2-5 Antenna Calibration
2-5-1 Calibration of Loop Antennas for EMI Measurements in the Frequency Range Below 30 MHz

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

This paper describes the calibration method of loop antennas for EMI measurements in the frequency range below 30 MHz. NICT developed the method by ourselves and started to provide the calibration service that is certified by ASNITE accreditation program. Because the ASNITE is compliant with the international standard ISO/IEC 17025, the loop antennas calibrated by NICT can be used for all tests such as validations of radio equipment and EMI measurements of electronic devices.

1 Introduction

New ways of using 30 MHz and lower radio frequencies have appeared in recent years: IH induction rice cookers, contactless chargers, contactless IC cards, etc., that differ from conventional radio broadcasts and commercial wireless communications. Both new and conventional uses share the same frequency band, so actually one must measure the electromagnetic fields, and check that there is no interference. Also, electric and electronic devices such as AC power supply adapters and LED lights that contain switching regulators are often used in our daily lives, so there are increasing needs to take measurements to regulate unintentionally emitted electromagnetic noise. In this environment, NICT obtained ASNITE certification to fulfill the ISO/IEC 17025 standard for loop antenna calibration, and began providing calibration services in July 2015. NICT developed a system that can issue internationally recognized calibration certificates which can be used for all measurements, without distinguishing between use for wireless communications or for electromagnetic noise measurements.

Electromagnetic field measurements of 30 MHz or lower have conventionally used loop antennas that have sufficiently smaller dimensions than the wavelengths. NICT has provided calibration services and performed research and development on calibration of loop antennas since the time of its Radio Research Laboratory [1]. The "standard magnetic field method" is used to calibrate loop antennas; this method theoretically obtains a magnetic field emitted from a transmitting loop antenna that interlinks with an antenna under calibration (receiving antenna). The strength of the magnetic field emitted from a transmitting antenna is determined by correctly measuring the RF current flowing through the element of the transmitting antenna. The RF current flowing through the element is measured by using the conversion component attached to the element, and converting the RF current flowing through the element into DC voltage. A resistor that converts RF current into heat, or a thermocouple in a vacuum tube that uses heat to generate DC voltage, are used for conversion components. In this case, correctness and traceability to national standards of the strength of the magnetic field emitted from the transmitting loop antenna can be maintained by correctly calibrating the conversion coefficient of the conversion component. However, there were limits to improving its precision, partly because this calibration is complex [2][3].

To solve this problem, NICT developed a new calibra-

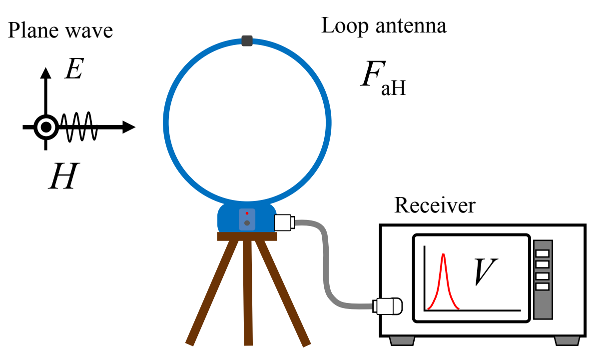


Fig. 1 Magnetic field measurement and definition of magnetic field antenna factor

tion method in recent years [4][5], and started providing calibration services. This method is classified the same as a conventional "standard magnetic field method", but instead of conventional calibration methods that calibrate from different physical quantities, this method uses an already calibrated loop antenna to calibrate another loop antenna. The advantages of this calibration method are that it measures RF power instead of RF current, and that it uses a loop antenna to obtain traceability to the national standard. This paper shows the result of calibrating an actual commercially sold loop antenna, and explains a method to evaluate uncertainty associated with the calibration result.

2 Definition of magnetic field antenna factor and how to use it

A loop antenna operates by electricity generated by a magnetic field that interlinks with the loop plane. Therefore, as shown in Fig. 1, the loop antenna's characteristic is defined by using the ratio of strength H of the magnetic field that interlinks with the loop plane, and voltage V generated in the receiver connected to the loop antenna.

$$F_{aH} = \frac{H}{V} \quad \text{[S/m]} \qquad (1)$$

This F_{aH} is called the "magnetic field antenna factor".

Usually, it is expressed using dB.

$$F_{\mathrm{aH}}^{\mathrm{dB}} = 20\log_{10} F_{\mathrm{aH}} \quad \text{[dB(S/m)]} \qquad (2)$$

The unit is dB(S/m). By calibrating the loop antenna, if the magnetic field antenna factor was already obtained, then one can read the output voltage V of the receiver, and use the following equation to know the strength of the magnetic field that interlinks with the antenna.

$$H^{\mathrm{dB}} \ [\mathrm{dB}(\mu\mathrm{A/m})] = V^{\mathrm{dB}} \ [\mathrm{dB}(\mu\mathrm{V})] + F_{\mathrm{aH}}^{\mathrm{dB}} \ [\mathrm{dB(S/m)}] \qquad (3)$$

If the transmitting source is sufficiently far, and plane waves are being received, then in addition to wave impedance in free space ($\eta_0 = 120\pi \approx 377.0\ \Omega$), one can use

$$E^{\mathrm{dB}} \ [\mathrm{dB}(\mu\mathrm{V/m})] = V^{\mathrm{dB}} \ [\mathrm{dB}(\mu\mathrm{V})] + F_{\mathrm{aH}}^{\mathrm{dB}} \ [\mathrm{dB(S/m)}] + 51.53\,[\mathrm{dB}(\Omega)] \qquad (4)$$

and convert into electric field strength.
($20\log_{10} 377.0 = 51.53$)

3 Calibration method

Several methods of calibrating loop antennas have already been proposed [6]–[8]. Some of these methods have been made international standards by the International Special Committee of Radio Interference (CISPR) [8]. There are also several classification methods; Table 1 classifies them into absolute calibration methods which obtain the loop antenna's magnetic field antenna factor from other physical amounts (RF current or RF power), and relative calibration methods that use a loop antenna with an already known magnetic field antenna factor to obtain the magnetic field antenna factor of the antenna under calibration (hereinafter written as "AUC"). Table 1 writes the types of devices needed for calibration, number of times to measure, features, etc.

This calibration method developed at NICT [4][5] is classified as a "relative calibration" method. It requires a loop antenna with an already known magnetic field antenna factor, but this calibration method has the advantages that it can ensure direct traceability to the national standard, and that it only needs one measurement. Requiring few measurements is an essential condition for reducing uncertainty of calibration.

Here, we consider using a "loop antenna with already known magnetic field antenna factor" (hereinafter, "Standard") as the transmitting antenna. The magnetic field antenna factor, as defined in Equation (1), is a parameter that expresses characteristics of the receiving antenna. If an antenna has reciprocity, then it can be used as the transmitting antenna.

As shown in Fig. 2, a circular loop antenna with radius size r_{Rx} for which we want to obtain the magnetic field antenna factor (AUC) is placed at distance d from the Standard (radius r_{Tx}), with its loop plane parallel to the Standard, with their centers aligned. Then, if we use a vector network analyzer (hereinafter, "VNA") to measure S_{21} between the Standard and AUC, the magnetic field antenna factor of the AUC can be determined from the following equation.

$$F_{\mathrm{aH}}(\mathrm{AUC}) = \frac{2K}{\omega\mu_0 Z_0 F_{\mathrm{aH}}(STD)} \frac{1}{|S_{21}|} \qquad (5)$$

Here,

$F_{\mathrm{aH}}(\mathrm{STD})$: Magnetic field antenna factor of Standard [S/m]

ω : Angular frequency ($2\pi f$ [rad/s])

μ_0 : Permeability of vacuum ($4\pi \times 10^{-7}$ H/m)

Z_0 : Characteristic impedance of measurement system (50 Ω)

Also,

$$K \approx \frac{\sqrt{1+(\beta R_0)^2}}{2\pi R_0^3}\left\{1+\frac{15}{8}\left(\frac{r_{\mathrm{Tx}} r_{\mathrm{Rx}}}{R_0^2}\right)^2+\frac{315}{64}\left(\frac{r_{\mathrm{Tx}} r_{\mathrm{Rx}}}{R_0^2}\right)^4\right\} \quad (6)$$

$$\beta = \frac{2\pi}{\lambda} = \frac{2\pi f}{c} \quad (\lambda \text{ is wavelength, } c \text{ is speed of light})$$

$$R_0 = \sqrt{d^2 + r_{\mathrm{Tx}}^2 + r_{\mathrm{Rx}}^2}$$

d Distance between planes of Standard and AUC [m]
r_{Tx} Loop radius of Standard [m]
r_{Rx} Loop radius of AUC [m]

Refer to [9]. If dB is used to calculate, then it is

$$F_{\mathrm{aH}}^{\mathrm{dB}}(AUC) = -45.9 - 20\log_{10} f_{MHz} - S_{21}^{\mathrm{dB}} + 20\log_{10} K - F_{\mathrm{aH}}^{\mathrm{dB}}(STD) \quad [\mathrm{dB(S/m)}] \quad (7)$$

(See its derivation in the Appendix).

4 Calibration results

This paper shows results of calibrating the loop antenna for EMI measurements shown in Fig. 3 (a) (Teseq, HLA-6210). This is a shielded loop antenna with $\phi_{\mathrm{AUC}} = 2.0$ cm and radius $r_{\mathrm{Rx}} =$ 30 cm. It contains a preamplifier.

On the other hand, as shown in Fig. 3 (b), the Standard at NICT is a shielded loop antenna with $\phi_{\mathrm{STD}} = 3.7$ mm and radius $r_{\mathrm{Rx}} =$ 5.0 cm (REPIC, M201A-100R). It is calibrated at the National Physical Laboratory (NPL) which maintains the UK's national standards. Figure 4 shows the traceability chart.

Table 2 shows the calibration points where NICT provides calibration values. NPL does not provide all the calibration points that NICT provides, so we use the interpolated values of NPL's calibration certificate. When interpolating, two regression curves are prepared with an 8 MHz frequency boundary, and used as the calibration values. The next chapter describes the size of uncertainty due to interpolation.

As shown in Fig. 2, measurements used a VNA (Rohde & Schwarz ZNB4) near the center in a semi-anechoic chamber, with antennas placed with distance between antennas d = 20 cm, height from ground plane until loop element's center h = 1.6 m, and S_{21} was measured. The VNA was calibrated by a procedure called "Unknown Thru" before measurement.

Figure 5 (a) shows calibration results. In the figure, the solid line shows calibration results at NICT. The dashed line shows calibration results at NPL. The loop under

Table 1 Loop antenna calibration method

	Name	Calibration instruments	No. of times measure	Note
Absolute calibration	TEM cell Method	TEM cell Power meter Signal generator Receiver	1	• Determine the intensity of the magnetic field propagating in the TEM cell from the input power. • The size of the AUC is restricted by the size of the TEM cell. • 1 measurement is enough.
	Current measurement Method	Transmitting loop (with thermo-couple or current probe)	1	• RF current through the element is measured, determining the strength of the magnetic field generated from the loop. Traceable with RF current. • Magnetic field strength depends on the input resistance of the thermocouple or current probe. • 1 measurement is enough.
	Three-antenna method	3 antennas VNA	3	• Traceable with RF attenuation. • Must measure 3 times.
Relative calibration	Substitution method	Transmitting loop Standard VNA	2	• If Standard and AUC have different dimensions, then must compensate. • Instead of the Standard, management of transmitting loop is required. • Must measure 2 times (compare measurements).
	Magnetic field antenna factor method	Standard VNA	1	• Antenna with already known magnetic field antenna factor is used for transmitting antenna to generate magnetic field. • 1 measurement is enough.
Note) VNA: Vector Network Analyzer. Can also calibrate a combination of a signal generator and receiver.				

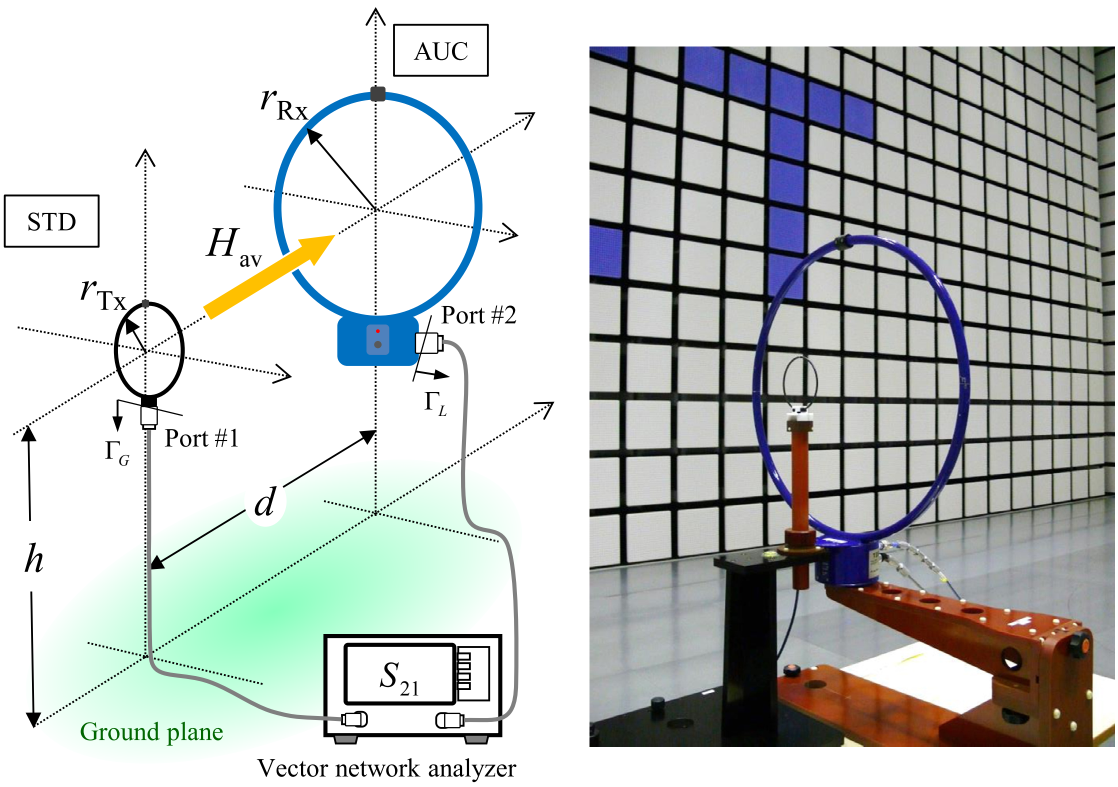


Fig. 2 Configuration to calibrate a loop antenna

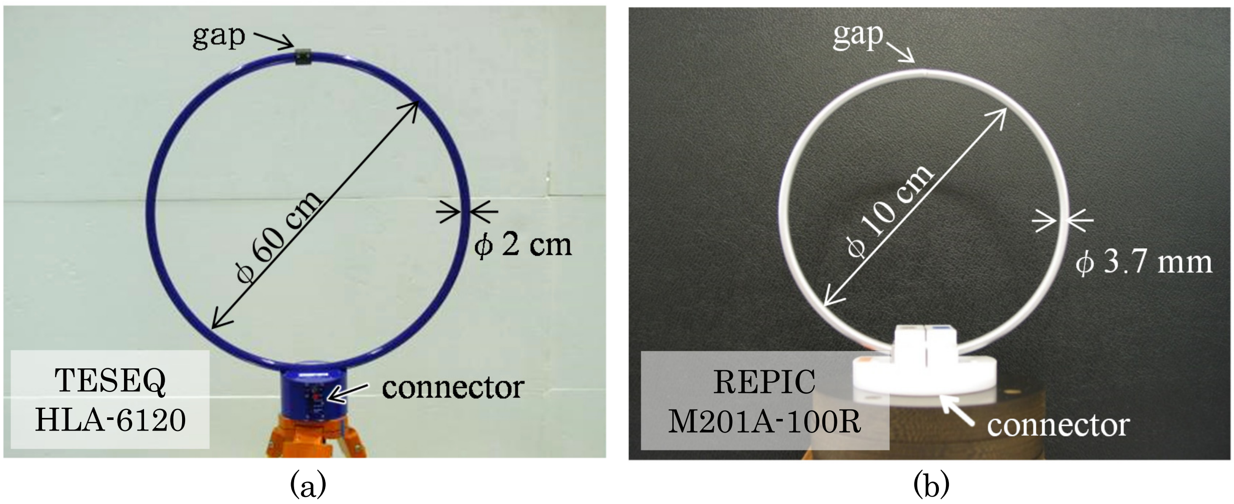


Fig. 3 Loop under calibration and standard
(a) AUC, (b) Standard

calibration is designed so its internal preamp's amplification ratio differs greatly depending on frequency [7], and we see that the AUC has almost the same magnetic field antenna factors for various frequencies. In NICT's calibration results, discontinuity occurs at 8 MHz frequency because calibration values of the Standard are interpolated, and with 8 MHz as the boundary, the regression curves are used separately in interpolation.

Figure 5 (b) shows the differences between two results. It is the value of NICT's calibration results minus NPL's calibration results. Looking at the results, about 1.0 dB differences occur in the low frequency band, and the difference decreases near 10 MHz, but the differences tend to increase again in higher frequencies. As described in the next chapter, this is caused by NPL's calibration values for the Standard, and measurements of the loop radii r_{Tx}, r_{Rx} and distance d between antennas.

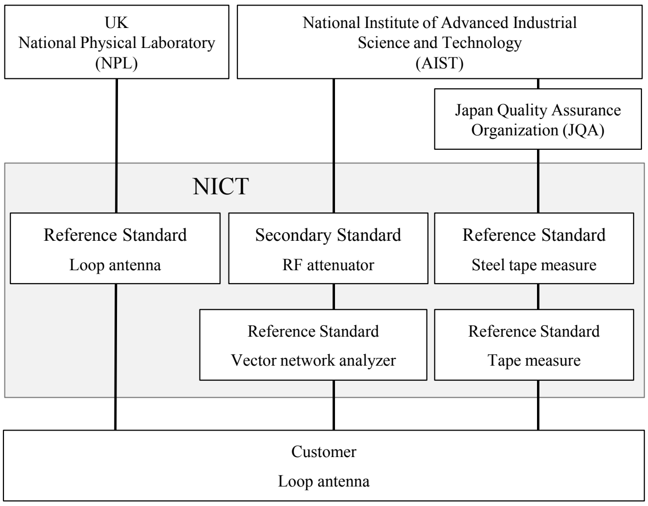


Fig. 4 Traceability chart

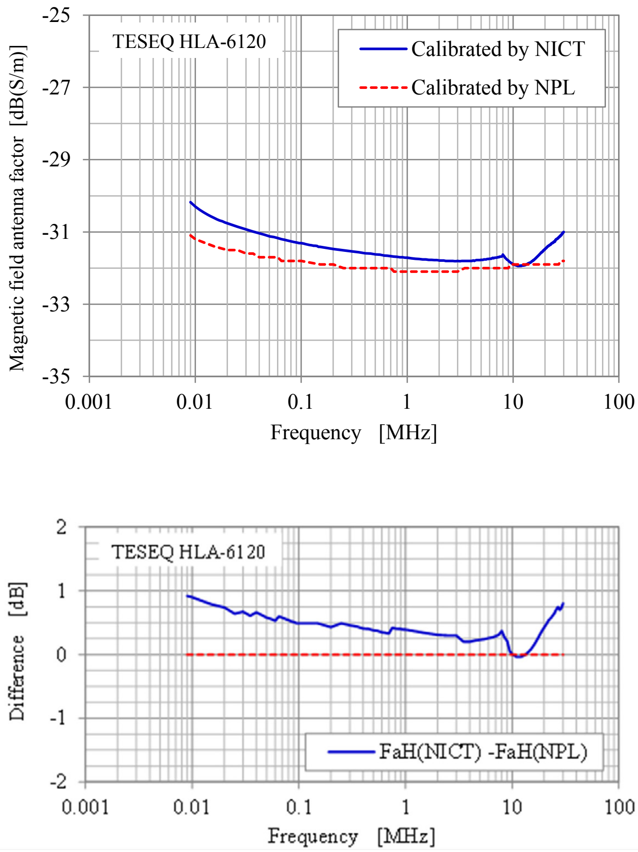


Fig. 5 Calibration results example (Teseq, HLA-6120)

5 Uncertainty

Uncertainty associated with calibration results expresses expanded uncertainty estimated to have approximately a 95% level of confidence. The size of its value can be estimated by using the following equation to combine uncertainty that occurs due to the multiple sources described below [10]. However, the sensitivity coefficients are all size 1, so it is omitted.

Table 2 Conditions and calibration points of loop antenna

Loop under calibration antenna conditions	Frequency range	Frequency interval	Frequency points
Radius 10 cm to 60 cm Type-N50 connector	9 kHz～19 kHz	1 kHz	11 points
	20 kHz～150 kHz	5 kHz	26 points
	150 kHz～1 MHz	50 kHz	17 points
	1 MHz～30 MHz	0.1 MHz	291 points

$$u(F_{aH}(AUC)) = \sqrt{u(S_{21}^{dB})^2 + u(K^{dB})^2 + u(F_{aH}^{dB}(\mathrm{STD}))^2 + u(H_{av}^{dB})^2 + u(I_{Tx}^{dB})^2 s^2} \quad [\mathrm{dB}] \quad (8)$$

Here,

$u(F_{aH}^{dB}(\mathrm{AUC}))$: Uncertainty of AUC

$u(S_{21}^{dB})$: Uncertainty of S_{21} measurements

$u(K^{dB})$: Uncertainty of the calculated value ($K^{dB} = 20\log_{10} K$)

$u(F_{aH}^{dB}(\mathrm{STD}))$: Uncertainty of Standard. Value written in the calibration certificate issued by NPL

$u(H_{av}^{dB})$: Uncertainty due to unevenness of incident magnetic field of AUC

$u(I_{Tx}^{dB})$: Uncertainty because the current distribution that conducts through the element of the Standard is uneven.

s : Variability of measurements

Values used when obtaining a constant number of terms in Equation (7): uncertainty of frequency can be ignored relative to other sources of uncertainty; permeability in a vacuum is a defined value so it has no uncertainty; uncertainty of characteristic impedance is handled as included in uncertainty of S_{21} measurements. Values of Equation (8): value are called “combined standard uncertainty,” so finally, multiply by coverage factor k=1.96, to obtain 95% level of confidence expanded uncertainty. However, we use coverage factor k=2 for simplicity, to obtain expanded uncertainty with an approximately 95% level of confidence (strictly speaking, 95.45%). Below, as a result of estimating uncertainty for each item, uncertainty at 30 MHz frequency is estimated as shown in the Table 3 (a) budget table; expanded uncertainty with an approximately 95% level of confidence is estimated at 1.2 dB.

5.1 $u(S_{21}^{dB})$: Uncertainty of S_{21} measurements

Table 3 (b) shows a budget table used to study and compose uncertainty sources of S_{21} Measurements. For the

VNA used to measure S_{21}, mainly the following 5 items were evaluated as main sources.

(1) Linearity

As shown in Fig. 4, linearity of the VNA's receiver part was validated using an RF attenuator (secondary standard) calibrated by the National Institute of Advanced Industrial Science and Technology (NMIJ/AIST). The largest difference between calibration values by the National Institute of Advanced Industrial Science and Technology written in the calibration certificate, and values displayed on the VNA, was taken as the upper limit of uncertainty.

(2) Incompleteness When VNA Was Calibrated

The VNA is used after calibration using standard devices called a calibration kit, compensating for characteristics of circuits in VNA and the connected coaxial cable. This time, compensation is performed by the calibration method called "Unknown Thru calibration", but the amount which could not be compensated for remains as uncertainty due to incompleteness of calibration. The 0.1 dB residual source match written in the VNA's data sheet was added to uncertainty. This is mismatch uncertainty, so the probability distribution is assumed to be a U-shaped distribution.

(3) Signal Leaks between Transmitting and Receiving Cables

We measure extremely weak signals at low frequency, and due to the loop antenna's structure, signal can leak to the cable's outer layer, which can create unneeded couplings between coaxial cables, affecting measurement values. These effects were estimated to have an upper limit of 0.1 dB uncertainty. Its probability distribution was assumed to be uniform.

(4) SN Ratio

Especially when the frequency is low, there is a weak coupling between loop antennas, and S_{21} reaches to around -100 dB. This time, the AUC contains a preamplifier, so sufficient signal strength could be obtained, but we provided 0.1 dB as the upper limit for uncertainty. Its probability distribution is uniform.

(5) Changes in Measurement Values due to Cable Bending and Stretching

We took measurements while bending and stretching the cable, and evaluated changes in measurement results. The frequencies are low, so changes like a microwave band do not occur. Therefore, we provided 0.1 dB as the upper limit for uncertainty. Its probability distribution is uniform.

We composed the five sources of uncertainty described above as shown in Table 3 (b). This resulted in our estimated 0.18 dB uncertainty for S_{21} measurements.

5.2 $u\left(K^{\mathrm{dB}}\right)$: Uncertainty of calculated values of K

Table 3 (c) shows the results from our estimation of uncertainty that occurs when calculating K. These values are determined from Equation (6) and results of calculations using the NEC2 electromagnetic field numerical simulation software based on the method of moments. For example, we calculated (1) The size of uncertainty of distance was the difference between value of K^{dB} calculated when we input d = 20 cm, versus the values of K^{dB} when we input d = 20 cm – 2 mm and d = 20 cm + 2 mm; (2) Uncertainty of measurement of the transmitting loop radius (5 cm ± 2 mm); (3) Uncertainty of measurement of the receiving loop radius (30 cm ± 3 mm); (4) Uncertainty of positioning of the Standard's loop plane parallel to the AUC's loop plane (± 5° when 0° parallel); (5) Uncertainty of positioning of the AUC's loop plane parallel to the Standard's loop plane (± 5° when 0° parallel); (6) Uncertainty that the Standard and AUC are positioned on the same axis (0 mm if positioned on the same axis, ± 10 mm); (7) Effects of reflection of the ground plane (we used the difference between value calculated if height is 1.6 m, versus value calculated if in free space); (8) Uncertainty from using the approximation equation (difference versus Equation (A.4) is used as uncertainty). We considered that values diverging further than these values would not be measured, providing upper limits and lower limits for all these values, and assumed a uniform probability distribution.

5.3 $u\left(F_{\mathrm{aH}}^{\mathrm{dB}}(\mathrm{STD})\right)$: Uncertainty of standard

As shown in the traceability system diagram in Fig. 4, the Standard that NICT maintains is calibrated by the NPL in the UK. NICT calibrates using as reference the calibration values and uncertainty written in the calibration certificate issued by NPL. The value of uncertainty written in the calibration certificate is expanded uncertainty for coverage factor k= 1.96 with approximately a 95 % level of confidence, so the value written in the calibration certificate divided by coverage factor k=2 is used for standard uncertainty. It is actually 1 dB, so we input 0.5 dB in Table 3 (a).

5.4 Uncertainty of interpolation

There is uncertainty from using the calibration points calibrated by NPL to interpolate magnetic field antenna factors at other frequencies. Figure 6 (a) shows results of calibration by NPL's Standard. The dB values of magnetic field antenna factors change linearly vs. values with logarithms removed for frequencies below 8 MHz, so we use a double logarithmic equation ($F_a^{dB} = a \ln f + b$) for the regression curve below 8 MHz, and use a third-order polynomial ($F_a^{dB} = af^3 + bf^2 + cf + d$) for above 8 MHz. For each, the largest divergence from the regression curve at a frequency is taken as the value of uncertainty. Divergence is within the maximum, so we assume a uniform probability distribution. Figure 6 (b) is a graph that shows how the regression curve diverges from the calibration values obtained by NPL, in units of dB. It exceeds 0.1 dB at 9 kHz and 10 kHz frequencies, but it is within 0.1 dB at greater than 40 kHz frequency, so we used 0.1 dB as the basis of uncertainty.

5.5 Uncertainty due to unevenness of magnetic field that interlinks with the loop area

As shown in Equation (1), the magnetic field antenna factor is defined when plane waves are incident. As shown in Fig. 7, the magnetic field strength is constant, but it has phase delay vs. the loop lane, and that tendency becomes much stronger with larger radius of the receiving loop. On the other hand, when calibrating, we use the average value of the magnetic field generated from the Standard placed opposite to and very near the AUC, and phase delay is not considered. Therefore, both differences are uncertain. Thus, we use the numerical integral to obtain the difference between when there was phase delay vs. when there was no phase delay, and use that as uncertainty. For the probability distribution, we consider the values obtained by calculation as worst case values providing the upper limit and lower limit, with a uniform distribution.

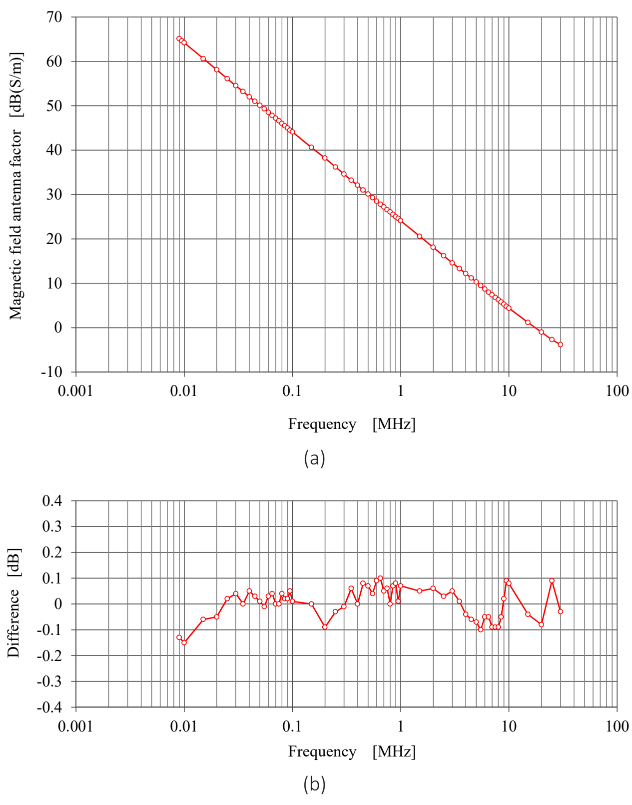


Fig. 6 Magnetic field antenna factor

(a) Magnetic field antenna factor by NPL, (b) Differences between calibration values by NPL and values obtained by interpolating calibration values

5.6 Uncertainty due to distribution of current conducting through the standard

K is calculated under the assumption that the distribution of current conducting through the standard is constant, but actually, the larger the standard loop antenna is compared to the wavelength, that is, the higher the frequency, this leads to greater current distribution occurring, so electric field component occurs, and unneeded links to the AUC occur. Numerical simulation using NEC2 shows there is a desired current value between the maximum value and the minimum value of the current distribution, and that difference was estimated to be uncertainty. We consider the values obtained provide an upper limit and lower limit for uncertainty, and with a uniform probability distribution.

5.7 Repeatability

If repeated measurements are taken, we consider the degree of variability; if measured again another day, we consider whether the same measurement results were obtained. In Table 3 (a), we substituted the variability (experimental standard deviation) when measured 3 times. For the calibration result, we use the average value of results from measuring 3 times, so standard uncertainty is the experimental standard deviation divided by the square root of the number of times measured ($\sqrt{3}$).

Sources of uncertainty that occurs when calibrating a loop antenna were described above. As you can see by looking at Table 3 (a), the main sources of greater uncertainty are uncertainty associated with the NPL's calibration values of the Standard, and uncertainty of calculated values of *K*. As you can see by looking at Table 3 (c), uncertainty of calculated values of *K* is dominated by uncertainty of mea-

Table 3 Uncertainty budget

30 MHz, r_{Tx}=5 cm, r_{Rx}=30 cm, d=20 cm

(a)

	Source	Value [dB]	Probability distribution	Divisor	Standard uncertainty u(xi)	Sensitivity coefficient c(xi)	Contribution [dB] |c(xi)|u(xi)	Note
1	S_{21}	0.18	–	–	0.18	-1	0.18	See Table 3 (b)
2	K	0.14	–	–	0.14	1	0.14	See Table 3 (c)
3	F_{aH}(STD)	1.00	Normal (k=2)	2	0.50	-1	0.50	Calibration certificate of superior calibration organization
4	Interpolation	0.10	Rectangle	$\sqrt{3}$	0.06	-1	0.06	
5	Incident magnetic field	0.04	Rectangle	$\sqrt{3}$	0.02	1	0.02	
6	Current distribution	0.03	Rectangle	$\sqrt{3}$	0.02	1	0.02	
7	Repeatability	0.10	Normal	$\sqrt{3}$	0.06	1	0.06	Measure 3 times
Combined standard uncertainty							0.56	
Expanded Uncertainty (Approx. 95 % level of confidence)							1.2	Coverage factor k=2

(b)

Uncertainty of S_{21} measurement(30 MHz, r_{Tx}=5 cm, r_{Rx}=30 cm, d=20 cm)

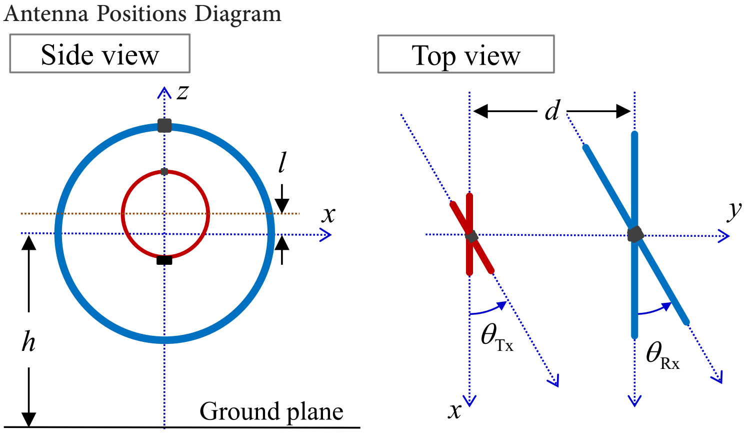
	Source	Value [dB]	Probability Distribution	Divisor	Standard uncertainty u(xi)	Sensitivity coefficient c(xi)	Contribution [dB] |c(xi)|u(xi)	Note
1	Linearity	0.20	Rectangle	$\sqrt{3}$	0.12	-1	0.12	Actually measured by RF attenuator
2	Imperfection of calibration	0.10	U-shape	$\sqrt{2}$	0.08	1	0.08	Spec. sheet of VNA
3	Signal leak between cables	0.10	Rectangle	$\sqrt{3}$	0.06	-1	0.06	
4	S/N ratio	0.10	Rectangle	$\sqrt{3}$	0.06	-1	0.06	S/N > 38 dB
5	Cable bending, stretching	0.10	Rectangle	$\sqrt{3}$	0.06	1	0.06	
Combined standard uncertainty							0.18	

(c)

Uncertainty of K(30 MHz, r_{Tx}=5 cm, r_{Rx}=30 cm, d=20 cm)

	Source	Value [dB]	Probability Distribution	Divisor	Standard uncertainty u(xi)	Sensitivity coefficient c(xi)	Contribution [dB] |c(xi)|u(xi)	Note
1	d	0.17	Rectangle	$\sqrt{3}$	0.19	1	0.099	d=20 cm±5 mm
2	r_{Tx}	0.01	Rectangle	$\sqrt{3}$	0.39	1	0.006	r_{Tx}=5 cm±2 mm
3	r_{Rx}	0.15	Rectangle	$\sqrt{3}$	0.04	1	0.087	r_{Rx}=30 cm±3 mm
4	θ_{Tx}	0.04	Rectangle	$\sqrt{3}$	0.01	1	0.024	θ_{Tx}=0°±5°
5	θ_{Rx}	0.03	Rectangle	$\sqrt{3}$	0.01	1	0.018	θ_{Rx}=0°±5°
6	l	0.01	Rectangle	$\sqrt{3}$	0.00	1	0.006	l=0 mm±10 mm
7	Effect of ground plane	0.01	Rectangle	$\sqrt{3}$	0.00	1	0.006	h=1.6 m
8	Approx. of Eqn. (6)	0.01	Rectangle	$\sqrt{3}$	0.00	1	0.006	Deviation from Eqn. (A.4)
Combined standard uncertainty							0.14	

Antenna Positions Diagram



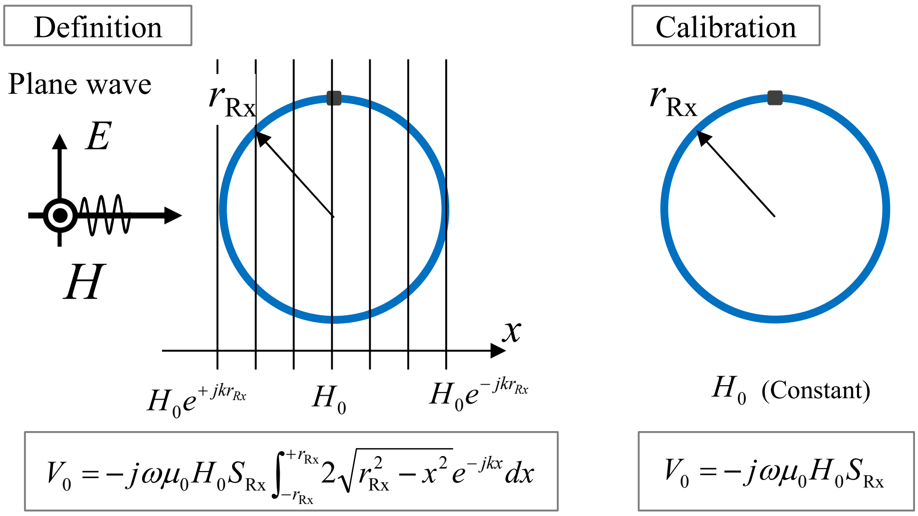


Fig. 7 Unevenness of magnetic field that interlinks with the loop area

surement of distance between antennas, and measurement of loop radii. Said another way, if we can accurately measure the loop radii and distance between antennas, then we can reduce uncertainty. There remains room to improve measurements of distance and radii, that is, "length".

6 Calibration and measurement capability

Calibration and measurement capability (hereinafter written as "CMC") is the smallest uncertainty associated with calibration results provided by NICT. ASNITE certification calibration is also for an AUC that does not contain a preamplifier, so the values of CMC are larger than the values of uncertainty estimated in Table 3. Table 4 shows CMC for calibration of a loop antenna for magnetic fields. If the AUC has small dimensions, then the receiving level (signal to noise ratio) decreases, and it becomes more difficult to measure, especially in the low frequency band under 40 kHz, so the frequency bands are divided for determining this. To improve the receiving level, inserting an external preamplifier is a possible method, but if the output port of the AUC has a large reflection coefficient, then one must sufficiently reduce effects of reflection of the preamplifier's input port.

7 Conclusion

We explained a loop antenna calibration method developed by NICT, using EMI measurements at 30 MHz or lower frequencies. Instead of conventional methods which measure RF current conducted through an element of the transmitting loop antenna, in the method NICT developed, if one measures incident power to the transmitting antenna, then one can determine the magnetic field strength, and there is no need to calibrate the thermocouple or current probe used to measure RF current. This method also has the advantages that for characteristics of the transmitting antenna, we use the magnetic field antenna factor when operating as a receiving antenna, making it easy to obtain traceability to the superior calibration organization, and we can minimize equipment for maintaining the Standard.

There are more diverse uses of radio waves below 30MHz for more purposes in recent years. In response, in addition to in tests of wireless equipment, to enable its use in electromagnetic interference (EMI) measurements, NICT obtained the ASNITE certification that it satisfies the ISO/IEC 17025 standard, and began providing internationally recognized calibration values. It is predicted that various forms of use will be developed, so it seems that demand will increase for high precision loop antenna calibration services.

Appendix. Derivation of Equation (5)

When incident power P_{in} (incident power, not power consumed in the antenna) is incident into the connector part of the Standard shown in Fig. 2, the current I_{Tx} conducting through power feed gap part of the loop element of the Standard can be obtained by using the magnetic field antenna factor $F_{\mathrm{aH}}(\mathrm{STD})$ of the Standard

$$I_{\mathrm{Tx}} = \frac{2}{\omega\mu_0\sqrt{Z_0}\, S_{\mathrm{Tx}} F_{\mathrm{aH}}(STD)} \sqrt{P_{in}} \qquad \text{(A.1)}$$

Here, ω is angular frequency (= $2\pi f$), μ_0 is permeability in a vacuum (= $4\pi\cdot 10^{-7}$ H/m), Z_0 is input impedance of the signal generator and receiver (= 50 Ω), and S_{Tx} is area of the loop antenna of the Standard.

Now, as shown in Fig. 2, at a place distance d from the Standard, the loop antenna for which we want to obtain the magnetic field antenna factor (AUC) is positioned so its loop plane is parallel to the Standard, with their centers aligned. Then, assuming the current I_{Tx} conducting through the transmitting loop element is constant, the average value H_{av} of the strength of the magnetic field that interlinks with the loop lane of the AUC can be obtained using the following Equation [1]–[6][9].

$$H_{av} = I_{Tx} S_{Tx} K \tag{A.2}$$

Therefore, if we substitute Equation (A.1), we obtain

$$H_{av} = \frac{2K}{\omega\mu_0 \sqrt{Z_0} F_{aH}(STD)} \sqrt{P_{in}} \tag{A.3}$$

Here, K is the value that expresses coupling due to the magnetic component between the two loop antennas, given by

$$K = \frac{1}{4\pi S_{Tx} S_{Rx}} \left| \oint_{C_{Tx}} \oint_{C_{Rx}} \frac{e^{-jkR}}{R} \mathrm{d}\boldsymbol{l}_{Rx} \cdot \mathrm{d}\boldsymbol{l}_{Tx} \right| \tag{A.4}$$

Here, S_{Tx} is the loop area of the Standard, S_{Rx} is the loop area of the receiving loop antenna, and R is the distance between line element vectors $\mathrm{d}l_{Tx}$ and $\mathrm{d}l_{Rx}$ on the loop elements. This integral can be applied to rectangular and triangular loop antennas, not only to circular loops. Numerical calculations can be done easily using a computer.

If the Standard and AUC are circular loop antennas with radius r_{Tx} and r_{Rx}, and the conditions $kR_0 \leq 1.0$ and $r_{Tx} r_{Rx} / R_0^2 \leq 1/16$ are satisfied, then

$$K \approx \frac{\sqrt{1+(\beta R_0)^2}}{2\pi R_0^3} \left\{ 1 + \frac{15}{8}\left(\frac{r_{Tx} r_{Rx}}{R_0^2}\right)^2 + \frac{315}{64}\left(\frac{r_{Tx} r_{Rx}}{R_0^2}\right)^4 \right\} \tag{A.5}$$

Here, it can be approximated by

$$R_0 = \sqrt{d^2 + r_{Tx}^2 + r_{Rx}^2}$$

$$\beta = \frac{2\pi}{\lambda} = \frac{2\pi f}{c} \quad (\lambda \text{ is wavelength, } c \text{ is speed of light})$$

and Equation (6) in the main text is obtained [9]. If the H_{av} obtained and the received voltage V measured at the receiver connected to the AUC are substituted into Equation (1), then the equation that obtains the magnetic field antenna factor of the AUC is expressed in the following equation.

$$F_{aH}(AUC) = \frac{2K}{\omega\mu_0 \sqrt{Z_0} F_{aH}(STD)} \frac{\sqrt{P_{in}}}{V} \tag{A.6}$$

This equation is for when the signal generator and receiver are each prepared separately, but as shown in Fig. 2, if a VNA is used to calibrate, then the reflection coefficient Γ_G of the signal generation side's port connected to the Standard, and the reflection Γ_L of the receiving side's port connected to the AUC, are both considered to be 0, so this becomes

$$|a_1| = \sqrt{P_{in}} \tag{A.7}$$

$$|b_2| = \left| \frac{V}{1+\Gamma_L} \right|_{\Gamma_L = 0} = V \tag{A.8}$$

and

$$|S_{21}| = \left| \frac{b_2}{a_1} \right| = \frac{V}{\sqrt{P_{in}}} \tag{A.9}$$

so Equation (A.6) becomes

$$F_{aH}(AUC) = \frac{2K}{\omega\mu_0 Z_0 F_{aH}(STD)} \frac{1}{|S_{21}|} \tag{A.10}$$

and we obtain Equation (5) in the main text. Using dB to obtain this, we take the log of both sides and multiply by 20 (20 $\log_{10}$), so it becomes

$$F_{aH}^{dB}(AUC) = -45.9 - 20\log_{10} f_{MHz} - S_{21}^{dB} + 20\log_{10} K - F_{aH}^{dB}(STD) \tag{A.11}$$

Here, the constant term of Equation (A.11) is the value obtained from

$$20\log_{10}\frac{2}{\omega\mu_0 Z_0} = 20\log_{10}\frac{2}{(2\pi\times 10^{+6})(4\pi\times 10^{-7})\cdot 50} - 20\log_{10} f_{MHz} = -45.9 - 20\log_{10} f_{MHz} \tag{A.12}$$

and f_{MHz} is the frequency when MHz is the unit.

Table 4 Maximum measurement capability

DUT loop radius, r_{Rx}	Frequency range	
	9 kHz ≤ Freq. < 40 kHz	40 kHz ≤ Freq. ≤ 30 MHz
5 cm ≤ r_{Rx} < 10 cm	1.6 dB	1.4 dB
10 cm ≤ r_{Rx} < 20 cm	1.4 dB	1.4 dB
20 cm ≤ r_{Rx} ≤ 30 cm	1.4 dB	1.4 dB

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Katsumi FUJII, Dr. Eng.

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

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

Iwao NISHIYAMA

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