3 Development of EMC Measurement and Calibration Methods

3-1 Uncertainty Estimation of Loop Antenna Calibration System in MF/HF Band

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The MF/HF band loop antenna calibration is performed by the standard magnetic field method in NICT. For the establishment of the standard magnetic field intensity, there are two method: LC (Loop Current) method and AF (Antenna Factor) method. In the LC method, the current on the loop antenna have to be controlled very accurately to generate the standard field. While the AF method hasn't been in officially used for actual calibration service in NICT, it has an advantage that the real loop current is not needed, which is very difficult to monitor in the actual calibration and is a major factor to increase the calibration uncertainty. AF method, however, the antenna factors have to be determined precisely, which can be done by the three antenna method.

The purpose of this paper is to investigate and compare the AF method and the LC method from the viewpoint of the loop antenna calibration accuracy, and to show the feasibility of the AF method for the actual use for the calibration service in NICT.

Keywords
MF/HF band, Loop antenna, Antenna factor, Antenna calibration, Uncertainty

1 Introduction

Recent years have seen dramatic improvement in equipment performance and measurement technology. In view of this trend, research is underway at NICT to establish greater accuracy in antenna calibration, including an examination of accuracy in loop antenna calibration. Traditionally, MF/HF-band loop antenna calibration has been performed under the standard magnetic field method, using a loop antenna to generate a standard magnetic field. In this case there are two means of establishing standard magnetic field intensity: via the loop current (LC) method, in which the current in the loop antenna is controlled, and the antenna factor (AF) method, which requires the determination of antenna factors in advance. NICT employs the LC method, for which calibration accuracy is estimated at between 0.5 and 1.0 dB. Under the LC method, the accuracy of the magnetic field intensity setting is determined principally by the accuracy of loop antenna current measurement.

The aim of this paper is to investigate the uncertainty inherent in calibration conducted using the conventional LC method for the commonly used bandwidth of 1 MHz to 30 MHz. Furthermore, in order to verify the practicability of the LC method, we also applied the AF method—which employs a markedly different principle from that of the LC method—to establish magnetic field intensity.

In section **2** of this paper, we outline the loop antenna calibration methods used for verification, including the AF method. In section **3**, we discuss the factors likely to lead to uncertainty expected in loop antenna calibration when applying the LC method. In section **4**, we describe uncertainty in the establishment of standard magnetic field strength.

2 Loop antenna calibration method

Two main methods are used for the calibration of loop antennas with bandwidths of 30 MHz and lower: (1) the standard antenna method and (2) the standard magnetic field method. The standard antenna method is also called the "reference" method, in which the subject loop antenna is calibrated using a standard loop antenna on the receiving side for comparison. This method requires theoretical calculation of the relationship between magnetic field strength and induced voltage. In comparison, the standard magnetic field method uses a standard loop antenna on the transmitting side, and the current in the transmitting loop antenna is controlled to set the strength of the magnetic field. NICT has employed the standard magnetic field method, in which the loop current is controlled.

2.1 Calculation of near-field magnetic field strength

Theoretical values are used for many purposes, such as for determining magnetic field strength and propagation loss between the loops. The near-field magnetic field strength, H_{av}, which is used as the basis of theoretical calculations, is computed using the following equation, as described in the cited reference document[1].

$$|H_{av}| \doteqdot I \; S_1 \; K(d) \quad [A/m] \tag{1}$$

Where
I : Loop current of transmitting antenna
S_1 : Loop area of transmitting antenna

$K(d)$ represents the propagation loss between the loop antennas. Although this variable is expressed as an infinite series in the reference document[1], the following approximation equation is used in most cases.

$$K(d) \doteqdot \frac{1}{2\pi \; R_0^{\,3}}\left[1 + \frac{15}{8}\left(\frac{r_1 \, r_2}{R_0^{\,2}}\right)^2 + \frac{315}{64}\left(\frac{r_1 \, r_2}{R_0^{\,2}}\right)^4\right] \times \left(1 + \beta^2 R_0^{\,2}\right)^{1/2} \tag{2}$$

Where
$R_0 = (d^2 + r_1^2 + r_2^2)^{1/2}$
d: Distance between antennas
r_1, r_2: Loop radiuses of transmitting and receiving antennas
β : $2\pi/\lambda$

2.2 Establishment of standard magnetic field intensity

Under the standard magnetic field method, a standard loop antenna is used to generate a reference magnetic field. The reference magnetic field is determined using the LC method and the AF method.

2.2.1 Loop current (LC) method

The LC method allows the calculation of magnetic field strength based on the loop current and the loop area, which are relatively easy-to-obtain parameters, as shown in equation (1). This method offers a particular advantage: if the loop current source is traceable, traceability is also ensured in the strength of the established magnetic field. As a result, NICT has adopted the LC method[2][3] for the establishment of standard magnetic field intensity.

If the loop antenna under calibration is a transmitting antenna, calibration is conducted by comparing the magnetic field intensities of the subject loop antenna and the standard loop antenna via an intermediary loop antenna. If the loop antenna under calibration is a receiving antenna, the output (monitored voltage or current) of the receiving loop is reevaluated based on the magnetic field strength set for the standard loop antenna.

Figure 1 shows the measurement system used for the calibration of a transmitting loop antenna. The calibration procedure set forth in the diagram is as follows:

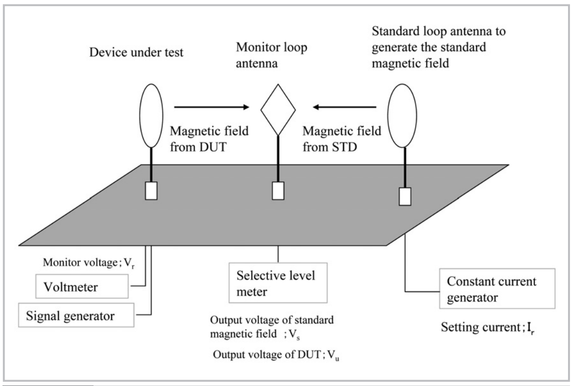

Fig. 1 Loop antenna calibration using standard magnetic field method (LC method) (For calibration of transmitting loop antenna)

(1) The standard loop antenna and the loop antenna under calibration are placed parallel to each other and symmetrically in relation to the intermediary loop antenna.

(2) A reference current is supplied to the standard loop antenna and the output voltage V_s of the intermediary loop antenna is measured.

(3) The circuit is switched to the loop antenna under calibration, a current is set that is equivalent to the reference current for the standard loop antenna, and output voltage V_u of the intermediary loop antenna is measured.

(4) Using the reference current for the standard loop antenna, the standard magnetic field strength H_s is calculated in accordance with equation (1).

(5) The magnetic field strength calibration factor ΔV is calculated for the loop antenna under calibration using the following equation.

$$\left.\begin{array}{l} V_s = H_s + M_a \quad \text{(dB)} \\ \quad \text{(measurement described in item (2))} \\ V_u = H_u + M_a \quad \text{(dB)} \\ \quad \text{(measurement described in item (3))} \\ \Delta V = V_s - V_u = H_s - H_u \quad \text{(dB)} \end{array}\right\} \quad (3)$$

Here, M_a is the conversion factor for the magnetic field strength and output voltage of the intermediary loop antenna, and H_u is the magnetic field strength resulting from the supply of the reference current to the loop antenna under calibration.

2.2.2 Antenna factor (AF) method

In the AF method, an electric current is not used for setting the magnetic field intensity, instead loop antenna input power featuring a proportionality relation is used[4][6]. Therefore, the antenna factor, L_{af}, which determines the input/output relation of the loop antenna, is defined by equation (4) below.

$$L_{af} = S_1 I / 2\sqrt{P_i} \quad [m^2/\Omega] \qquad (4)$$

Here, S_1 is the loop area, I is the loop current, and P_i is the loop input power. For example, if the antenna factor L_{af} of the standard loop antenna can be determined by the three-antenna method or a similar technique, the magnetic field strength H_{av} can be calculated using equation (5) below.

$$|H_{av}| = 2 L_{af} K(d) \sqrt{P_i} \quad [A/m] \qquad (5)$$

2.2.3 Features of LC method

The upper-limit frequency for a constant-current source is presently 10 kHz. Therefore, if the frequency is too high and prevents direct setting of the loop current, the voltage monitored by a thermocouple built into the loop is used as an intermediary. In other words, a constant-current source is used in advance to obtain the relationship between the input current and monitored voltage at 10 kHz, and a current value is determined thereafter by performing current conversion for high-frequency input based on the indicated monitored voltage. This operation is based on the principle that thermocouples theoretically do not feature frequency characteristics. Figure 2 shows an example of a thermocouple-embedded general-purpose loop antenna setup.

Figure 3 shows the relationship between the loop antenna input current setting and the voltage monitored by the thermocouple circuit at 10 kHz. We confirmed that the relationship indicated in Fig. 3 remained unchanged even with DC power and at 60 Hz, and that no frequency characteristics were displayed at frequencies below 10 kHz.

For the LC method, however, a number of topics remain to be addressed, such as (1) frequency characteristics of the current-detection circuit at frequencies above 10 kHz, (2) temperature characteristics of the current-detection circuit, (3) loop current conversion from the loop antenna circuit current, and (4) traceability at frequencies over 10 kHz. Process (3), loop current conversion from the loop antenna circuit current, is required when impedance is inserted in parallel to the loop.

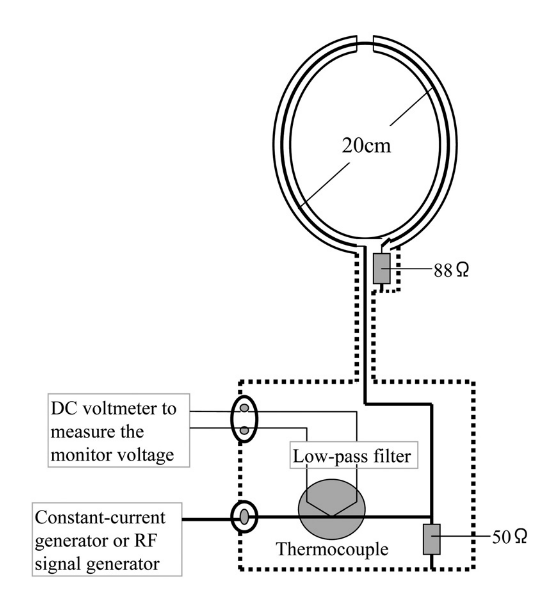

Fig.2 Example of general-purpose loop antenna setup

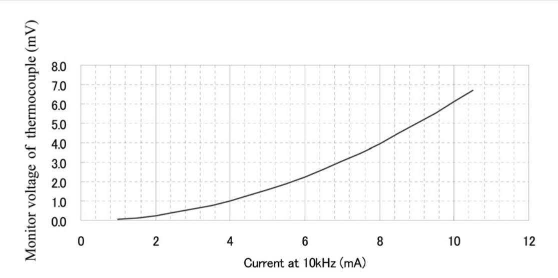

Fig.3 Relationship between loop antenna input current and monitored voltage

3 Factors attributable to anticipated uncertainty in loop antenna calibration

3.1 Magnetic field strength computational error

3.1.1 Theoretical value computational error

If the prerequisites for a valid theoretical equation are ignored in the calculations, a discrepancy will arise between measured and calculated values due to the failure to comply with these prerequisites. In the following, this error is referred to as “theoretical computational error”.

Equation (1), used for the calculation of near-field magnetic field strength, assumes an extremely small loop, that the loop wire diameter is significantly smaller than the loop diameter, and that the loop current is consistent. Further, in the equation actually used, higher-order calculations are omitted. These factors are expected to produce theoretical value computational error when equation (1) is used.

In this paper, the moment method is used to examine possible errors (see reference document[5]). Figure 4 shows the results when calculating transmitting loop current distribution characteristics at a frequency of 30 MHz, with a loop radius of 0.1 m and a wire radius of 2.5 mm. The horizontal axis of the graph indicates the segment numbers for 100 equally divided parts of the loop, while the vertical axis shows dB values normalized with the maximum current in the segments. For the simulation, loops of the same type were established for transmission and reception at intervals of 1 m and at a height of 1.5 m above the perfect conductor; a voltage of 1 V was applied to segment 1 of the transmitting loop and a load of 50 Ω was applied to segment 1 of the receiving loop.

In the graph, maximum non-uniformity of approximately 0.2 dB was generated in the current distribution characteristic. Similar simulations were also conducted by varying the distance between the loops in the range of

0.2 m to 1.0 m while maintaining a height relative to the perfect conductor of 1.5 m, but no significant change was observed in the distribution characteristic resulting from the variation in distance. We also confirmed that the distribution characteristic flattened at lower frequencies.

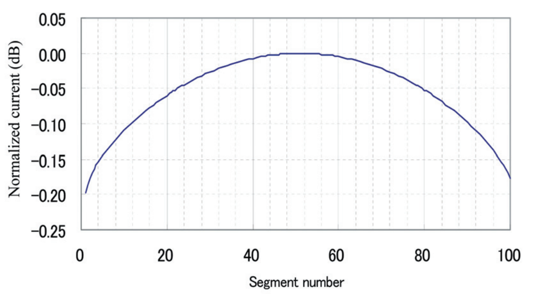

Fig.4 *Transmitting loop current distribution characteristic based on moment method*

Based on the above results, we conducted a verification experiment for equation (1) as follows:

(1) The average value of the transmitting loop current distribution in Fig. 4 was used as the current value in equation (1).

(2) Although equation (1) yields magnetic field strength H_{av}, this value was obtained based on the receiving current calculated using the moment method and arrangement of the transmitting loop antenna and receiving loop antenna.

(3) The difference between the magnetic field strength calculated based on the moment method and the magnetic field strength calculated in (1) was examined.

Comparison of the magnetic field strength values obtained in the above procedures indicated that the value obtained based on the moment method was slightly smaller, with this difference equivalent to approximately 0.27 dB. Although it would be inappropriate to assume that the moment method always provides the correct results, since simulation settings of 30 MHz, a position of 1.5 m above the perfect conductor, and a distance of 1.0 m between the loops were practical, we used the results of this method as a guide and estimated the error of equation (1) to be within ±0.27 dB.

3.1.2 Equipment setting error

When calculating propagation loss based on equation (1), the distance between the loop antennas and the loop radiuses are used. However, if the values used in the calculation differ from the actual settings, a discrepancy will arise between the measured and calculated values. We examined this difference separately from the error mentioned above resulting from the use of the theoretical equation.

For example, calculations using the theoretical equation are premised on the condition that the opposing loops are parallel to each other and symmetrically positioned. Here, external interference or noise is not taken into consideration. We therefore estimated the extent of deviation in equipment settings based on actual measurements. When the distance setting error is considered to be ±5 mm per 1 m, the magnetic field strength error is estimated as ±0.12 dB. This value is based on the calculation of distance R_0^3 in equation (2). In terms of face-to-face alignment error, for a positional shift of ±10 mm in the vertical direction and deviation in parallelism of ±5 degrees, error of approximately 0.05 dB is anticipated for each of these quantities. Figure 5 shows actual measurements relating to the accuracy of face-to-face alignment. For this measurement, 20 cm-diameter loop antennas of equal specifications were set up 1 m apart. Figure 5 indicates the difference in the transmission levels between accurate positioning and positioning with a slight deviation in face-to-face alignment. Although the graph shows a certain difference between the measurements, we suspect that this was caused by the use of the precisely aligned setup to obtain an absolute reference value; as a result, we anticipate no noticeable difference between any two given values in practice.

If there is interference or noise near the established magnetic field, an error of approximately 0.27 dB is estimated when the SN ratio is 30 dB.

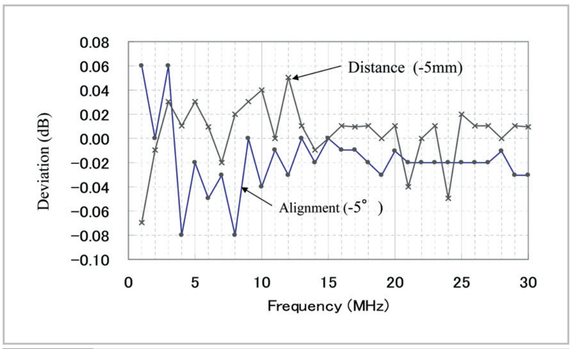

Fig.5 *Effect of loop antenna face-to-face alignment accuracy on propagation characteristic*

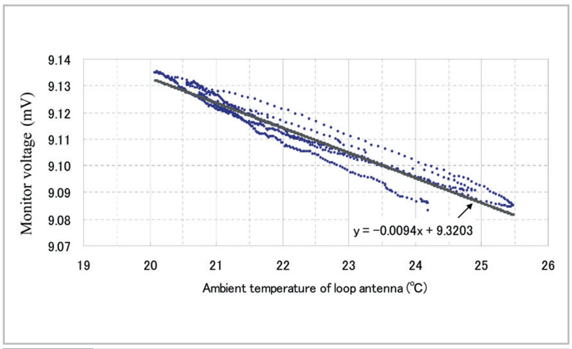

Fig.6 *Temperature characteristic of monitored voltage (general-purpose loop antenna)*

3.2 Loop current measurement error

3.2.1 In the case of LC method

(1) Temperature characteristic of current-detection circuit

Figure 6 shows the temperature characteristic of monitored voltage in a general-purpose loop antenna. The graph's horizontal axis indicates the ambient temperature near the loop antenna, and the vertical axis shows the monitored voltage. The indicated values are averages of continuous 1-minute measurements. In view of practical implementation, signals of 10 MHz and +5 dBm were input to the loop antenna for approximately 1 minute in 5-minute intervals, and the ambient temperature and monitored voltage were measured. The entire measuring system (excluding the loop antennas) was installed in a temperature-controlled room. According to the measurement results shown in Fig. 6, the monitored voltage fluctuated by approximately 0.1% per 1˚C change in temperature. Similar results were obtained when the loop antenna was placed in temperature/humidity test equipment and the temperature was varied. Since current conversion based on monitored voltage uses an error value of 0.1% for each 1˚C difference from the temperature at which the relationship between the input current and monitored voltage was measured, a deviation of approximately 0.01 dB per 1˚C relative to the actual loop current would be generated.

(2) Frequency characteristic of current detection circuit

Figure 7 shows the frequency characteristic of NICT's standard loop antenna. For the LC method, the graph shows the current conversion values obtained using monitored voltage as a reference. With respect to the AF method, on the other hand, the graph indicates the values calculated using antenna factors and input power in equation (4). According to the graph, the LC method yields slightly larger values and generates an error of approximately 0.28 dB at 1 MHz. Although these results reflect both the temperature characteristic and the effect of parallel impedance (as described below), in terms of the frequency characteristic these methods reveal very similar tendencies. Based on these results, we concluded that for the standard loop antenna the frequency characteristic can be ignored with a current setting that uses the monitored voltage as an intermediary.

(3) Effect of parallel impedance

In the general-purpose loop antenna used to obtain the results shown in Fig. 2, a resistance of 50 Ω was inserted in parallel to the loop as viewed from the input side. This resis-

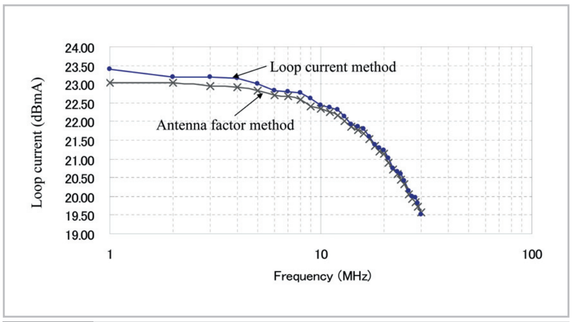

Fig.7 *Frequency characteristic of loop current (standard loop antenna)*

tance is designed to produce an input impedance of 50 Ω, but it in effect this component generates a difference between the loop current and the current passing through the thermocouple. Although this parallel impedance is not inserted in the standard loop antenna, a certain amount of current variation is generated as compared to the AF method, as shown in Fig. 7. Using this current difference as a guideline, we estimated a current conversion error of 0.28 dB for purposes of this paper, with due consideration to the frequency characteristic described above and the effect of parallel impedance.

A few issues remain to be addressed concerning parallel impedance in general-purpose loop antennas. Figure 8 indicates the frequency characteristic of the general-purpose loop antenna shown in Fig. 2, and shows a comparison of the LC method and the AF method. Figure 8 illustrates two different means of current conversion within the LC method: (1) the shunt ratio of the load resistance and parallel resistance is applied to the current passing through the thermocouple, as indicated in the antenna's instruction manual, and (2) the loop inductance is taken into consideration in the calculation of load resistance. Inductance was calculated based on a loop radius of 10 cm and a wire radius of 0.25 cm and otherwise in accordance with the equation in the reference document[3]. Figure 8 shows a maximum difference of approximately 2.0 dB between the LC method and the AF method. The loop current was converted incorrectly under both methods. However, when inductance is taken into consideration, the frequency characteristic obtained with the LC method was similar to that obtained with the AF method. Accordingly, we expect that a careful selection of the indicated parallel resistance value could improve this characteristic. These results attest to the difficulty of loop current conversion for general-purpose loop antennas.

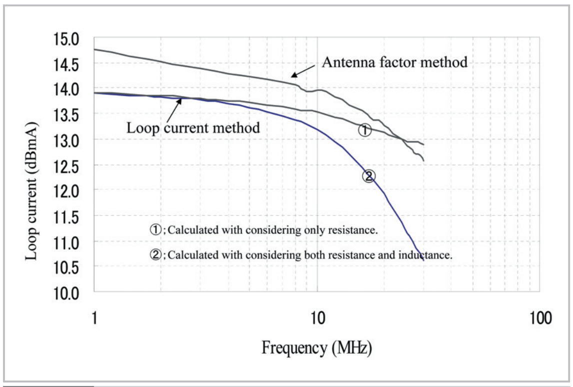

Fig.8 Frequency characteristic of loop current (general-purpose loop antenna)

4 Examination of accuracy in establishing magnetic field

4.1 Calculation of uncertainty

The degree of inaccuracy of measurement results can be expressed as "uncertainty"[7]. Uncertainty can be expressed using two methods. The first, Type A, indicates the uncertainty caused by random effects. In the other, Type B, uncertainty is determined based on factors such as manufacturing specifications. To determine general uncertainty based on both Type A and Type B, standard uncertainty $u(x_i)$ is determined based on the distribution profile for each error item, and then the resultant values are combined using the RSS (root-sum-square) method, taking the sensitivity factor into consideration. Combined standard uncertainty, $u_c(y)$, is generally expressed by the following equation.

$$u_c(y) = \left\{ \sum_{i=1}^{n} \left[c_i \, u(x_i) \right]^2 \right\}^{\frac{1}{2}} \tag{6}$$

Where y is the formula for measurement expressed by, $y = f(x_1, x_2, x_3, \ldots)$ and "$x_1, x_2, x_3, \ldots$" are estimated measured values for measurement items 1, 2, 3, and so forth. Note that c_i is the sensitivity factor and is expressed by $c_i = \delta f / \delta x_i$.

4.2 Uncertainty of LC method

In section **3**, we described the items of uncertainty anticipated with the LC method and the estimated associated error values.

Based on these results, the uncertainty items used for setting a magnetic field under the LC method and under the AF method and the specific values for these uncertainty items were determined as shown in Table 1. The uncertainty items were classified by relevance into an electric power measurement group, a loop current measurement group, and a propagation calculation group. Since thermocouple electromotive force is used to detect current under the LC method, there is no uncertainty item relating to electric power mismatch.

The standard uncertainty value of the loop current measurement group u_I is 0.18 dB, as indicated in equation (7) below. Similarly, the standard uncertainty value of the propagation calculation group uk is 0.24 dB.

$$u_I=[(0.28^2+2\times0.10^2+0.05^2+0.02^2)/3]^{1/2} \fallingdotseq 0.18\ [\mathrm{dB}] \tag{7}$$

Therefore, the combined standard uncertainty value for magnetic field strength with the LC method, u_{tl}, can be obtained using equation (8) when the error in the loop surface area S_l is ignored in the dB indication of equation (1). The calculated uncertainty is therefore 0.30 dB.

$$u_{tl}(H_{av})=\left\{(\frac{\delta H_{av}}{\delta I}\times 0.18)^2+(\frac{\delta H_{av}}{\delta K(d)}\times 0.24)^2\right\}^{\frac{1}{2}} =\left\{0.18^2+0.24^2\right\}^{\frac{1}{2}}=0.30[dB] \tag{8}$$

The expanded uncertainty of the LC method is ±0.60 dB based on the coverage factor, $k = 2$, which is equivalent to a reliability coefficient of 95%.

Figure 9 shows the results of comparison of the magnetic field strengths set using the LC method and the AF method under the same conditions and in accordance with the specified calibration procedure. With the LC method, a standard loop antenna was used to establish a specified magnetic field strength, while under the AF method a general-purpose loop antenna was used for this purpose. An intermediary loop antenna was used to measure the magnetic field strength with each of these methods to obtain the difference value. Figure 9 indicates the difference between the two based on the magnetic field strength of the LC method as a reference. The difference between the two methods was approximately

Table 1 *Uncertainty of magnetic field setting using the LC method and AF method*

Uncertainty factor	Uncertainty (±dB)		
	LC method	AF method	Distribution profile
Uncertainty of electric power measurement			
(1) Stability of signal generator output level	–	0.05 (actual measurement)	Rectangular
(2) Stability of level indicator indication	–	0.02 (actual measurement)	Rectangular
(3) Level calibration accuracy	–	0.10 (spec.)	Rectangular
(4) Impedance mismatch	–	0.10 (calculation)	U-shaped
Uncertainty of loop current, etc.			
(1) Loop current conversion error	0.28 (actual measurement)	–	Rectangular
(2) Temperature characteristic of current detection circuit 20	0.10 (actual measurement)	–	Rectangular
(3) Stability of signal generator output level	0.05 (actual measurement)	–	Rectangular
(4) Error in monitored voltage measuring instrument indication	0.10 (spec.)	–	Rectangular
(5) Constant current source calibration accuracy	0.02 (spec.)	–	Rectangular
(6) Antenna factor measurement error	–	0.19 (actual measurement)	Standard uncertainty
Uncertainty of propagation calculation			
(1) Approximation error in near-field theoretical calculation	0.27 (MM method)	0.27 (MM method)	Rectangular
(2) Distance setting error (±5 mm/m)	0.12 (calculation)	0.12 (calculation)	Rectangular
(3) Face-to-face alignment error (±5 deg.)	0.05 (actual measurement)	0.05 (actual measurement)	Rectangular
(4) Height setting error (±1 cm/1.5 m)	0.05 (actual measurement)	0.05 (actual measurement)	Rectangular
(5) Noise, interference (SN 30 dB)	0.27 (calculation)	0.27 (calculation)	Rectangular

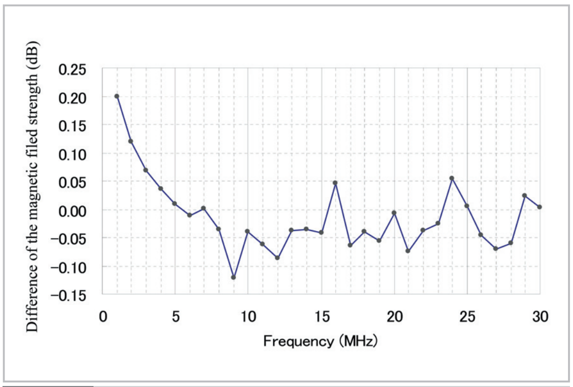

Fig.9 *Example of difference in magnetic field strengths set by AF method and LC method*

0.2 dB (maximum). Since the two methods generated an uncertainty of approximately ±0.6 dB, the difference in actual measurements was within the allowable range.

4.2 Use of general-purpose loop antenna

When a general-purpose loop antenna is used as a standard magnetic field generator, the LC method requires the incorporation of a current-monitoring circuit such as a thermocouple. When setting the magnetic field, it is necessary to pay attention to the difference between the circuit current and loop current, as mentioned earlier above. Our examination uncovered a number of issues related to the shunt ratio calculation for the circuit current and loop current viewed from the loop input side; these issues must be addressed and resolved.

On the other hand, when a general-purpose loop antenna is to be calibrated, no problem arises either in transmission or reception. In other words, the loop antenna used as a lower-level standard magnetic field generator required a thermocouple circuit or the like to monitor current, but since the calibration value is reevaluated based on the circuit current converted from the monitored voltage, this circuit current can be used to calibrate a lower-level loop antenna. On the other hand, when a general-purpose loop antenna is used as a standard antenna on the receiving side, the calibration value is reevaluated based on the output voltage and the like of the loop antenna; therefore, it is possible to use such a general-purpose antenna as a lower-level standard using this particular reference method.

5 Conclusions

NICT has been reviewing calibration accuracy for many kinds of antennas, as a response to the increasing precision of measuring equipment and continued advances in measuring technology. As part of these efforts, we examined loop antenna calibration accuracy in the range of 1 MHz to 30 MHz, and conducted a verification experiment using the AF method, which has yet to be applied in practical use. As a result, general uncertainty, with a reliability coefficient of 95%, was found to be ±0.60 dB under the LC method.

Based on the results of our experiment, we confirmed that the previously estimated uncertainty of approximately ±0.5 to 1.0 dB for the LC method was an appropriate value.

Furthermore, the AF method, which we used for verification, enables the setting of magnetic field strength under a method that differs dramatically from the conventional LC method, and which has proven very effective for use in supplementing or verifying the LC method.

In the course of future research, we will conduct similar investigations for frequencies below 1 MHz, and will resolve the problem limiting use of the shunt ratio as a standard only for specific loop antennas under the present LC method, thus enabling the substitution of a general-purpose loop antenna for a standard loop antenna.

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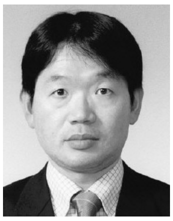
Calibration



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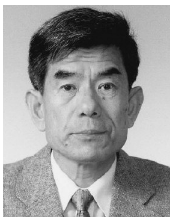

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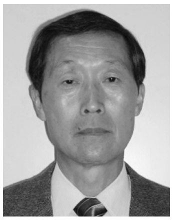

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Calibration