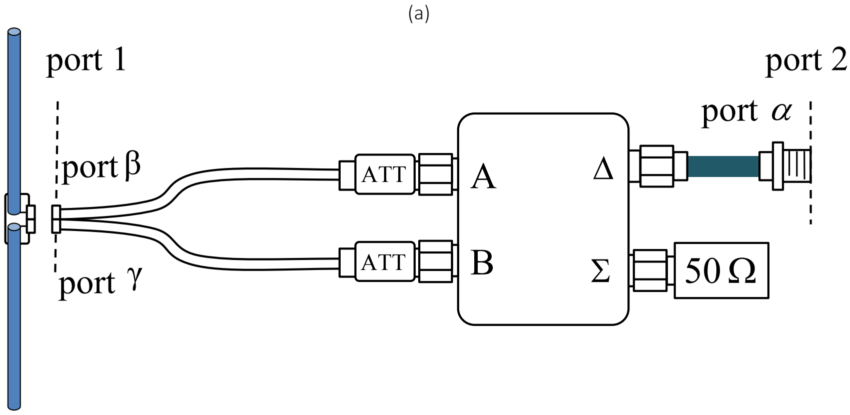


Fig. 6 Standard antenna method



(a)



(b)

Fig. 7 Standard antenna (Schaffner-Chase, Model 6500)

3.3 Standard antenna

We show the standard antenna that NICT employs in Fig. 7 (a), which is a commercially available half-wavelength resonant dipole antenna (Schaffner-Chase, Model 6500) [10]-[13]. The antenna consists of dipole element components that can resonate at 24 frequencies and an attachment circuit component, having a structure enabling the separation of the antenna into two components so that element exchange can be carried out according to the frequency—Fig. 7 (b) shows the inner structure. The attachment circuit consists of a 180 degree hybrid circuit, fixed attenuators, and a semi-rigid coaxial cable. The 180 degree hybrid circuit divides the input signal from Port Δ into two signals with an equivalent amplitude and opposite phases, outputting them from Port A and B; inversely, when two signals with an equivalent amplitude and mutually opposite phases are input from Port A and B, the circuit composes the two signals into a coordinate phase signal, outputting it from Port Δ. We configure the circuit to prepare Port β and γ to mount an antenna element through connecting fixed attenuators and coaxial cables with equivalent characteristics. Then, we can treat the whole attachment circuit, when calling Port Δ as Port α, as a 3 port circuit to express it using S-parameters. The NICT Standard Antenna uses a BMA connector to connect Port β, γ and an element. It can measure S-parameters by inserting a conversion adapter to SMA and using a vector network analyzer (hereinafter, referred to as “VNA”). Figure 8 shows the element supporter and the conversion adapter.

Furthermore, we will try to treat the whole attachment circuit as a 2-port circuit through applying the concept of Mixed-mode S-parameter which enables us to consider Port β and γ as a port that supports differential signals. The relation shown in Equation (9) is obtained by assigning a port made from Port β and γ to Port 1 and Port α to Port 2.

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} \dfrac{S_{\beta\beta}+S_{\gamma\gamma}-S_{\beta\gamma}-S_{\gamma\beta}}{2} & S_{\beta\alpha}-S_{\gamma\alpha} \\ \dfrac{S_{\alpha\beta}-S_{\alpha\gamma}}{2} & S_{\alpha\alpha} \end{bmatrix} \quad (9)$$

In Equation (9), Port 1’s characteristic impedance to differential signals is 100 Ω (Z'_0 = 100 Ω), and Port 2’s characteristic impedance is 50 Ω (Z_0 = 50 Ω). We can determine the antenna factor by putting dipole element’s input impedance Z_0 and its effective length l_e, which can be obtained by an electromagnetic numerical analysis simulator such as NEC2, into Equation (4) or (5). Note that, because in actual measurement situations, the antenna element for 30 and 35 MHz bends down due to the gravity force caused by its own weight, we estimate how deep the element bends when conducting such calculations.

We show, in Table 2, the instances of standard antenna factors at a height of 2 m above the ground plane determined by the procedures described above; there we show the determined antenna factors over the 24 frequencies for three years (2013 to 2015). The variation of determined antenna factors is in the range of less than 0.05 dB at any frequency; it indicates that the standard antennas are well kept in a stable condition.

4 Results of calibration

NICT has been conducting antenna factor determinations at a height of 2 m, F_a(2 m) for its half-wavelength resonant dipole antennas once per year, confirming calibration applicability.

The half-wavelength resonant dipole antennas used for AUC are: Anritsu, Model MP 652-B dipole antenna (30 to 250 MHz) or Schwarzbeck, Model UHAP (100 to 1,000MHz). The antenna used for transmission is a Schaffner-Chase, Model CBL6111 hybrid antenna with configuration implemented at an antenna separation distance of around 20 m (30 to 250 MHz) and around 10 m (300 to 1,000 MHz). In the case of measurements above the ground plane, the waves radiated from the transmitting antenna arrive at the receiving antenna in the following two ways: directly from the transmitting antenna to the receiving antenna, and reflected by the ground plane to the receiving antenna. Therefore, due to the interference of the two kinds of waves, the electric field strength at around the height of 2 m may decrease significantly at some frequencies. To solve this problem, we raise receiving voltage to its maximum level by changing the transmitting antenna height in the range of 1 to 4 m, making calibrations at those heights.

We show, in Fig. 9, the trends in the results of calibration made at frequencies 50, 100, 300, and 1,000 MHz for ten years from 2006 to 2015. Fig. 9 shows that the variation of antenna factors is within the range of − 0.02 to + 0.02 dB for any of the frequencies, indicating that NICT has provided good and stable calibrations.

5 Uncertainty evaluation

We evaluated the uncertainties of calibration in the cases where half-wavelength resonant dipole antennas are calibrated by the standard antenna method, showing below

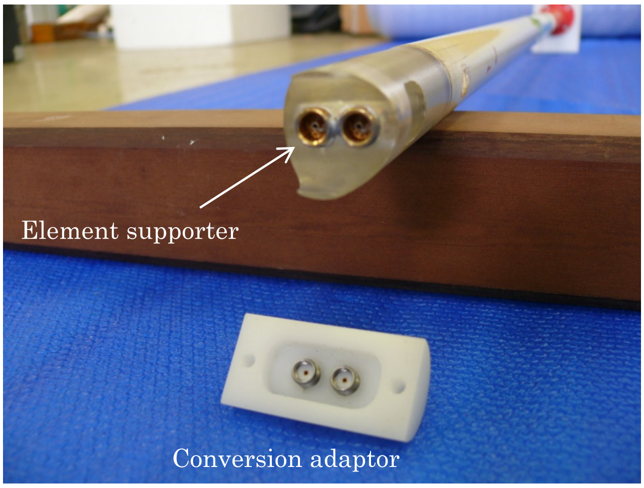


Fig. 8 Element supporter and conversion adaptor

Table 2 Age variation in antenna factor of the standard antenna
Antenna height is 2 m (h = 2 m)

Frequency MHz	Antenna Factor dB (1 / m)		
	2013	2014	2015
30	1.81	1.81	1.81
35	3.69	3.70	3.70
40	5.27	5.28	5.28
45	6.58	6.58	6.58
50	7.59	7.59	7.59
60	8.94	8.95	8.95
70	9.53	9.53	9.53
80	9.91	9.90	9.91
90	10.74	10.74	10.75
100	11.97	11.98	11.98
120	14.41	14.41	14.42
140	15.65	15.65	15.65
160	16.06	16.07	16.07
180	17.31	17.32	17.32
200	18.72	18.73	18.72
250	20.05	20.07	20.06
300	21.93	21.95	21.94
400	24.26	24.27	24.27
500	26.59	26.59	26.60
600	28.15	28.16	28.18
700	29.54	29.56	29.57
800	30.99	30.98	31.02
900	31.98	31.98	32.01
1,000	32.89	32.93	32.92

the evaluation results [14]. We determined the uncertainty using Equation (8); therefore, we can estimate the standard uncertainty in AUC calibration, $u(F_a^{dB}(\mathrm{AUC}))$, by combining the three factors as shown in Equation (10) [15],

$$u\left(F_a^{dB}(\mathrm{AUC})\right)=\sqrt{u\left(F_a^{dB}(\mathrm{STD})\right)^2+u\left(V^{dB}(\mathrm{STD})\right)^2+u\left(V^{dB}(\mathrm{AUC})\right)^2} \tag{10}$$

where the uncertainties are as shown in the following table.

$u(F_a^{dB}(\mathrm{STD}))$: Standard Uncertainty of Standard Antenna Factor

$u(V^{dB}(\mathrm{STD}))$: Standard Uncertainty of the Receiving Voltage Measured with Standard Antenna

$u(V^{dB}(\mathrm{AUC}))$: Standard Uncertainty of the Receiving Voltage Measured with AUC

Note that, because absolute values of all sensitivity coefficients for Equation (10) are "1," we did not use those factors in the equation.

We show combined results in Table 3 (a). We make evaluations on each of the uncertainty causes in the following sections; in Table 3 (b): showing the standard uncertainty of standard antenna factor; in Table 3 (c): showing the standard uncertainty of receiving voltage measured with AUC, along with that measured with the standard antenna. Ideally, we should show the individual evaluations at each of the frequencies; instead, we took, as the evaluation, the worst (largest) uncertainty we obtained for the 24 frequencies within the range of 30 to 1,000 MHz.

5.1 Uncertainty of standard antenna antenna factor

We determined the antenna factor of standard antenna, F_a (STD), using S-parameter measurements and calculations via the electromagnetic field numerical simulator, NED2; therefore, we took the following five items as the factors of the overall uncertainty of standard antenna antenna factors.

(1) Measurement uncertainty of attachment circuit S-parameter

We determined the uncertainty using the uncertainty information of the VNA (Agilent Technologies, Model E8362-B) that we used for the measurement; the information has been released by the manufacture [16]. Applying our measurement conditions, we obtained an S-parameter measurement uncertainty of less than 0.10 dB where the probability function is assumed to be a normal distribution with coverage factor k=3 (99.73 % level of confidence).

(2) Measurement uncertainty of antenna length

A length measurement of the antenna element is required as the input data for NEC2 calculations of the input impedance or the effective length of the element. The measurement uncertainty for an element length—we did the measurement with a measurement tape—is in the range

Fig. 9 Results of calibrations

(a) 50 MHz, (b) 100 MHz, (c) 300 MHz, (d) 1,000 MHz of − 3 to + 3 mm in the measurement case for 30 MHz and in the range of − 1 to + 1 mm for 1,000 MHz. The calculation results of antenna factor by NEC2 for various frequencies showed that the variation in antenna factor is within the range of – 0.02 to + 0.02 dB, on the assumption that variations will be distributed according to a rectangular probabilistic distribution.

(3) Uncertainty due to the gap at element power feeder

As shown in Fig. 7 (b), the standard antenna is structured so that its antenna element is power fed through the inner conductors of the two semi-rigid coaxial cables connected to Port 2 of the attachment circuit. As shown in Fig. 10, the antenna element feeder has a gap of around 9 mm because the feeder has BMA connectors for ensuring an easy mounting or replacement of elements. However the calculations by NEC2 of the theoretical antenna values—using the end-to-end length of element—are conducted on the assumption that the feeder has no gaps. Therefore, due to the feeder gap existing in the actual situation, NEC2 will produce an input impedance and an effective length that correspond to the values for a longer element by the length of the gap. Such an impact from the gap will become larger as the frequency of applied frequency goes higher.

Therefore, we added the case where the element is shorter by 9 mm, obtaining antenna factors for the two cases—actual length or shorter length—taking the difference of the two antenna factors as the uncertainty of feeder gap as the frequency goes higher and the difference becomes larger to reach its maximum of 0.2 dB at the range of 700 to 1,000 MHz, assuming that the probabilistic distribution is rectangular.

(4) Uncertainty due to common mode component

A dipole antenna is driven by a differential signal component (differential mode component), and a common mode component is unnecessary. The characteristics of the attachment circuit will significantly impact the rise of the common mode component. As for the NICT standard antennas, we make measurements of S-parameter, estimating its magnitude [14][17] in the following way.

We can obtain, using the S-parameter shown as Equation (9), the differential mode component S_{1D} and the common mode component S_{1C}, which are characteristic of the attachment circuit and respectively expresses as Equation (11) and (12),

$$S_{1D} = S_{21} = \frac{S_{\alpha\beta} - S_{\alpha\gamma}}{2} \qquad (11)$$

$$S_{1C} = S_{\alpha\beta} + S_{\alpha\gamma} \qquad (12)$$

where the ratio of S_{1C} to S1D, S_{1c}/S_{1D}, is calculated as approximately 0.01 for all the frequencies. It indicates that the rise of common mode is sufficiently small.

We estimated the impacts of common mode on the assumption that the S_{1C}/S_{1D} portion of the common mode current flows into the λ/4 monopole antenna and superimposes on the induced voltage due to the common mode. We calculated the antenna factor according to the assumption, obtaining the following result: the antenna factor variation is less than 0.07 dB for the S_{1c}/S_{1D} ratio of 0.01. Note that the probabilistic distribution is assumed to be rectangular.

(5) Uncertainty in numerical calculations

The numerical electromagnetic field simulator NEC2 executes numerical calculations based on the moment method, where an element is divided into a number of segments—each segment is shorter than the wavelength; it is known that the results depend on the number of such divisions. Among moment methods, while NEC2 employs

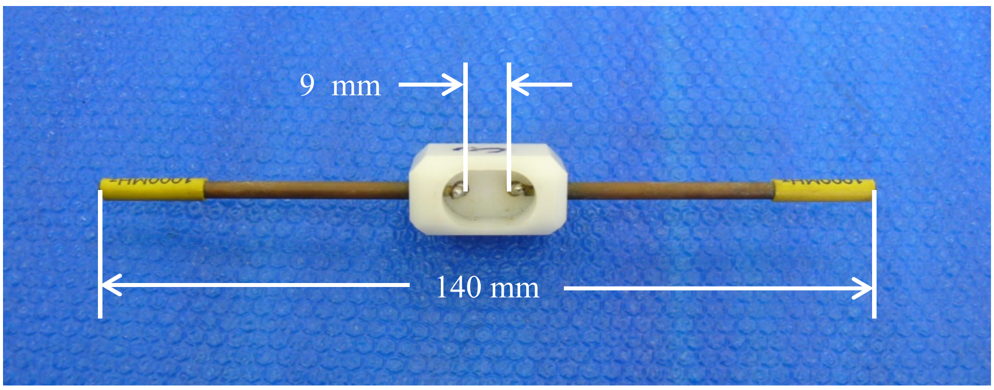


Fig. 10 Gap in element feeder
(1,000 MHz half-wavelength resonant element)

Table 3 Uncertainty budget

Half-wavelength resonant dipole antenna, 30 to 1,000 MHz, Antenna height of 2 m

(a) Uncertainty of AUC's antenna factor

Sources	Standard uncertainty	Sensitivity coefficient	Contribution	Remarks
(1) F_a(STD)	0.140 dB	1	0.140 dB	see Table 3(b)
(2) V(STD)	0.154 dB	-1	0.154 dB	see Table 3(c)
(3) V(AUC)	0.154 dB	1	0.154 dB	see Table 3(c)
Combined standard uncertainty			0.259 dB	
Expanded uncertainty (Approx. 95 % level of confidence)			0.52 dB	Coverage factor k = 2

(b) Uncertainty of standard antenna

Sources	Value dB	Distribution	Divisor	Standard uncertainty	Sensitivity coefficient	Contribution dB
(1) S-parameter of attachment circuit	0.10	Normal (k = 3)	3	0.033	1	0.033
(2) Element length	0.02	Rectangle	$\sqrt{3}$	0.012	1	0.012
(3) Gap in element feeder	0.20	Rectangle	$\sqrt{3}$	0.116	1	0.116
(4) Common mode component	0.07	Rectangle	$\sqrt{3}$	0.041	1	0.041
(5) Numerical simulation	0.10	Rectangle	$\sqrt{3}$	0.058	1	0.058
Combined standard uncertainty						0.140

(c) Uncertainty in receiving voltage

Source	Value dB	Distribution	Divisor	Standard uncertainty	Sensitivity coefficient	Contribution dB
(1) Antenna height	0.05	Rectangle	$\sqrt{3}$	0.029	1	0.029
(2) Antenna distance	0.02	Rectangle	$\sqrt{3}$	0.012	1	0.012
(3) Antenna direction	0.05	Rectangle	$\sqrt{3}$	0.029	1	0.029
(4) Unwanted coupling	0.10	Rectangle	$\sqrt{3}$	0.058	1	0.058
(5) Directivity	–	–	–	–	1	0.000
(6) Resolution of digital Indication	0.005	Rectangle	$\sqrt{3}$	0.003	1	0.003
(7) Linearity of receiver	0.05	Rectangle	$\sqrt{3}$	0.029	1	0.029
(8) Signal-to-noise ratio	0.15	Rectangle	$\sqrt{3}$	0.081	1	0.081
(9) Mismatch	0.05	U-shape	$\sqrt{2}$	0.029	1	0.033
(10) Repeatability	0.10	Normal	$\sqrt{1}$	0.100	1	0.100
Combined standard uncertainty						0.154

a technique called the "point matching method," a technique called the "Galerkin method" is often used. It is well-known that different methods often lead to different results. We confirmed, through repeating calculations for different methods or different numbers of segments, that the uncertainty is less than 0.1 dB, where the probabilistic distribution is assumed to be rectangular.

We estimated the standard dipole antenna's antenna factor uncertainty as 0.14 dB by convolving the uncertainties so far mentioned, as shown in Table 3 (b).

5.2 Uncertainty in reception voltage measurement

We considered the ten factors below in relation to uncertainty in the measurements when measuring, with a standard dipole antenna, the strength of the electric field induced by the emission from the transmitter, estimating the uncertainty magnitude for each of the factors.

(1) Uncertainty of antenna height

The uncertainty of the antenna height is in the range of − 1 to + 1 cm for the height of 2 meters, which is the normal height at which the antenna is set. As we stated in Section **4**, in an actual measurement situation, we conducted measurements with a different transmitting antenna height for a different frequency so we could measure with the maximum receiving voltage for the frequency. In a physical configuration where the receiving voltage is maximum—the direct waves to the receiving antenna and the reflected waves are cooperatively added—the electric field strength has smaller height dependency in the vertical direction. As a consequence, the electric field strength will vary just within the range of − 0.05 to + 0.05 dB for all frequencies for the height variation of − 1 to + 1 cm; such variation of the receiving voltage will lead to the variation of AUC antenna factor—the final target of our analysis—of the range of − 0.05 to + 0.05 dB. Note that the probabilistic distribution is assumed to be rectangular.

(2) Uncertainty in antenna separation distance

We conducted our measurements by setting a standard antenna or AUC separated at a distance of 20 or 10 m; where we can assume that the uncertainty in the setting is within the range of − 1 to + 1 cm. As a consequence, we can make such an estimation that, for the variation of antenna positions of − 1 to + 1 cm, the electric field strength varies within the range of − 0.02 to + 0.02 dB for all frequencies, and the AUC antenna factor varies within the range of − 0.02 to + 0.02 dB. Note that the probabilistic distribution is assumed to be rectangular.

(3) Uncertainty in antenna direction

For making accurate measurements, we have to set the transmitting antenna and the receiving antenna so that they exactly face to one another. However, in an actual measurement situation, a direction error in the range of − 2 to + 2 degrees can occur. We predicted, from NEC2 simulations, that the error can lead to an AUC antenna factor uncertainty of less than 0.05 dB. Note that the probabilistic distribution is assumed to be rectangular.

(4) Uncertainty due to unwanted coupling occurring between the transmission and receiving antennas

In order to prevent unwanted coupling, we have to set the standard antenna or AUC sufficiently— compared to the wavelength—away from the transmitting antenna. While we are conducting our measurements by setting the separation distance at 20 meters for the frequency of 30 MHz, the wavelength corresponding to the frequency of 30 MHz is 10 meters; so, the two antennas are just two wavelength's distance away from each other. We obtained, by NEC2 simulations, a result such that the impact of unwanted coupling in like cases will be less than 0.01 dB. Note that the probabilistic distribution is assumed to be rectangular.

(5) Uncertainty due to the difference in directional characteristics

In the standard antenna method, in the case where a standard antenna and AUC have mutually different mechanical structures—having different directional characteristics—such difference in directional characteristics can introduce some uncertainty to the calibration results. In Section **4**, because AUC is a half-wavelength resonant dipole antenna—no difference exists in directional characteristics—we were able to assume that the uncertainty would be 0 dB. However, when making calibrations of an antenna with directional characteristics, compared to doing such for a standard antenna, we have to consider as a factor of uncertainty the differences in the situations of the reflections from surrounding objects or the ground plane from those of the calibration configuration in Section **4**.

(6) Uncertainty in indicator resolution of measurement equipment

We use, for calibrations, a VNA (Agilent Technologies, Model 8357-A), of which the digital indicator has a measurement resolution of 0.01 dB; therefore, we estimated the uncertainty due to indicator resolution as − 0.005 to + 0.005dB. Note that the probabilistic distribution is assumed to be rectangular.

(7) Uncertainty in measurement equipment linearity

We made measurements of the linearity of the VNA we used, with an RF attenuator traceable back to the National Standards, confirming that the differences in values obtained for the various frequencies for the value shown on the display of the VNA are less than 0.05 dB for all frequencies. Therefore, we used the value 0.05 dB as the estimation of the uncertainty on the assumption its probabilistic distribution is rectangular. Note that variations in the output level of a signal generator are not able to impact calculation results because we know—by measuring using VNA—the exact value of the level at the time of calibration.

(8) Uncertainty due to measurement equipment's S / N ratio

We made our estimation using our measurements for the frequency 1,000 MHz because the reception level hits its lowest at that frequency. S / N (signal to noise) ratio still remains over at 35 dB even at 1,000 MHz. There, the standard uncertainty is less than 0.15 dB. Note that its probabilistic distribution is assumed to be normal.

(9) Uncertainty due to mismatching

We can estimate the impact of mismatching by applying to Equation (13) the reflection coefficient Γ_a of a standard antenna or AUC, and Γ_L, which is the actually measured reflection coefficient from the end of the cable connected to the antenna toward the receiver. Note that, for the sign in Equation (13), we use the one at which the equation produces the largest value.

$$u(M) = 20\log_{10}\left(1 \pm |\Gamma_a||\Gamma_L|\right) \quad \text{[dB]} \tag{13}$$

The actual uncertainty is less than 0.05 dB, independent of frequency, because, for reducing multiple reflections, fixed attenuators of 6 dB are inserted at the cable ends. Note that we assumed the U-shaped probabilistic distribution. Mismatching can occur between the signal generator and the transmitting antenna. However, because in the standard antenna method measurements are executed twice, the impacts by mismatching are cancelled during the two measurement times; therefore, the uncertainty of the AUC antenna factor is not affected.

(10)Repeatability of measurements

We estimated the uncertainty of measurement repeatability as 0.10 dB (0.10 / $\sqrt{1}$) because the experimental standard uncertainty we have experienced and documented so far is 0.10 dB [15]. Note that we assumed that its probabilistic distribution is normal.

In our actual calibration operations, we take measurements twice; and confirm that the difference between the two measurements is in the range of − 0.15 to + 0.15. Our calibration procedure requires the following: in the case where the difference goes beyond the range, we must investigate the cause and then repeat the measurement.

By combilning the uncertainty sources described above, we can obtain the uncertainty in a reception voltage measurement as shown in Table 3 (c). Therefore we estimated its uncertainty as 0.199 dB.

5.3 Uncertainty budget

We show, in Table 3 (a), the composite uncertainty obtained by combining the uncertainty sources, where we made calculations by using the coverage factor (k = 2) so that the level of confidence is approximately 95 %, and we obtained a result of 0.63 dB.

Table 3 (a) to (c) suggest the following: with regard to the antenna factor uncertainty, the gap in the element feeder produces the most significant impact. To solve this problem the element feeder should be improved in its physical structure so that the gap width becomes narrower as the frequency goes higher. On the other hand, with regard to the uncertainty of the receiving voltage measurement, as the uncertainty of S/N ratio shown in Item (8), and the repeatability shown in Item (10) significantly impact the improvement of S/N ratio and repeatability, we have to make measurements at a narrower transmitting and receiving antennas separation distance. However, because as shown in Item (4) the shorter distance from the transmitter leads to the occurrence of unwanted coupling, we have to choose, according to the applied frequency, an appropriate separation distance between the transmitting antenna and the receiving antenna taking care to avoid unwanted coupling.

6 Conclusions

We described the methods for calibrating, by the standardantenna method, half-wavelength resonant dipole antennas used for the frequency range of 30 to 1,000 MHz.

At the same time, we introduced our estimations of the uncertainties accompanying calibrations. The results of our calibration of dipole antennas distribute within the range of − 0.2 to + 0.2 dB, showing a good coincidence with the uncertainty we estimated. It suggests that we have conducted calibrations so far with good stability. Furthermore, we estimated the expanded certainty (k=2) in dipole antenna calibrations by standard antenna method as 0.65 dB

In the current situation where radio communication using 30 to 1,000 MHz is widely used, the demand for the calibration of EMI measurement antennas used in this frequency range has been growing. Therefore, we are preparing a plan to study calibrations applying large anechoic chambers.

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Iwao NISHIYAMA

Electromagnetic Compatibillity Laboratory, Applied Electromagnetic Research Institute
Calibration of Measuring Instruments and Antennas for Radio Equipment

Kojiro SAKAI

Technical Expert, Electromagnetic Compatibility Laboratory, Applied Electromagnetic Research Institute
Calibration of Measuring Instruments and Antennas for Radio Equipment

Tsutomu SUGIYAMA

Senior Researcher, Electromagnetic Compatibillity Laboratory, Applied Electromagnetic Research Institute
Calibration of Measuring Instruments and Antennas for Radio Equipment

Kouichi SEBATA

Senior Researcher, Electromagnetic Compatibillity Laboratory, Applied Electromagnetic Research Institute
Calibration of Measuring Instruments and Antennas for Radio Equipment, geodesy

Katsumi FUJII, Dr. Eng.

Research Manager, Electromagnetic Compatibility Laboratory, Applied Electromagnetic Research Institute
Calibration of Measuring Instruments and Antennas for Radio Equipment, Electromagnetic Compatibility