3-3 Developments of ISO/IEC17025 Calibration Systems in Wireless Communications Department

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Wireless Communications Department / EMC Center started its attempt for obtaining the ISO/IEC17025 accreditation in 2004. The standard demands both good ability of calibration and proper resource for correct calibration. After we constructed our quality system, we applied for the accreditation to the National Institute of Technology and Evaluation in April 2005. The surveillance of papers and actual laboratory check was continuously performed during the year 2005. After a number of improvements and revisions of our system, we were granted the accreditation for the JCSS and the ASNITE-CAL on 1 March 2006. In this paper, the objective and motivation for ISO/IEC17025, the development of the system and calibration systems accredited are described.

Keywords
Calibration, RF power meter, RF attenuator, Calibrator, ISO/IEC17025, JCSS, ASNITE

1 Background and purpose

The National Institute of Information and Communications Technology (NICT) has been providing calibration services in accordance with the Radio Law. Since the Radio Law is a domestic law, the results of calibrations conducted by NICT are fundamentally valid only in Japan. Therefore, when Japanese equipment manufacturers sell their products overseas, the products must be recalibrated in the various destination countries. In some cases, equipment has to be recalibrated in each country where it is used. To resolve this inconvenience, mutual recognition arrangements (MRAs) with various countries have been promoted to facilitate acceptance of the results of wireless equipment calibration among countries. However, concluding such arrangements with other countries is complicated and time-consuming. In view of these challenges, a series of regulations[1]-[4], starting with the ISO/IEC Guide 22 (currently ISO/IEC 17050), were established to provide a framework of accreditation to organizations that provide calibration services based on international standards, and to allow for international recognition of the results of calibrations conducted by such accredited calibration laboratories. The conditions that an organization must meet for accreditation are specified in the ISO/IEC 17025 standard (referred to below as “ISO 17025”)[3]. In Japan, this standard was incorporated into the Measurement Law and became part of the Japanese Industrial Standards (JIS Q17025)[5].

In Japan, there are two types of ISO 17025 accreditation: jcss/JCSS accreditation based on the Measurement Law, and accreditation for each body that does not fall within the scope of this Law. Further, two types of institutions are involved in accreditation based on the Measurement Law: those that perform calibration using national standards directly, and those that use transfer standards traceable to national standards. The former laboratories provide ‘jcss’ accreditations, while the latter issue ‘JCSS’ accreditations. However, if there is no traceable national standard in a given case, it is possible to issue ISO 17025 accreditations—for example, using a standard traceable to the national standard of another country. In such a case, the accreditation body issues its original accreditation.

In January 2003, the Applied Research and Standards Department within NICT was granted ISO/IEC 17025 (jcss) accreditation for frequency calibration using the national standards it had itself devised.

By comparison, the standards used by the Wireless Communications Department for calibration services (RF power meters, RF attenuators, Calibrators, etc.) are not national standards; thus, the department could not obtain ISO/IEC 17025 (jcss) accreditation at the same time as the Applied Research and Standards Department. Later, the Wireless Communications Department was able to clarify the conditions applicable to its national standards system and to identify traceability for the types of calibration it performs. Accordingly, in April 2004 the department began activities aimed at obtaining ISO/IEC 17025 (JCSS) accreditation.

Some accreditation bodies are organized based on ISO17025 in Japan, and their ranges of services vary from institution to institution. In consideration of the variety of services provided by the Wireless Communications Department, we selected the National Institute of Technology and Evaluation (NITE) as our accreditation body, and applied for accreditation under this organization.

2 Scope of accreditation

To date NICT has been providing calibration services for the devices shown in Table 1.

Given the present circumstances, it is difficult to ensure traceability to overseas standards (“standards calibration traceability”) in view of the cost and the time required for the upper-level calibration of transfer standards. Therefore, we selected RF power meters, RF attenuators, and calibrators as service items subject to ISO 17025 accreditation, since the transfer standards for these devices have been calibrated by standards organizations in Japan, allowing for traceability within the scope of the Measurement Law. In addition, we structured our calibration to conform with the calibration points of our upper-level calibration laboratory, and refrained from expanding the scope of calibration (see Table 2).

However, for the AC current of the calibrators included in the scope of accreditation, we examined traceability to another institution, as the number of calibration points provided by our upper-level calibration laboratory was very limited. The standards used by NICT are generated by FLUKE, and FLUKE’s head office in the United States is accredited under the A2LA (an ISO 17025 accreditation body with traceability to NIST). This allows us to obtain relatively rapid calibration results from FLUKE. We therefore decided to establish traceability to NIST, the upper-level calibration laboratory used by FLUKE. However,

Table 1 *Calibration services provided by NICT*

Calibration of measurement instruments for registered inspection business operators (Article 24-2 of Radio Law)	(1) Frequency meter
	(2) Spectrum analyzer
	(3) Field strength meter
	(4) RF power meter
	(5) Voltage/current meter
	(6) Standard signal generator
	(7) Frequency standard oscillator*
Entrusted calibration (Article 102-18 of Radio Law and Article 10 of Regulations Concerning the Calibration of Measuring Instruments, etc.)	(1) Frequency standard oscillator*
	(2) Dipole antenna
	(3) Bi-conical antenna
	(4) Field strength meter
	(5) Standard magnetic field generator
	(6) Calibration receiver
	(7) Horn antenna
	(8) Calibrator
	(9) RF power meter
	(10) RF attenuator
	(11) SAR (Specific Absorption Rate) probes

* Calibration services including jcss calibration services provided by another department

Table 2 *Scope of calibrations subject to ISO/IEC 17025 accreditation*

Classification		Type of service		Calibration scope
Former classification: At the time of application (until July 2005)	New classification (from July 2005)			
Electrical Calibration.	Electrical Calibration. (DC/LF)	Calibrator	DC current source	1V, 10V, 100V (JCSS)
			DC voltage source	100mA, 1A, 10A (JCSS)
			AC voltage source	100 V at 50 Hz, 60 Hz, 400 Hz (JCSS)
			AC current source	1 A, 10 A at 50 Hz, 60 Hz (JCSS)
			AC current source	200 μA, 2.0 mA, 20 mA, 200 mA at 1 kHz, 5 kHz, 10 kHz (ASNITE-Calibration)
	Electrical Calibration (HF)	RF power meter	Low power meter	1 mW at 10 MHz, 15 MHz, 20 MHz, 25 MHz, 30 MHz, 40 MHz, 50 MHz, 60 MHz, 70 MHz, 80 MHz, 90 MHz, 100 MHz, 150 MHz, 200 MHz, 250 MHz, 300 MHz, 400 MHz, 500 MHz, 600 MHz, 700 MHz, 800 MHz, 900 MHz, 1.0 GHz, 1.2 GHz, 1.3 GHz, 1.4 GHz, 1.5 GHz, 1.6 GHz, 1.8 GHz, 2.0 GHz, 2.5 GHz, 3.0 GHz, 4.0 GHz, 5.0 GHz, 6.0 GHz, 7.0 GHz, 8.0 GHz, 9.0 GHz, 10 GHz, 11 GHz, 12 GHz, 13 GHz, 14 GHz, 15 GHz, 16 GHz, 17 GHz, 18 GHz (JCSS)
			High power meter	10/ 10 W at 10 MHz, 15 MHz, 20 MHz, 30 MHz, 40 MHz, 50 MHz, 60 MHz, 70 MHz, 80 MHz, 100 MHz, 120 MHz, 140 MHz, 150 MHz, 160 MHz, 180 MHz, 200 MHz, 250 MHz, 300 MHz, 400 MHz, 450 MHz, 500 MHz, 600 MHz, 700 MHz, 800 MHz, 900 MHz, 1.0 GHz, 1.1 GHz, 1.2 GHz, 1.3 GHz, 1.4 GHz, 1.5 GHz, 1.6 GHz, 1.8 GHz, 1.9 GHz, 2.0 GHz; and 0.1 W, 0.5 W, 1 W, 3 W, 5 W, 7 W, 20 W, 30 W, 50 W at 100 MHz (JCSS)
High frequency		RF attenuator		10 dB, 20 dB, 30 dB, 40 dB, 50 dB, 60 dB, 70 dB, 80 dB, 90 dB at 10 MHz, 30 MHz, 100 MHz, 500 MHz, 1.0 GHz, 5.0 GHz, 10 GHz; and 10 dB, 20 dB, 30 dB, 40 dB, 50 dB, 60 dB at 18 GHz (JCSS)

since this traceability is not recognized by the Measurement Law and thus puts JCSS accreditation out of reach, we decided to obtain ASNITE-Calibration accreditation, NITE's original ISO 17025 accreditation system.

3 Course of accreditation

3.1 Preparation for application

We began preparing quality-related documents in the spring of 2004. For documents for management requirements of our quality system, we referred to ones from the Applied Research and Standards Department. Although we established documents for technical requirements based on actually implemented procedures, we revised many parts of these procedures in accordance with the ISO 17025 requirements. When the first edition was completed in January 2005 and the relevant documents were established, we began using the ISO 17025 standard system. At the end of the same month, the Wireless Equipment Calibration Committee, in charge of executive management of the system, held its first meeting.

In February, the first internal audits were carried out. Since we did not perform actual calibration during the period from initial implementation of the ISO 17025 standard system operation through the start of these internal audits, the advice and recommendations we received were based on the results of the examination conducted by comparing quality documents and actual conditions. The corrective actions we implemented included document corrections and improvements to inadequate equipment and indicating components. In order to verify the results of these corrective actions, a follow-up audit was conducted in March.

Following the pre-application preparations referred to above, we submitted an application for system accreditation to NITE in April 2005.

3.2 Assessment for accreditation

(1) Assessment

The assessment for accreditation proceeded as expected. The accreditation body, NITE, organized a team of assessors and examined the documents and operation sites.

The scope of application encompassed two JCSS classifications (“electrical calibration” and “electromagnetic calibration”) and one ASNITE-Calibration classification (“electrical calibration”). In May, we were notified of the members of the assessment team.

During the assessment, the ISO 17025 standard was revised (ISO/IEC 17025:2005). Although the classifications and conditions were partially changed, the assessment for our accreditation was conducted based on the standards and specifications effective at the time the application was submitted.

(2) Document and record review

The documents submitted with the application were examined through comparison with the ISO 17025 standard. We received a set of questions dated June 26. We examined the questions and determined policies for measures to be implemented, and submitted our reply on July 25. We received a second set of questions dated September 12, and sent our reply on October 11. Although the questions ranged widely, we were asked mainly to clarify details of the calibration tasks that had been standard practice in our calibration operations.

(3) On-site assessment

The on-site assessment was conducted to investigate whether there were any discrepancies between the submitted documents and actual work conducted and whether actual calibration services were appropriate. The auditing of our group lasted two days—from November 10 through November 11. On the first day, the documents and conditions of implementation were examined. On the second day, actual calibration work was assessed.

In response to the items pointed out in the on-site assessment, we submitted a report on corrective actions on December 27. In connection with this report, we were asked about the estimation of aging changes in the transfer standards that would result in uncertainty. In response, we submitted an examination report on February 8.

(4) Proficiency testing

Accreditation bodies conduct proficiency testing at regular intervals, in addition to certification assessments. However, due to scheduling limitations, we could not receive an ordinary proficiency test; instead, NITE provided us with individual tests. Since our application covered two classifications, tests were conducted for two types of equipment—calibrators and RF attenuators—during the period from the end of January to early February.

3.3 Assessment results

Following the above-mentioned assessment, we became a registered laboratory for JCSS (under international MRAs) and ASNITE-Calibration as of March 1, 2006.

As a point of note, the Measurement Law was amended in July 2005, resulting in major changes in items related to ISO 17025 accreditation. Consequently, JCSS-accredited laboratories are now referred to as “registered” JCSS laboratories. The business classifications were also revised. As a result, the scope of application submitted by the Wireless Communications Department was reclassified as “electrical calibration (DC/LF)” and “electrical calibration (HF)”.

3.4 Compliance with ISO 17025:2005

The ISO 17025 standard was revised in May 2005. In the previous version (1999), the quality system was based on the 1994 version of ISO 9000s. Since ISO 9000s was revised in 2000, the recent revision of ISO 17025 was designed to align this standard with the new version of ISO 9000s. The revised standard calls for a stronger commitment from top management, effective use of customer feedback, and confirmation of the validity of the management system.

Since the assessment was conducted at the time the 2005 version entered into effect, discrepancies between the current system and the new version were pointed out as items for observation. Specifically as a result, we must determine measures for the three points cited above with respect to the revised standard in 2006 and report on our progress to the accreditation body.

3.5 Changes resulting from accreditation

In the near future, calibration services based on the ISO/IEC 17025 will be added to our conventional calibration services (the two types described below) based on the Radio Law. Since the target and scope of these two calibration systems are different, we must be able to provide easy-to-understand explanations to customers.

(1) Calibration based on Radio Law (in accordance with Table 1)
  - For registered inspection business operators
  - Entrusted calibration

(2) Calibration based on ISO/IEC 17025 (in accordance with Table 2)

The calibration method is determined based on each type of service, not on the type of calibration involved. However, the documents submitted to applicants as a result will consist either of a “notice of calibration completion”, a “calibration record”, or a “calibration certificate”.

4 Outline of calibration system

4.1 RF power meter

4.1.1 Introduction

The target calibration systems examined in the context of this recent accreditation can be divided roughly into the following two types.

Low power calibration systems:
Calibration frequency range: 10 MHz to 18 GHz; calibration power range: 1 mW
High power calibration systems:
Calibration frequency range: 10 MHz to 2 GHz; calibration power range: 0.1 mW to 50 mW

The scope of the recent JCSS accreditation covered some of these systems, as shown in Table 2.

4.1.2 Low power calibration systems[6]

Figure 1 illustrates a low power calibration system. The signal from the source is distributed to the device under test (DUT) or to the transfer-standard power meter and indicator (the latter consisting of a thermistor mount, bridge circuit, and digital voltmeter) via power splitter. The thermistor mount converts high-frequency power to resistance change, which is detected by the high-precision bridge cir-

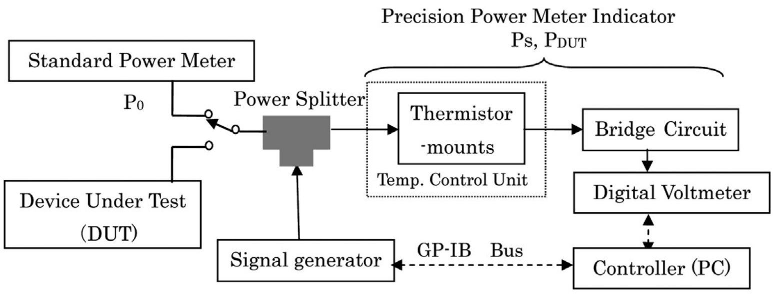


Fig. 1 *Low power calibration system*

cuit. The DC current (voltage) required to compensate for that change is then measured by the digital voltmeter. The temperature inside the thermistor mount is maintained at 60°C, so the effect of outside temperature change on the resistance value can be disregarded.

(1) Evaluation of indicator

The signal source of the calibration system is adjusted such that the transfer-standard power meter, [calibrated by the National Metrology Institute of Japan (NMIJ), within the National Institute of Advanced Industrial Science and Technology (AIST)], indicates at a given power, and the calibration value at a specific power value (provided by the NMIJ) are used to evaluate the indicator. This process is conducted at least once a year for each frequency.

(2) Calibration of DUT

The DUT is connected for calibration to the test measurement terminal of the power splitter; automatic adjustment of the signal source SG is then conducted such that the indicated value of the DUT corresponds to the power value P_0 specified in the application form for calibration. The value (Ps) read on the indicator at that time is then recorded. Next, the transfer-standard power meter is connected to the test measurement terminal of the power splitter, and the signal source is adjusted such that the indicated value corresponds to the calibration power value P_0 specified by the upper-level calibration laboratory. The value (P_{DUT}) read on the indicator at that time is then recorded. The calibration coefficient is calculated in the following formula using the above values and the upper-level calibration coefficient of the transfer standard.

$$\begin{aligned}&\text{Calibration coefficient}\\&\quad = \text{Transfer-standard measurement } (P_s)\\&\quad\quad / \text{ DUT measurement } (P_{DUT})\\&\quad\quad \times \text{ Upper-level calibration coefficient}\\&\quad\quad\quad \text{of transfer standard}\end{aligned} \tag{1}$$

4.1.3 High power calibration system

The calorimeter method is known for its ability to provide accurate measurement of a large quantity of high-frequency power, but is impractical in that this method requires the use of bulky equipment and entails cumbersome maintenance. Therefore, we employed a more practical calibration system involving the use of a directional coupler. This calibration method is also used for comparison of international power standards. The method provides accurate results when the coupling coefficient of the directional coupler is measured precisely using a calibrated standard power meter. Figure 2 illustrates the operating principle of this calibration system.

(1) Evaluation of calibration system

According to the following procedure, the value shown on the indicator of the calibration system is evaluated for the frequency range of calibration.

(a) Calibration of the monitoring power meter

The monitoring power meter is calibrated using the low power calibration system.

(b) Calculation of the degree of coupling, kcf, in the forward direction of the directional coupler

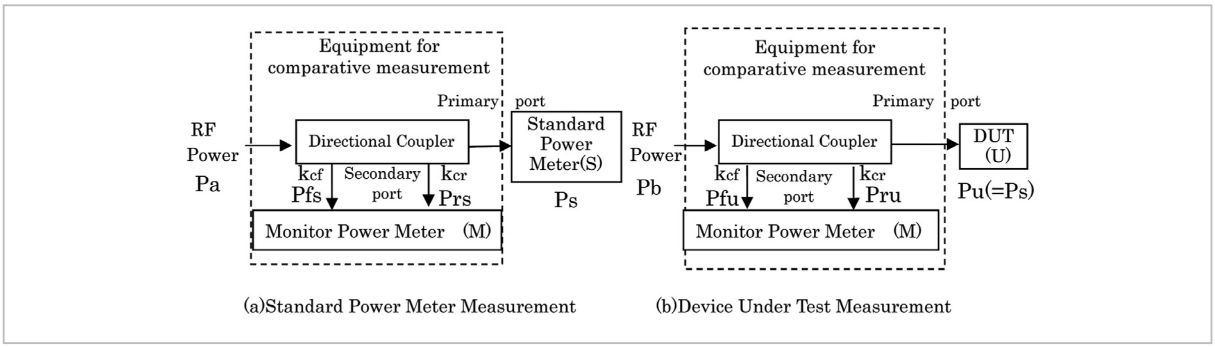


Fig.2 High power calibration system

As shown in Fig. 2 (a), our standard (the transfer standard) is connected to the primary port of the directional coupler. The RF power is then adjusted such that the indicated value of the standard power meter shows the specified value, P_0 (for example, 10 W; however, note that the JQA calibration value is P_0'). In this process, the traveling-wave power Pfs is read from the monitoring power meter, and the degree of coupling in the forward direction is calculated using the following equation.

$$kcf = Pfs / P_0' \quad (2)$$

(c) Calculation of the degree of coupling, kcr, in the reflecting direction of the directional coupler

The input and output of the directional coupler are reversed in (b), and RF power is applied in the same manner as described above. The reflecting-wave power Pfr is read when the indicated value of the standard power meter corresponds to the specified value P_0 (for example, 10 W; however, note that the JQA calibration value is P_0'). The degree of coupling in the reflecting direction is then calculated using the following equation.

$$kcr = Pfr / P_0' \quad (3)$$

(2) Measurement of incident power to the standard power meter

Using the degrees of coupling (kcf and kcr) obtained above, the following measurement is conducted using the standard.

As shown in Fig. 2 (a), the transfer standard is connected to the primary port of the directional coupler, and RF power is adjusted such that the indicated value of the transfer standard corresponds to the specified power value, Ps. At this time, the forward power Pfs and the reflected power Prs are measured. Input power, Ps_0, to the transfer standard is then obtained using the following formula.

$$Ps_0 = kcf \times Pfs - kcr \times Prs \quad (4)$$

(3) Measurement of incident power to the DUT

The DUT is similarly calibrated.

As shown in Fig. 2 (b), the DUT is connected to the primary port of the directional coupler, and RF power is adjusted such that the indicated value of the DUT corresponds to the specified power value, Pu (= Ps). At this point, the forward power Pfu and the reflected power Pru are measured. Input power, Pu_0, to the DUT is then obtained using the following formula.

$$Pu_0 = kcf \times Pfu - kcr \times Pru \quad (5)$$

(4) Calibration of the DUT

The calibration value Δ_{DUT} is determined using Ps_0 and Pu_0 obtained above, applying the formula shown below. Note that Δ_{STD} is the upper-level calibration value (i.e., the value provided by the upper-level calibration laboratory) for the standard.

$$\Delta_{DUT} = \frac{P_{uo}}{P_{so}} \times \Delta_{STD} \quad (6)$$

4.1.4 Estimation of uncertainty of calibration

(1) The case of a low power meter

The following items are suspected as factors contributing to the uncertainty of calibration of low power meters. The following describes these factors together with an outline of methods for calculating their respective values.

(a) Uncertainty of transfer standard: The value (varies depending on the frequency range) indicated on the calibration certificate is applied [normal distribution].

(b) Error deriving from mismatch between transfer standard and splitter: The reflection coefficient between the transfer standard and splitter is measured, and error is calculated using the measured value [U-shaped distribution].

(c) Error deriving from mismatch between DUT and splitter: The reflection coefficient between the transfer standard, DUT, and the splitter is measured, and error is calculated using the measured value [U-shaped distribution].

(d) Measurement deviation: Measurement is performed 30 times and deviation is assessed.

(e) Fluctuation of upper-level calibration value of transfer standard due to temperature: Fluctuation is measured at 23 ±2°C.

(f) 1/2-digit error in the indication of DUT measurement: The least significant digit of the indicated value of the indicator is divided by two.

(g) Aging change in transfer standard: A value is obtained based on the fluctuation in the calibration results of the transfer standard provided by the upper-level calibration laboratory.

As described in (c), uncertainty is dependent on the DUT. Figure 3 shows the uncertainty of a typical power sensor (Agilent 8481A) as an example. For other types of DUT, the reflection coefficient of the DUT is measured, and the obtained value is used to calculate uncertainty. According to the JCSS definition, the best measurement capability can be achieved when factor (c) is ignored.

(2) The case of high power meter

The items listed below are suspected factors contributing to calibration uncertainty in high power meters. Following is a description of these factors, together with an outline of methods for calculating their values.

(a) Uncertainty of transfer standard: The value (varies depending on the frequency range) indicated on the calibration certificate is used [normal distribution].

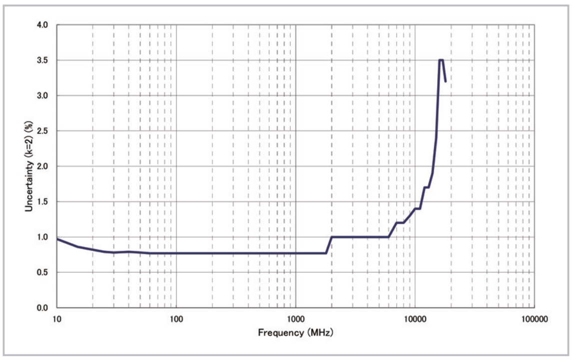


Fig.3 *Example of calibration uncertainty in low power meter (Agilent 8481A)*

(b) Error deriving from mismatch between transfer standard and directional coupler: The reflection coefficient between the transfer standard and directional coupler is measured, and error is calculated using the measured value [U-shaped distribution].

(c) Error deriving from mismatch between DUT and directional coupler: The reflection coefficient between the DUT and directional coupler is measured, and error is calculated using the measured value [U-shaped distribution].

(d) Error deriving from mismatch between monitoring power meter and directional coupler: The reflection coefficient between the monitoring power meter and directional coupler is measured, and error is calculated using the measured value [U-shaped distribution].

(e) Incompleteness of directional coupler: The S parameter of the directional coupler is measured, and the incompleteness value is calculated using the measured value [U-shaped distribution].

(f) Measurement deviation: Measurement is conducted 20 times and deviation is assessed.

(g) Fluctuation of upper-level calibration value of transfer standard due to temperature: Fluctuation is measured at 23 ±2°C.

(h) 1/2-digit error in the indication of DUT: The least significant digit of the indicated value on the indicator is divided by 2.

(i) Aging change in transfer standard: Value is obtained based on fluctuation of the calibration results with the transfer standard provided by the upper-level calibration laboratory.

As described in (c), uncertainty is dependent on the DUT. For uncertainty in a typical power sensor (Agilent 8482A) and a 30-dB attenuator, for example, the worst value is

±4.2% (inclusion coefficient k = 2). For other types of DUT, the reflection coefficient of the DUT is measured and the value obtained is used to calculate uncertainty.

4.2 RF attenuator

4.2.1 Introduction

The scope of DUT calibration of the accredited RF attenuator calibration systems covers the attenuation ranges of 0 dB to 90 dB (10 MHz to 10 GHz) and 0 dB to 60 dB (18 GHz). Following is a discussion of the definition of attenuation, the calibration procedure, and uncertainty assessment.

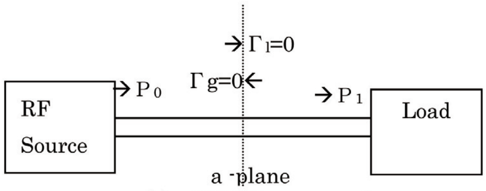
4.2.2 Definition of attenuation

As illustrated in Fig. 4 (a), when the power supplied from the power source to the load via a matched transmission line is defined as P_1, and a dual-aperture element is then inserted on plane a ($\Gamma g = \Gamma l = 0$) shown in Fig. 4 (a), the power supplied to the load is defined as P_2 as shown in Fig. 4 (b). Under these conditions, attenuation A (dB) can be expressed by the following formula[7].

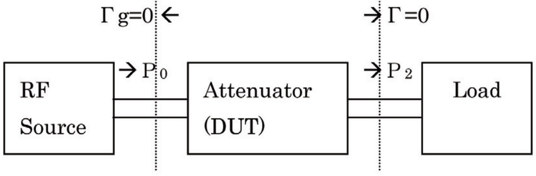
$$A = 10 \log_{10}(P_1 / P_2) \qquad \text{(dB)} \qquad (7)$$

4.2.3 Calibration method

Figure 5 shows a block diagram of the system used for the calibration of an RF attenuator with a frequency range of 10 MHz to 18 GHz.



(a) DUT disconnected



(b) DUT connected

Fig.4 Definition of attenuation

The receiving section consists of a frequency converter (TEGAM 8852) developed for attenuator measurement and a receiver (TEGAM VM-7) for the measurement of a 30 MHz intermediate frequency level. The attenuator under calibration is connected between two matching attenuators.

If the DUT is a fixed attenuator, the difference between the measurement value obtained with the test attenuator inserted and the measurement value obtained without the test attenuator is determined as the calibration value.

If the DUT is a stepped attenuator, the difference between the measurement value obtained in the “through” condition (attenuation set to 0) and the measurement value obtained when attenuation is added is determined as a calibration value.

4.2.4 Estimation of uncertainty of calibration

(1) The case of a stepped attenuator

The factors causing RF attenuator calibration uncertainty and their values are shown in Table 3.

For factor (b) in Table 3, we divided the least significant digit of the indicated value on the measuring instrument by two. For factor (c), actual measurement (based on the results of 20 repeated measurements) was used. Factor (d) was calculated based on actual measurements and in accordance with reference document[8]. We confirmed that factor (e) was included in measurement deviation and in the 1/2-digit error based on actual measurements; therefore, we determined this factor to be zero. For factor (f), our examination of the previous upper-level calibration results showed no noticeable effects. Thus, we determined the aging change value as zero, but we adopted the largest threshold value in order to take fluctuation into consideration. Although there were no previous calibration values for 70 dB, 80 dB, and 90 dB, we used this same threshold value. In actual calibration, the value of (d2) is obtained in actual measurement of the DUT attenuator.

Here, the best measurement capability in calibration is calculated using the values in the

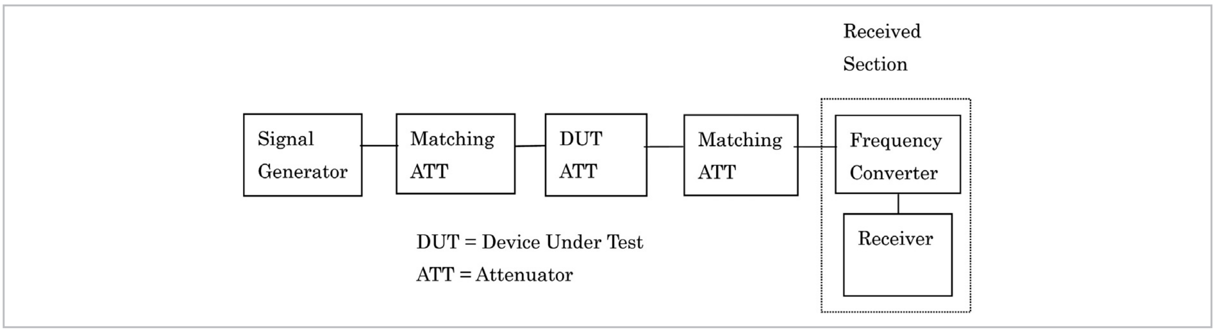


Fig.5 Block diagram of calibration system for RF attenuator with a frequency range of 10 MHz to 18 GHz

Table 3 Calibration uncertainty for stepped attenuator with a frequency range 10 MHz to 10 GHz at 10, 20, 30, 40, 50, 60, and 70 dB

Uncertainty factor	Contribution (± dB)	Distribution type
(a) Uncertainty of transfer-standard attenuator calibration as determined by NMIJ	0.01 (k=2)	Normal
(b) Digital resolution (1/2-digit error)	0.005	Uniform
(c) Measurement deviation in attenuator calibration(*)	0.006	Normal
(d1) Mismatch in transfer-standard attenuator(*)	0.03	U-shaped
(d2) Mismatch in DUT attenuator calibration(*)	Actual measurement	U-shaped
(e) Fluctuation due to deviation from upper-level calibration environment (temperature) of transfer standard	0	Uniform
(f) Aging change	0.02	Uniform

(*) Dependent on frequency. Worst value.

above table, as shown below. In this calculation, we assumed that the uncertainty due to the mismatch of the DUT (d2) was the same as the uncertainty due to the mismatch of the transfer standard (d1). The combined standard uncertainty is as follows.

$$U_{\max} = \sqrt{(\mathrm{a}/2)^2 + 2(\mathrm{b}/\sqrt{3})^2 + 2\mathrm{c}^2 + (d_1/\sqrt{2})^2 + (d_2/\sqrt{2})^2 + (\mathrm{e}/\sqrt{3})^2 + (\mathrm{f}/\sqrt{3})^2} \qquad (8)$$

Since (d1) and (d2) are the same and (e) is 0, the above formula can be rewritten as follows:

$$U_{\max} = \sqrt{(0.01/2)^2 + 2\times(0.005/\sqrt{3})^2 + 2\times 0.006^2 + 2\times(0.03/\sqrt{2})^2 + 0 + (0.02/\sqrt{3})^2} = 0.034 \qquad (9)$$

According to this formula, the best measurement proficiency is 0.068 dB (k = 2).

It should be noted that, in practice, the uncertainty of the DUT is calculated using actual measurement of the contributing factor (d2) for the DUT.

Uncertainty for 80 dB and for 90 dB is shown in Table 4. In this case, the best measurement capability is 0.26 dB (k = 2).

Uncertainty for 18 GHz is shown in Table 5. In this case, the best measurement capability is 0.11 dB (k = 2).

(2) Calculation of uncertainty due to mismatch in stepped attenuator

Using the network analyzer, we measured the reflection coefficient Γ_G on the signal side; the reflection coefficient Γ_L on the receiver side; S_{11}, S_{22}, and S_{21} in the through condition for the stepped attenuator; and S_{11}, S_{22}, and S_{21} in the state in which the attenuation value was

Table 4 Calibration uncertainty for step attenuator with a frequency range of 10 MHz to 10 GHz at 80 dB, 90 dB

Uncertainty factor	Contribution (± dB)	Distribution type
(a) Uncertainty of transfer-standard attenuator calibration as determined by NMIJ	0.02 (k=2)	Normal
(b) Digital resolution (1/2-digit error)	0.005	Uniform
(c) Measurement deviation in attenuator calibration(*)	0.014	Normal
(d1) Mismatch in transfer-standard attenuator(*)	0.126	U-shaped
(d2) Mismatch in DUT attenuator calibration(*)	Actual measurement	U-shaped
(e) Fluctuation due to deviation from upper-level calibration environment (temperature) of transfer standard	0	Uniform
(f) Aging change	0.02	Uniform

(*) Dependent on frequency. Worst value.

Table 5 Calibration uncertainty for step attenuator at a frequency of 18 GHz at 10, 20, 30, 40, 50, 60 dB

Uncertainty factor	Contribution (± dB)	Distribution type
(a) Uncertainty of transfer-standard attenuator calibration as determined by NMIJ	0.01 (k=2)	Normal
(b) Digital resolution (1/2-digit error)	0.005	Uniform
(c) Measurement deviation in attenuator calibration(*)	0.006	Normal
(d1) Mismatch in transfer-standard attenuator(*)	0.05	U-shaped
(d2) Mismatch in DUT attenuator calibration(*)	Actual measurement	U-shaped
(e) Fluctuation due to deviation from upper-level calibration environment (temperature) of transfer standard	0	Uniform
(f) Aging change	0.02	Uniform

(*) Dependent on frequency. Worst value.

applied. When attenuation was 10 dB to 70 dB, the uncertainty Ms due to mismatching of the step attenuator was calculated using formula (1) (formula 16 in reference document[8]).

Note that we determined that $S_{12} = S_{21}$. Symbol b indicates the through condition, while symbol e indicates the state in which the attenuation value is applied.

$$M_S = 10\log_{10}\left|\frac{(1-\Gamma_G s_{11e})(1-\Gamma_L s_{22e})-\Gamma_G\Gamma_L s_{12e}s_{21e}}{(1-\Gamma_G s_{11b})(1-\Gamma_L s_{22b})-\Gamma_G\Gamma_L s_{12b}s_{21b}}\right|^2 \quad (10)$$

When the attenuation is 80 dB to 90 dB, Γ_G cannot be measured. Therefore, the mismatch Ms of the step attenuator is calculated using the catalog value (SWR = 2) in formula (11) (formula 2 in reference document[7]).

$$M_S = \frac{8.686}{\sqrt{2}}\sqrt{|\Gamma_G|^2\left(|S_{11b}|^2+|S_{11e}|^2\right) + |\Gamma_L|^2\left(|S_{22b}|^2+|S_{22e}|^2\right) + |\Gamma_G|^2|\Gamma_L|^2\left(|S_{21b}|^4+|S_{21e}|^4\right)} \quad (11)$$

(3) The case of a fixed attenuator

With a fixed attenuator, measurement deviation in attenuator calibration is approximately 10 times greater than with a step attenuator. Furthermore, because the formula for the calculation of uncertainty due to mismatch in the fixed attenuator uses an absolute value without taking the phase component into consideration, as shown below, the calculated uncertainty value becomes greater. Since digital resolution affects both the standard attenuator and the DUT attenuator, the degree was set to 2.

Uncertainty Ms due to mismatch in the fixed attenuator is calculated as follows.

Using the network analyzer, we measured the reflection coefficient Γ_G on the signal side; the reflection coefficient Γ_L on the receiver side; and S_{11}, S_{22}, and S_{21} of the fixed attenuator. We then calculated the uncertainty Ms due to the mismatch in the fixed attenuator using the following formula. When the attenuation is 80 dB to 90 dB, Γ_G cannot be measured; therefore, we used the catalog value (SWR = 2).

$$\begin{aligned}
M_{S1} &= 20\log_{10}(1+|\Gamma_G|\cdot|\Gamma_L|)\\
M_{S2} &= 20\log_{10}(1+|\Gamma_G|\cdot|S_{11}|)\\
M_{S3} &= 20\log_{10}(1+|\Gamma_L|\cdot|S_{22}|)\\
M_{S4} &= 20\log_{10}(1+|\Gamma_G|\cdot|\Gamma_L|\cdot|S_{21}{}^2|)\\
M_S &= \sqrt{M_{S1}{}^2+M_{S2}{}^2+M_{S3}{}^2+M_{S4}{}^2}
\end{aligned} \quad (12)$$

The following shows the value of fixed RF attenuator calibration uncertainty in each range calculated based on the above results.

Table 6 *Fixed RF attenuator calibration uncertainty (typical values)*

Frequency	Attenuation（dB）	Uncertainty（k=2）
10MHz－10GHz	10,20,30,40,50,60,70dB	0.13dB
	80,90dB	0.33dB
18GHz	10,20,30,40,50,60dB	0.11dB

4.3 Calibrator[9]-[11]

4.3.1 Theory of calibration

The calibrator used as a reference standard in the calibration described in this paper generates DC voltage/current and AC voltage/current.

For DC voltage, the gain of hybrid reference amplifiers with excellent linearity is zero-adjusted, and its calibration is conducted at the maximum reading point. Then, the linear gain is determined by applying interpolation based on collinear approximation. Next, pulse-width modulation is applied to the reference voltage in order to generate the desired DC voltage through rectification and adjustment (i.e., division or amplification).

The range gain constants for the DC±11 V range and the DC±22 V range are determined through direct comparison of the output value of the external 10 V voltage standard with the output value of the built-in 11/22 V-range hybrid reference amplifier, which features excellent freedom drift and hysteresis characteristics. For output values in other ranges, use of a range-switching amplifier and a divider offering specifications that guarantee extend-ed-time stability should maintain the range conversion values verified at the factory prior to shipment.

AC voltage is supplied directly from the built-in AC/DC transfer standard. This output is independent, and is locked in a calibrated state traceable to NIST at the factory prior to shipment.

The output of DC/AC current is based on Ohm's law with reference to the voltage that appears across the resistance, evaluated through comparison with an external standard resistor.

However, to check AC current output, an AC/DC transfer process is employed to convert the AC current to DC. Since an unavoidable conversion error occurs in this process and low-frequency currents, including voltage, are strictly speaking nonlinear, we must acknowledge that it is not possible to extend the AC voltage/current based on the measurement method due to the difficulty of applying interpolation.

Traceability of each output value to exclusive selected values is ensured by direct point calibration conducted by an accredited calibration laboratory.

Furthermore, the internal DC voltage references (6.5 V and 13 V voltage standards consisting of the zener diodes) and the resistance references (1.0 Ω and 1.9 Ω resistance standards) are directly evaluated by the external voltage standard and external standard resistor, and these references are used when output values are checked.

4.3.2 Calibration method

To calibrate calibrators, output from our transfer standard (JCSS and ASNITE calibration standard) and output from the DUT are compared by indicators, which consists of a digital multimeter (DMM) or a combination of a DMM and current shunt. Each calibration point is calibrated by an upper-level calibration laboratory [Japan Electric Meters Inspection Corporation (JEMIC)]. Following is a description of the simplified procedure.

(1) The output of the DUT is set to the requested calibration value, G_{DUT}, and the value indicated on the DMM is read.

(2) The DUT is replaced with the transfer standard.

(3) The output of the transfer standard is adjusted such that it is equal to the value indicated for the DMM, as measured in step (1). The output value G_{STD} of the transfer standard is corrected after adjustment using the upper-level calibration value, G_S (nominal value G_{STD0}), to obtain the calibration value Gc.

$$G_C = G_{STD} * G_S / G_{STD0} \qquad (13)$$

Here, the current is converted to a voltage by the shunt inside the DMM, and it is measured as a voltage value. It is then converted to a current value and indicated. For the calibration of DC 10 A, an additional current shunt is connected externally for voltage measurement as shown in Fig. 6.

4.3.3 Estimation of uncertainty of calibration

Measurement uncertainty can be calculated based on (a) uncertainty of the calibration system, (b) uncertainty of the transfer standard, (c) stability of the calibration system, (d) measurement deviation, (e) DMM digit reading error, (f) DMM resolution error, and (g) effect of thermal electromotive force (EMF).

For (a), uncertainty of the calibration system, the equipment manufacturer supplies uncertainty data traceable to the National Institute of Standards and Technology (NIST) in the United States. This uncertainty includes calibrator stability, the temperature coefficient, linearity, line regulation, and load regulation in a range from full load to no load, as well as calibration uncertainty for external standards (i.e., manufacture's transfer standards: standard DC voltage generator, two standard resistors). For this uncertainty, the absolute uncertainty specification (95% value) for a one-year period after the last external calibration is used.

As for (b), uncertainty of our transfer standards, the calibration certificate issued by the upper-level calibration laboratory provides uncertainty data of k = 2 for each calibration

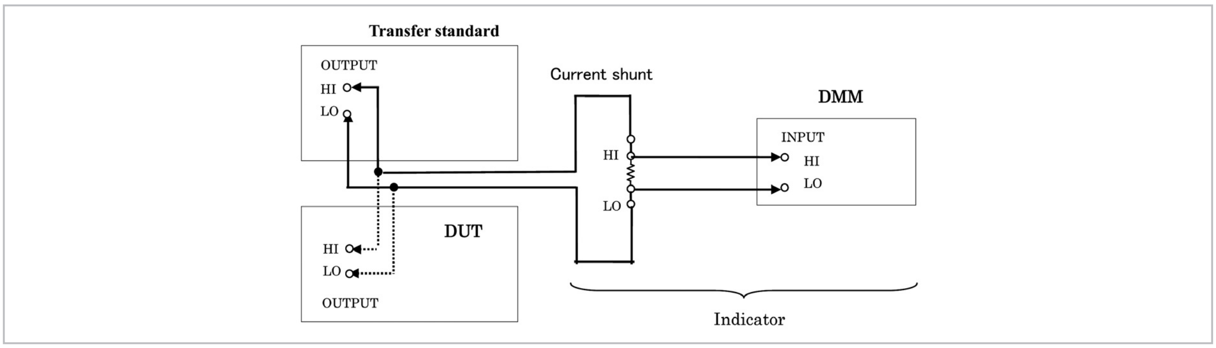


Fig.6 Example of generator calibration method (current shunt is used only for 10 A current)

point.

For (c), stability of the calibration system, the standard deviation calculated using the actual measurement of the value generated by the calibrator (for more than 15 continuous minutes) obtained with the DMM is used.

For (d), measurement deviation, the standard deviation in five measurements conducted under the procedure used in actual measurement is adopted [t-distribution]

For (e), DMM digit reading error, and (f), DMM resolution error, the uniform distribution of the ±1/2-digit error in the least significant digit of each indication is used.

For (g), the effect of thermal EMF, the value is estimated based on the test lead thermal EMF specification (1.3 μV/°C or lower) and the uniform distribution of the temperature difference between the transfer standards and the DUT. For the temperature difference between the transfer standard and the DUT, a value of 1.4°C is used as a normal measurement taken at the base of the binding post after power is turned on and immediately before the start of calibration, since the temperature difference is expected to be greatest at that time. In the case of DUT calibration in which the temperature difference may be greater than this value, it is necessary to recalculate uncertainty. The maximum standard temperature difference after six seconds from the test lead connection is less than 0.3°C. Furthermore, this temperature difference occurs on a contact surface; hence, its effect becomes negligible over time.

Based on the above, the calibration uncertainty, Um (k = 2), can be calculated using the following formulas.

$$U=\sqrt{\begin{aligned}&(\text{Uncertainty of calibration system}/2)^2\\&+(\text{Uncertainty of transfer standards}/2)^2\\&+(\text{Stability of calibration system})^2\\&+(\text{Measurement deviation})^2\\&+(\text{DMM 1/2 effective digit reading error}/\sqrt{3})^2\times 2\\&+(\text{DMM resolution}/\sqrt{3})^2\times 2\\&+(\text{Effect of thermal EMF}/\sqrt{3})^2\end{aligned}} \tag{14}$$

$$Um = 2\times U \qquad (k=2) \tag{15}$$

Examples of uncertainty calculation are shown in Table 7 (JCSS) and Table 8 (ASNITE).

5 Future plans

Through recent accreditation activities, we were able to obtain a variety of useful information, including a determined lack of clarity in the documentation of procedures and neglected uncertainty factors. In the future, we must work to maximize the quality system to ensure the provision of high-quality, accurate calibration results and also to maintain and to improve calibration quality.

We were granted accreditation for three equipment types: the calibrator, RF power meter, and RF attenuator, but our group offers calibration services for other types of equipment as well. We plan to obtain JCSS accreditation for antennas subject to increasing demands for calibration. For RF power meters and RF attenuators, for which we have

Table 7 *Uncertainty of calibrator calibration (JCSS) (typical values)*

DC

Item	Voltage			Current		
	1V	10V	100V	0.1A	1A	10A
Uncertainty (k = 2)	±9.7μV	±81μV	±960μV	±7.6μA	±110μA	±4100μA

AC

Item	Voltage		Current			
	100V		1A		10A	
	50Hz, 60Hz	400Hz	50Hz	60Hz	50Hz	60Hz
Uncertainty (k = 2)	±10mV	±9.8mV	±0.70mA	±0.70mA	±5.2mA	±5.1mA

Table 8 *Uncertainty of calibrator calibration (ASNITE) (typical values)*

AC Current

Item	200μA			2mA		
	1kHz	5kHz	10kHz	1kHz	5kHz	10kHz
Uncertainty (k = 2)	±54nA	±170nA	±410nA	±440nA	±1700nA	±4100nA
Item	20mA			200mA		
	1kHz	5kHz	10kHz	1kHz	5kHz	10kHz
Uncertainty (k = 2)	±4.2μA	±17μA	±41μA	±42μA	±170μA	±410μA

received accreditation, there is increasing demand for the calibration in higher frequency ranges; therefore, we intend to expand the scope of calibration in specific steps. To that end, maintaining traceability in Japan is of the utmost importance. In this regard, we intend to work closely with the National Institute of Advanced Industrial Science and Technology (AIST), a main supplier of measurement standards.

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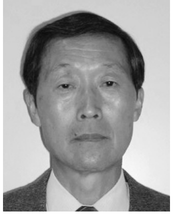

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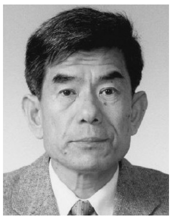

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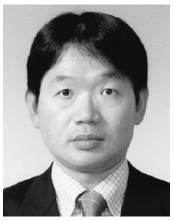

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