3-3 SAR Measurement and Uncertainty Estimation

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This article describes about the uncertainty evaluation of Specific Absorption Rate (SAR) assessment of a portable wireless device with an instance such as a cellular phone device, which is required in a compliance test of the portable wireless device to guideline limits in terms of SAR in the radio law.

1 Introduction

Specific Absorption Rate (SAR) is one index for assessing EMF exposure from devices and equipment that emit electromagnetic waves, such as wireless mobile devices and base stations and so on. In Japan and overseas, SAR guidelines are established to protect against electromagnetic waves [1]. Tests to evaluate compliance with those limit values (SAR tests) are performed in accordance with standards and regulations in Japan and overseas [2]–[5]. Chapter **2-7** described SAR probe calibration for these compliance tests. This chapter describes research on SAR measurement methods performed at NICT, and evaluation of its uncertainty in compliance evaluation.

For wireless devices used globally such as mobile phones, if tests are performed under each country's own conditions, then depending on the country, the compliance evaluation results can differ for the same device. This not only becomes a barrier to international trading, it also makes it difficult to obtain reliable safety evaluation. Therefore, SAR measurement methods for mobile devices and so on are standardized internationally, and tests are also performed internationally under the same measurement conditions.

SAR measurement methods are formulated to enable highly reliable confirmation that mobile phones being tested comply with radio radiation protection guidelines. Verification of the measurement systems and evaluation of their uncertainty is raised as an important requirement to ensure reliability. International standards specify in detail the uncertainty evaluation items and methods to evaluate each uncertainty source. Also, system verification is specified that compares SAR measured values with reference values determined by numerical calculation under simple conditions. In addition to high reliability for compliance evaluation methods, it must also be possible to perform them with simple devices and procedure.

NICT is the only national institute promoting research on exposure evaluation of electromagnetic fields in Japan. NICT studies uncertainty evaluation and verification of the exposure evaluation, thus contributing to establishment of international standards, domestic standards, report on inquiry commission, and so on. This paper explains system verification and uncertainty evaluation for SAR measurement systems, including evaluation examples at NICT. Details about measurement methods are described in [2] and [3], therefore this paper will only outline them, and focus on methods to evaluate uncertainty and so on. Unless specifically mentioned otherwise, this paper evaluates 10 g local SAR in accordance with the evaluation index of radio radiation protection guidelines [1].

2 Definitions

2.1 Radio radiation protection guidelines [1]

When using electro-magnetic waves, the human body is affected by them (protection guidelines only cover the frequency range from 10 kHz to 300 GHz). These are recommended guidelines for safe conditions where those electro-magnetic waves do not have possible undesirable biological effects on the human body.

2.2 Specific Absorption Rate (SAR) [1]

SAR is defined below. It is electric power absorbed by biological tissues.

The SAR in media (phantom liquid, and so on) that has loss is related to both the electric field (E), and the gradient of changes over time of temperature (dT/dt) in media. Therefore, the equation below is provided based on this relationship.

$$SAR = \sigma \frac{E^2}{\rho} = c_k \frac{dT}{dt}\Big|_{t=0} \quad (1)$$

Here, the variables are:

σ Conductivity
ρ Density of the media
C_k Specific heat

Electric fields in media with loss can also be measured indirectly by measurement of temperature gradients inside.

2.3 Local exposure guideline [1]

The guideline is used for electromagnetic fields that have a partial absorption on part of the human body, caused by electromagnetic waves emitted from, for example, wireless devices used very close to the human body.

2.4 Local SAR [1]

SAR is provided as a number per very small volume element. It has a spatial distribution function dependent on the place in the biotissues, and radiation conditions of the electro-magnetic waves. For this distribution, SAR averaged over the localized volume containing a certain mass of tissue such as 1 g or 10 g is called local SAR; the maximum value within this is called local peak SAR. However, in assessing compliance with guidelines to protect against electric fields in Japan, it is defined as a 10 g cube of tissue, and assessed as an average over any length of time. In Japan, this is the average over 6 minutes.

2.5 Phantom [1]

This is a quasi-human body model used to estimate SAR experimentally. If the same material is used across the entire model, then it is called a uniform phantom. If it faithfully models the electrical characteristics for each corresponding tissue, then it is called an inhomogeneous phantom. This measurement method uses a uniform phantom comprised of an outer shell (container) to model the human body shape, and the liquid that fills it (phantom liquid). Among phantoms used in compliance evaluation, there is the Specific Anthropomorphic Mannequin (SAM) used for the head, and the device evaluation flat phantom used for the body other than the head.

3 SAR measurement principles and compliance evaluation methods of wireless Device [1]–[5]

As shown in Equation (1), SAR can be measured from electric field strength or temperature rise in the phantom. However, wireless mobile devices actually used such as mobile phones have relatively small output power, therefore detectable temperature rise does not occur in such devices. Therefore, in compliance tests, evaluation methods that use electric field strength measurements with more sensitivity are used. An outline of an evaluation method is described as follows.

First, a phantom shell that simulates a human head or body is filled with phantom liquid, and test equipment is set at the phantom. Next, test equipment is set to continually transmit maximum output power during measurement, by using a base station simulator or device test mode. With this setup, a miniature electric field probe scans in the phantom liquid, and from the relationship in Equation (1), measured electric field strength is used to obtain the SAR maximum value. This is compared to the SAR limit value to evaluate compliance. Figure 1 shows a measurement system outline. Japanese and foreign standards specify the sizes and shapes of the standard head phantom (SAM) and flat phantom, the positioning of wireless devices, and dielectric constants of the phantom liquid.

4 Evaluation of uncertainty of SAR measurements, and measurement system validation tests [1][2]

Verification of the validity of measurement equipment by measurements using a standard antenna is called system validation. System validation tests can be a comprehensive

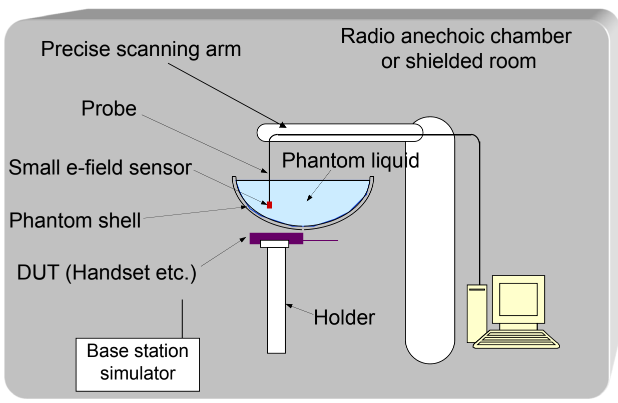

Fig. 1 SAR Measurement System Outline

system validation test to confirm operation of measurement devices and ensure measurement accuracy (system validation), or a simple performance test for a simple check of reproducibility of measurements (system check). International standards and so on require that a system validation shall be performed at least once per year (if the system is repaired, modified, calibrated and so on, then also immediately afterward).

In system validation, an antenna with specified dimensions is used as a standard wave source. The antenna's position relative to the phantom is also specified. In system validation, SAR measurement values for a standard antenna installed in a specified position are compared against reference values shown in the standards and so on, to check validity. Reference values shown in standard values and so on are determined from numerical calculations performed by multiple research institutes.

This paper describes an example of system validation using a standard dipole antenna, for an example of evaluation of uncertainty of SAR measurements.

4. 1 Procedure for system validation

① Construction of validation system

Evaluation is performed using a flat phantom of the bottom (in this paper, a phantom with flat bottom and round wall (ELI phantom made by SPEAG) is used) and a standard antenna.

The test environment's required conditions are: in a shielded room or anechoic chamber, and so on, room temperature 18 to 25 °C, and temperature change of the liquid should not exceed ±2 °C from before to after evaluation.

First, while checking the level of the liquid, adjust the heights of the phantom shell's legs, so the bottom of the phantom used in evaluation is horizontal to the floor. Next, fill the phantom shell with phantom liquid.

Figure 2 shows an evaluation system using a dipole antenna as the standard wave source. Spacers are used to adjust distance between the element and phantom, set at 15 mm for lower than 1 GHz, or 10 mm for higher than 1 GHz. Figure 3 is a photo of the elliptical phantom used.

② Measurement of S_{11} of dipole antenna

Use a network analyzer to measure S_{11} of the dipole antenna. When a phantom is filled with phantom liquid, check that S_{11} is −20 dB or less as specified in the standard.

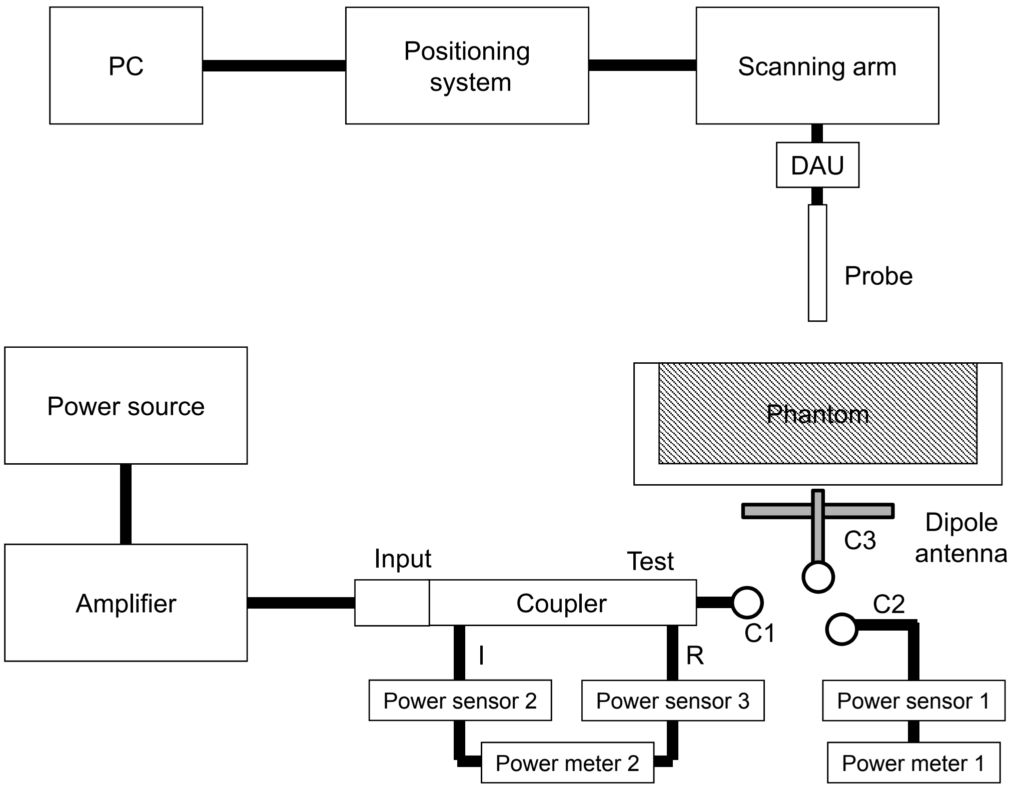

Fig. 2 Evaluation System Components

③ Determination of power supplied to the dipole antenna

Use the steps below to adjust the power value at the dipole antenna input port (C1 port in Fig. 2), so incident power is a fixed value within the range ±0.1 dBm during the test. Incident power is kept 24.0 dBm at lower than 1 GHz, or 22.0 dBm above 1 GHz in NICT.

(a) Connect C1 to C2, and adjust the signal generator's output level so the incident power of the read of power meter 1 connected to C1 port is at the desired level.

(b) When adjustment of the signal generator described in (a) is completed, adjust by applying the offset to the read of power sensor 2, so the read of power meter 2 connected to the directionality coupler's I port is the same as the read of power meter 1. That is, set power sensor 2's read value so it shows the incident power into C1 port.

(c) During the measurement, connect C1 to C3, and adjust the signal generator's output level, so the read of power meter 2 (= incident power into C1 port) is the desired level. The read at power sensor 3 on the R port side is not used directly in output adjustment, but check its values frequently to confirm whether there are abnormal reflections during the measurement.

Fig. 3 Flat phantom (Elliptical Shape)

④ In the settings described above, measure local SAR in the SAR measurement system, and for the 10-g SAR is obtained by considering the antenna's S_{11} value measured in ① and normalizing the incident power into the dipole to 1 W. Compare this measurement result against the SAR reference value in the standard, and check that both values are in good agreement within uncertainty of the system validation, to confirm that the system is operating properly.

4.2 Example of uncertainty evaluation of system validation

Based on the uncertainty budget in IEC62209–1 [4], uncertainty of the system validation was evaluated. Evaluation methods of each item are shown below. The probability distributions in the uncertainty budget table are N: Normal distribution, and R: Rectangular distribution (uniform distribution).

- Probe calibration

  Use the value in the calibration certificate, and so on. This time, the uncertainty of calibration performed at NICT (refer to Chapter **2-7** for calibration uncertainty of the SAR probe) was used. A normal probability distribution was used.

- Uncertainty of Dielectric Constant Measurements of Phantom liquid

  Evaluation was performed based on the budget shown in Table 1. Detailed evaluation methods for each item are described below. A normal probability distribution was assumed.

Table 1 Uncertainty of dielectric constant measurements of phantom liquid

	a		*b*	*C*	$u_i = (a/b) \times (c)$	
Source of uncertainty	Uncertainty value (± %)	Probability distribution	Divisor	Sensitivity factor c_i	Standard uncertainty (± %)	Degrees of freedom v_i or v_{eff}
Repeatability of measurements		N	1	1		*N*-1
Deviation from standard value of dielectric constant (εr′ or *σ*)		R	$\sqrt{3}$	1		*N*-1
Network analyzer uncertainty, and so on		R	$\sqrt{3}$	1		∞
Combined expanded uncertainty						

① Repeatability of Measurements

Measure permittivity and conductivity 10 times, and the standard deviation obtained is divided by the average value measured, to obtain the tolerance value. A normal probability distribution was used.

② Deviation from Standard Value of Dielectric Constant

For tolerance values, derive the standard deviations of the average values of permittivity and conductivity measured above, and of the target values of dielectric constants of each phantom liquid. At NICT a rectangular probability distribution was used.

③ Uncertainty of Network Analyzer, and so on

Uncertainty evaluation software that employs the Monte Carlo method, developed by NPL in the UK, was used to derive measurement uncertainty of the network analyzer. A rectangular probability distribution was used.

- Probe isotropy

If measuring an actual device, the polarization direction of the incident electromagnetic wave is unknown and may differ from the polarization in probe calibration. Accordingly, both axial isotropy and hemispherical isotropy shall be considered. Equation (2) derives uncertainty of probe isotropy.

$$\mathrm{u}_{\mathrm{isotoroy}}[\%] = 100 \times \sqrt{(1-w_j) \times \mathrm{u}_{\mathrm{axialisotoroy}} + w_j \times \mathrm{u}_{\mathrm{hemisphericalisotoroy}}} \quad (2)$$

Here, $u_{axialisotoropy}$ is the axial isotropy of the probe, $u_{hemisphericalisotoropy}$ is the hemispherical isotropy of the probe, and w_i is a weighting function.

These measurements were performed to satisfy the conditions that the axis of the probe is within ±30° from the normal vector direction of the phantom surface when f ≤ 3 GHz, and ± 20° when 3 GHz < f ≤ 6 GHz. Therefore, w_i = 0.5 is used in principle based on IEC 62209−1. For probe axial isotropy and hemispherical isotropy, values from the uncertainty budget in the manufacturer's manual of the SAR measurement system (axial isotropy: 4.7 %, hemispherical isotropy: 9.6 %) [6] were used. In this case, the value of probe isotropy is 7.69 ($k = 2$). A detailed evaluation method for probe isotropy is in IEC62209−1 B.4 Isotropy [4]. A rectangular probability distribution was used.

- Boundary effect

When the probe tip is close to the boundary surface between the different dielectric materials such as a phantom surface, boundary effect is observed, that is, the probe sensitivity differs from "true" sensitivity due to the electrical coupling between these dielectric materials.

Uncertainty of the boundary effect is derived from Equation (3) and (4) below.

$$\mathrm{SAR}_{\mathrm{tolerance}}[\%] = \Delta\mathrm{SAR}_{\mathrm{be}}[\%]\frac{\left(d_{be}+d_{step}\right)^2}{2d_{step}}\frac{\left(e^{-d_{be}/(\delta/2)}\right)}{\delta/2},$$

$$\left(d_{be}+d_{step}\right)<10\mathrm{mm}\ \delta \text{ and } f \leq 3\mathrm{GHz} \quad (3)$$

$$\mathrm{SAR}_{\mathrm{uncertainty}}[\%] = \Delta SAR_{\mathrm{be}}[\%]\frac{\delta}{\delta\text{ -}d_{\mathrm{be}}},\ d_{be}<\delta \text{ and } f > 3\mathrm{GHz} \quad (4)$$

Here, d_{be} mm is the distance from the surface to the closest volume-scan measurement point. d_{step} mm is the distance from the measurement point noted above to the closest measurement point. δ mm is the skin depth in the phantom liquid. ΔSAR_{be} [%] is the difference between the SAR theoretical value and measured value in the calibration waveguide obtained from Equation (7) in Chapter **2-7** at distance d_{be}.

- Probe linearity

As described in Chapter **2-7**, in SAR measurements, calibration is performed due to non-linearity of the diodes of the probe and so on. Probe linearity after calibration is evaluated as a linear approximation, for the relationship between input power and SAR measurement value in a range including input power where SAR is from 0.12 W/kg to 100 W/kg. The difference between the SAR approximation value obtained from this linear approximation, and the SAR measurement value, is the uncertainty of linearity. This paper uses the value of uncertainty of probe linearity in the certificate of the SAR probe manufacturer (1.5 %). A normal probability distribution was used.

- Probe detection limit

The detection limit of linearity of the probe described above is evaluated by the difference between the SAR measurement value with or without linear approximation at a certain input power (in [4], the S/N ratio is 6 dB). This paper uses the value (1.0 %) of the uncertainty budget in the manual of SAR measurement system manufacturer [6]. A normal probability distribution was used.

- Modulation response

  The system validation this time is not carried out using a modulated signal, therefore the value 0 % is used.

- Step response time

  In this paper, measurements were basically made on a continuous wave basis, and based on the specifications of international standards, 0 % was used.

- Integration time of signal

  In SAR measurements, time integration processing of signals is performed, but for usual continual waves such as pulse waveforms and burst waveforms, uncertainty of signal integration time must be considered separately. Since continuous wave is measured in this paper, and the duration of SAR measurement per point is sufficiently long, about 500 ms, compared to signal frequency and probe response time, uncertainty of integration time is negligible.

- RF ambient environment noise

  Use values of SAR measurement while there is no RF input. Use a rectangular probability distribution. In this paper actual SAR measurement without RF signal was not used. Instead, as the worst case evaluation, the value of 0.012 W/kg, specified as the detection lower limit in the standard, was used.

- RF ambient environment reflection

  During SAR measurements, place the electromagnetic wave absorber close to the dipole antenna, and compare the SAR measurement result values to measurements taken under ordinary conditions. A rectangular probability distribution was used.

- Mechanical restrictions of probe scanning device

  When the probe is installed to the robot arm, differences between the actual position of the probe (sensor) and the position recognized by the robot control system occurs, due to the robot's limited precision. In this mechanism, for this item, the uncertainty of position precision in the horizontal direction was evaluated.

$$\mathrm{SAR}_{\mathrm{uncertainty}}[\%]=\frac{d_{\mathrm{ss}}}{\delta/2}\times 100 \tag{5}$$

  Here, d_{ss} is the maximum value of error between the probe positions that the robot's control system determined and the actual probe position. From the specification of position accuracy of the robot, 0.2 mm was used as the maximum distance error. A rectangular probability distribution was used.

- Positional accuracy for phantom shell

  Equation (6) below provides the accuracy of determining probe positions at the phantom surface in the normal direction toward the shell inner surface of the phantom. This paper evaluated position accuracy in the normal direction.

$$\mathrm{SAR}_{\mathrm{uncertainty}}[\%]=\frac{d_{\mathrm{ph}}}{\delta/2}\times 100 \tag{6}$$

  Here, d_{ph} also includes uncertainty of the surface detection sensor of the probe, and therefore it represents the maximum distance error between the phantom surface and probe tip. The value provided in the manual of the SAR measurement device is employed. A rectangular probability distribution was used.

- Post-processing of data

  The value (2.0 %) of the uncertainty budget in the manual of the manufacturer of the SAR measurement system [6] was used. A normal probability distribution was used.

- Difference between actual dipole antenna and numerical model of dipole antenna used for the calculation of reference value

  This evaluation is for uncertainty concerning the difference between the actual antenna dimensions and so on used in the test, and the numerical antenna model used to determine the reference values provided in specifications. For example, evaluation is possible using the calibration certificate provided by the manufacturers of that standard antenna, and so on. Here, the values of the uncertainty budget in the SAR measurement system manufacturer's manual [6] were used. A normal probability distribution was used.

- Incident power drift

  Measure the drift of incident power during measurement. A rectangular probability distribution is used.

- Distance between wave source and phantom liquid

  In IEC 62209–1 [4], this is treated as "Other contributions related to standard source." This is equivalent to positioning and manufacturing errors of a standard dipole antenna. It can be derived by Equation (7).

$$\mathrm{SAR}_{\mathrm{tolerance}}[\%]=\left(\frac{(a+d)^2}{a^2}-1\right)\times 100 \tag{7}$$

  Here, a is distance between the dipole antenna and phantom, 15 mm at less than 1 GHz, or 10 mm at greater than 1 GHz. d is manufacturing precision of the dipole antenna (0.1 mm). Though IEC62209−1 does not mention uncertainty of spacers manufacturing precision, spacers of less effect on measurement results must be used. A rectangular probability distribution was used.

- Uncertainty of phantom shell

The standard antenna (or handset under test) is positioned at a certain distance separated from the bottom of the phantom shell. Consequently, uncertainty of the thickness of the phantom shell is that of the distance from the wave source to the phantom (phantom liquid), which affects SAR measurement results. Therefore, as in the previous item, use Equation (8) to evaluate uncertainty of phantom thickness. Also, at 3 GHz or higher, this is given by Equation (9), and effects of the dielectric constants of the phantom shell are also considered.

$$\mathrm{SAR}_{\mathrm{tolerance}}[\%] = \left(\frac{(a+d)^2}{a^2} - 1\right) \times 100 \qquad f < 3\mathrm{GHz} \qquad (8)$$

$$\mathrm{SAR}_{\mathrm{tolerance}}[\%] = \sqrt{\left[\left(\frac{(a+d)^2}{a^2} - 1\right) \times 100\right]^2 + \left(5 \times \left|\varepsilon_{r,\,shell} - 4\right|\right)^2}$$

$$3\mathrm{GHz} \le f \qquad (9)$$

Here, $2 \le \varepsilon_{r,\,shell} \le 5$

Here, a is the distance between the phantom liquid and line current of the electric wave source, and d is the tolerance or shape and thickness of the phantom shell. 0.1 mm was used for d, from the specification by the manufacturer. a is a value concerning thickness of the test terminal; this paper used 5 mm typically seen in the literature [4]. Also, $\varepsilon_{r,\,shell}$ is relative permittivity of the phantom shell, taken as 3.7 from the specification by the manufacturer. A rectangular probability distribution was used.

- SAR correction algorithm

In the IEC62209−1 standard, if deviation of the dielectric properties of phantom liquid from that of the standard exceeds 5 % but not more than 10 %, then correction can be applied but that uncertainty shall be evaluated. Here, in this paper, since SAR calibration was not applied for SAR measurements, this was taken as 0.

- Temperature dependency of dielectric constants (conductivity and permittivity) of phantom liquid

Evaluation of temperature dependency of the phantom liquid is derived from Equation (10) below.

$$\varepsilon\_\mathrm{temp\_liquid}_{\mathrm{uncertainty}}[\%] = 100 \times \left| \frac{2 \times \left[\varepsilon_r(\mathrm{T_{high}}) - \varepsilon_r(\mathrm{T_{low}})\right]}{\varepsilon_r(\mathrm{T_{high}}) + \varepsilon_r(\mathrm{T_{low}})} \times \frac{2\ {}^{\circ}\mathrm{C}}{\mathrm{T_{high}} - \mathrm{T_{low}}} \right|$$

$$\sigma\_\mathrm{temp\_liquid}_{\mathrm{uncertainty}}[\%] = 100 \times \left| \frac{2 \times \left[\sigma(\mathrm{T_{high}}) - \sigma(\mathrm{T_{low}})\right]}{\sigma(\mathrm{T_{high}}) + \sigma(\mathrm{T_{low}})} \times \frac{2\ {}^{\circ}\mathrm{C}}{\mathrm{T_{high}} - \mathrm{T_{low}}} \right| \qquad (10)$$

Here, $\varepsilon\_\mathrm{temp\_liquid}_{\mathrm{uncertainty}}$ and $\sigma\_\mathrm{temp\_liquid}_{\mathrm{uncertainty}}$ are the uncertainties of temperature dependency of permittivity and conductivity. ε_r (T_{high}) and ε_r (T_{low}) and σ (T_{high}) and σ (T_{low}) are the permittivity and conductivity at the temperature of T_{high} and T_{low}. T_{high} is 25 °C and T_{low} is 18 °C. Dielectric constant at each temperature was measured 10 times, and their average was used in evaluation. A rectangular probability distribution was used.

Next, Tables 2 to 13 show examples of uncertainty of system validation using a dipole antenna. For uncertainty cited from the calibration certificate and so on, the divisor is 2, assuming a normal distribution. The DASY52 for the SAR measurement equipment, and the EX3DV4 for the probe, both manufactured by Schmidt & Partner Engineering AG (SPEAG) were used. Regarding probe isotropy, in these measurements, the probe was inserted almost vertically to the phantom bottom, thus only the axial isotropy was considered.

Table 2 Example of evaluating uncertainty of system validation using a dipole antenna(733 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	7.68	N	2	1	3.84	∞
Isotropy (axial isotropy)	4.70	R	$\sqrt{3}$	1	2.71	∞
Boundary effect	0.53	R	$\sqrt{3}$	1	0.31	∞
Linearity (k = 2)	1.50	R	2	1	0.75	∞
Detection limits (k = 2)	1.00	N	2	1	0.58	∞
Modulation response	0.00	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.00	N	1	1	0.00	∞
Response time	0.00	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.00	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.09	R	$\sqrt{3}$	1	0.05	∞
RF ambient conditions - reflection	0.41	R	$\sqrt{3}$	1	0.24	∞
Probe positioner mechanical tolerance	0.13	R	$\sqrt{3}$	1	0.08	∞
Probe position with respect to phantom shell	1.03	R	$\sqrt{3}$	1	0.59	∞
Post processing (k = 2)	2.00	N	2	1	1.15	∞
System validation source						
Deviation of experimental source from numerical source	5.50	N	1	0.84	5.50	∞
Input power and SAR drift measurement	0.93	R	$\sqrt{3}$	1	0.54	∞
Other source contribution	1.34	R	$\sqrt{3}$	1	0.77	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	1.34	R	$\sqrt{3}$	1	0.77	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	2.37	R	$\sqrt{3}$	0.71	0.44	∞
Liquid conductivity (measured)	1.10	N	1	0.26	0.78	9
Liquid permittivity (Temperature uncertainty)	0.18	R	$\sqrt{3}$	0.71	0.00	∞
Liquid permittivity (measured)	1.03	N	1	0.26	0.27	9
Combined standard uncertainty		RSS			7.58	
Coverage factor k (95 % confidence level)		1.96				79862
Expanded uncertainty					14.9	

Table 3 Example of evaluating uncertainty of system validation using a dipole antenna(835 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration	8.11	N	2	1	4.06	∞
Isotropy (axial isotropy)	4.70	R	$\sqrt{3}$	1	2.71	∞
Boundary effect	0.50	R	$\sqrt{3}$	1	0.29	∞
Linearity	1.50	R	$\sqrt{3}$	1	0.75	∞
Detection limits	1.00	R	$\sqrt{3}$	1	0.58	∞
Modulation response	0.00	R	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.30	N	1	1	0.30	∞
Response time	0.00	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.00	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.09	R	$\sqrt{3}$	1	0.05	∞
RF ambient conditions - reflection	0.41	R	$\sqrt{3}$	1	0.24	∞
Probe positioner mechanical tolerance	0.14	R	$\sqrt{3}$	1	0.08	∞
Probe position with respect to phantom shell	1.11	R	$\sqrt{3}$	1	0.64	∞
Post processing	2.00	R	$\sqrt{3}$	1	1.15	∞
System validation source						
Deviation of experimental source from numerical source	5.50	N	1	0.84	5.50	∞
Input power and SAR drift measurement	0.46	R	$\sqrt{3}$	1	0.27	∞
Other source contribution	1.34	R	$\sqrt{3}$	1	0.77	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	1.34	R	$\sqrt{3}$	1	0.77	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	1.51	R	$\sqrt{3}$	0.71	0.28	∞
Liquid conductivity (measured)	0.86	N	1	0.26	0.61	9
Liquid permittivity (Temperature uncertainty)	0.07	R	$\sqrt{3}$	0.71	0.00	∞
Liquid permittivity (measured)	1.28	N	1	0.26	0.33	9
Combined standard uncertainty		RSS			7.67	
Coverage factor *k* (95 % confidence level)		1.96				223584
Expanded uncertainty					15.0	

Table 4 Example of evaluating uncertainty of system validation using a dipole antenna(900 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (*k* = 2)	7.41	N	2	1	3.71	∞
Isotropy (axial isotropy)	4.70	R	$\sqrt{3}$	1	3.77	∞
Boundary effect	0.81	R	$\sqrt{3}$	1	2.71	∞
Linearity (*k* = 2)	1.50	R	2	1	0.47	∞
Detection limits (*k* = 2)	1.00	N	2	1	0.75	∞
Modulation response	0.00	N	$\sqrt{3}$	1	0.58	∞
Readout electronics	0.30	N	1	1	0.00	∞
Response time	0.00	R	$\sqrt{3}$	1	0.30	∞
Integration time	0.00	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.29	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - reflection	1.48	R	$\sqrt{3}$	1	0.17	∞
Probe positioner mechanical tolerance	0.17	R	$\sqrt{3}$	1	0.85	∞
Probe position with respect to phantom shell	1.40	R	$\sqrt{3}$	1	0.10	∞
Post processing (*k* = 2)	2.00	N	2	1	0.81	∞
System validation source						
Deviation of experimental source from numerical source	5.50	N	1	0.84	5.50	∞
Input power and SAR drift measurement	0.23	R	$\sqrt{3}$	1	0.13	∞
Other source contribution	1.34	R	$\sqrt{3}$	1	0.77	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	1.34	R	$\sqrt{3}$	1	0.77	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	1.49	R	$\sqrt{3}$	0.71	0.28	∞
Liquid conductivity (measured)	1.32	N	1	0.26	0.94	9
Liquid permittivity (Temperature uncertainty)	0.11	R	$\sqrt{3}$	0.71	0.00	∞
Liquid permittivity (measured)	1.28	N	1	0.26	0.33	9
Combined standard uncertainty		RSS			7.59	
Coverage factor *k* (95 % confidence level)		1.96				38676
Expanded uncertainty					14.9	

Table 5 example of evaluating uncertainty of system validation using a dipole antenna(1,450 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	7.26	N	2	1	3.63	∞
Isotropy (axial isotropy)	4.70	R	$\sqrt{3}$	1	2.71	∞
Boundary effect	0.20	R	$\sqrt{3}$	1	0.12	∞
Linearity (k = 2)	1.50	R	2	1	0.75	∞
Detection limits (k = 2)	1.00	N	2	1	0.58	∞
Modulation response	0.00	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.30	N	1	1	0.30	∞
Response time	0.00	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.00	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.23	R	$\sqrt{3}$	1	0.13	∞
RF ambient conditions - reflection	0.97	R	$\sqrt{3}$	1	0.56	∞
Probe positioner mechanical tolerance	0.19	R	$\sqrt{3}$	1	0.11	∞
Probe position with respect to phantom shell	1.52	R	$\sqrt{3}$	1	0.88	∞
Post processing (k = 2)	2.00	N	2	1	1.15	∞
System validation source						
Deviation of experimental source from numerical source	5.50	N	1	0.84	5.50	∞
Input power and SAR drift measurement	0.69	R	$\sqrt{3}$	1	0.40	∞
Other source contribution	2.01	R	$\sqrt{3}$	1	1.16	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	0.89	R	$\sqrt{3}$	0.71	0.16	∞
Liquid conductivity (measured)	0.82	N	1	0.26	0.58	9
Liquid permittivity (Temperature uncertainty)	0.14	R	$\sqrt{3}$	0.71	0.00	∞
Liquid permittivity (measured)	1.53	N	1	0.26	0.40	9
Combined standard uncertainty		RSS			7.59	
Coverage factor k (95 % confidence level)		1.96				260008
Expanded uncertainty					14.9	

Table 6 Example of evaluating uncertainty of system validation using a dipole antenna(1,624 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	9.12	N	2	1	4.56	∞
Isotropy (axial isotropy)	4.70	R	$\sqrt{3}$	1	2.71	∞
Boundary effect	0.36	R	$\sqrt{3}$	1	0.21	∞
Linearity (k = 2)	1.50	R	2	1	0.75	∞
Detection limits (k = 2)	1.00	N	2	1	0.58	∞
Modulation response	0.00	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.30	N	1	1	0.30	∞
Response time	0.00	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.00	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.23	R	$\sqrt{3}$	1	0.13	∞
RF ambient conditions - reflection	0.97	R	$\sqrt{3}$	1	0.56	∞
Probe positioner mechanical tolerance	0.20	R	$\sqrt{3}$	1	0.12	∞
Probe position with respect to phantom shell	1.62	R	$\sqrt{3}$	1	0.94	∞
Post processing (k = 2)	2.00	N	2	1	1.15	∞
System validation source						
Deviation of experimental source from numerical source	5.50	N	1	0.84	5.50	∞
Input power and SAR drift measurement	0.53	R	$\sqrt{3}$	1	0.31	∞
Other source contribution	2.01	R	$\sqrt{3}$	1	1.16	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	1.70	R	$\sqrt{3}$	0.71	0.31	∞
Liquid conductivity (measured)	0.77	N	1	0.26	0.55	9
Liquid permittivity (Temperature uncertainty)	0.40	R	$\sqrt{3}$	0.71	0.01	∞
Liquid permittivity (measured)	1.64	N	1	0.26	0.43	9
Combined standard uncertainty		RSS			8.08	
Coverage factor k (95 % confidence level)		1.96				430338
Expanded uncertainty					15.8	

Table 7 Example of evaluating uncertainty of system validation using a dipole antenna(1,767.5 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	8.11	N	2	1	4.06	∞
Isotropy (axial isotropy)	4.70	R	$\sqrt{3}$	1	2.71	∞
Boundary effect	0.53	R	$\sqrt{3}$	1	0.31	∞
Linearity (k = 2)	1.50	R	2	1	0.75	∞
Detection limits (k = 2)	1.00	N	2	1	0.58	∞
Modulation response	0.00	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.30	N	1	1	0.30	∞
Response time	0.00	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.00	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.23	R	$\sqrt{3}$	1	0.13	∞
RF ambient conditions - reflection	0.97	R	$\sqrt{3}$	1	0.56	∞
Probe positioner mechanical tolerance	0.21	R	$\sqrt{3}$	1	0.12	∞
Probe position with respect to phantom shell	1.65	R	$\sqrt{3}$	1	0.95	∞
Post processing (k = 2)	2.00	N	2	1	4.12	∞
System validation source						
Deviation of experimental source from numerical source	5.50	N	1	0.84	5.50	∞
Input power and SAR drift measurement	0.23	R	$\sqrt{3}$	1	0.13	∞
Other source contribution	2.01	R	$\sqrt{3}$	1	1.16	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	1.82	R	$\sqrt{3}$	0.71	0.75	∞
Liquid conductivity (measured)	0.72	N	1	0.26	0.51	9
Liquid permittivity (Temperature uncertainty)	0.48	R	$\sqrt{3}$	0.71	0.07	∞
Liquid permittivity (measured)	1.70	N	1	0.26	0.44	9
Combined standard uncertainty			RSS		7.84	
Coverage factor k (95 % confidence level)			1.96			497662
Expanded uncertainty					15.4	

Table 8 Example of evaluating uncertainty of system validation using a dipole antenna(1,950 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration	7.68	N	2	1	3.84	∞
Isotropy (axial isotropy)	4.70	R	$\sqrt{3}$	1	2.71	∞
Boundary effect	0.89	R	$\sqrt{3}$	1	0.51	∞
Linearity	1.50	R	$\sqrt{3}$	1	0.75	∞
Detection limits	1.00	R	$\sqrt{3}$	1	0.58	∞
Modulation response	0.00	R	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.30	N	1	1	0.30	∞
Response time	0.00	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.00	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.23	R	$\sqrt{3}$	1	0.13	∞
RF ambient conditions - reflection	0.97	R	$\sqrt{3}$	1	0.56	∞
Probe positioner mechanical tolerance	0.21	R	$\sqrt{3}$	1	0.12	∞
Probe position with respect to phantom shell	1.67	R	$\sqrt{3}$	1	0.96	∞
Post processing	2.00	R	$\sqrt{3}$	1	1.15	∞
System validation source						
Deviation of experimental source from numerical source	5.50	N	1	0.84	5.50	∞
Input power and SAR drift measurement	0.46	R	$\sqrt{3}$	1	0.27	∞
Other source contribution	2.01	R	$\sqrt{3}$	1	1.16	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	2.53	R	$\sqrt{3}$	0.71	1.04	∞
Liquid conductivity (measured)	0.95	N	1	0.26	0.67	9
Liquid permittivity (Temperature uncertainty)	0.47	R	$\sqrt{3}$	0.71	0.07	∞
Liquid permittivity (measured)	1.99	N	1	0.26	0.52	9
Combined standard uncertainty		RSS			7.80	
Coverage factor *k* (95 % confidence level)		1.96				160659
Expanded uncertainty					15.3	

Table 9 Example of evaluating uncertainty of system validation using a dipole antenna(2,018 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	8.05	N	2	1	4.03	∞
Isotropy (axial isotropy)	4.70	R	$\sqrt{3}$	1	2.71	∞
Boundary effect	1.21	R	$\sqrt{3}$	1	0.70	∞
Linearity (k = 2)	1.50	R	2	1	0.75	∞
Detection limits (k = 2)	1.00	N	2	1	0.58	∞
Modulation response	0.00	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.30	N	1	1	0.30	∞
Response time	0.00	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.00	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.30	R	$\sqrt{3}$	1	0.17	∞
RF ambient conditions - reflection	0.48	R	$\sqrt{3}$	1	0.28	∞
Probe positioner mechanical tolerance	0.27	R	$\sqrt{3}$	1	0.16	∞
Probe position with respect to phantom shell	2.14	R	$\sqrt{3}$	1	1.24	∞
Post processing (k = 2)	2.00	N	2	1	1.15	∞
System validation source						
Deviation of experimental source from numerical source	5.50	N	1	0.84	5.50	∞
Input power and SAR drift measurement	0.69	R	$\sqrt{3}$	1	0.40	∞
Other source contribution	2.01	R	$\sqrt{3}$	1	1.16	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	3.47	R	$\sqrt{3}$	0.71	1.42	∞
Liquid conductivity (measured)	1.42	N	1	0.26	1.01	9
Liquid permittivity (Temperature uncertainty)	0.47	R	$\sqrt{3}$	0.71	0.07	∞
Liquid permittivity (measured)	2.12	N	1	0.26	0.55	9
Combined standard uncertainty		RSS			8.03	
Coverage factor k (95 % confidence level)		1.96				36213
Expanded uncertainty					15.7	

Table 10 Example of evaluating uncertainty of system validation using a dipole antenna(2,450 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	8.12	N	2	1	4.06	∞
Isotropy (axial isotropy)	4.70	R	$\sqrt{3}$	1	2.71	∞
Boundary effect	2.68	R	$\sqrt{3}$	1	1.55	∞
Linearity (k = 2)	1.50	R	2	1	0.75	∞
Detection limits (k = 2)	1.00	N	2	1	0.58	∞
Modulation response	0.00	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.30	N	1	1	0.30	∞
Response time	0.00	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.00	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.30	R	$\sqrt{3}$	1	0.17	∞
RF ambient conditions - reflection	0.48	R	$\sqrt{3}$	1	0.28	∞
Probe positioner mechanical tolerance	0.29	R	$\sqrt{3}$	1	0.17	∞
Probe position with respect to phantom shell	2.32	R	$\sqrt{3}$	1	1.34	∞
Post processing (k = 2)	2.00	N	2	1	1.15	∞
System validation source						
Deviation of experimental source from numerical source	5.50	N	1	0.84	5.50	∞
Input power and SAR drift measurement	0.23	R	$\sqrt{3}$	1	0.13	∞
Other source contribution	2.01	R	$\sqrt{3}$	1	1.16	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	3.46	R	$\sqrt{3}$	0.71	1.42	∞
Liquid conductivity (measured)	1.10	N	1	0.26	0.78	9
Liquid permittivity (Temperature uncertainty)	0.70	R	$\sqrt{3}$	0.71	0.11	∞
Liquid permittivity (measured)	2.14	N	1	0.26	0.56	9
Combined standard uncertainty		RSS			8.15	
Coverage factor k (95 % confidence level)		1.96				106629
Expanded uncertainty					16.0	

Table 11 Example of evaluating uncertainty of system validation using a dipole antenna(2,585 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	12.15	N	2	1	6.08	∞
Isotropy (axial isotropy)	4.70	R	$\sqrt{3}$	1	2.71	∞
Boundary effect	1.38	R	$\sqrt{3}$	1	0.80	∞
Linearity (k = 2)	1.50	R	2	1	0.75	∞
Detection limits (k = 2)	1.00	N	2	1	0.58	∞
Modulation response	0.00	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.30	N	1	1	0.30	∞
Response time	0.00	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.00	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	1.17	R	$\sqrt{3}$	1	0.68	∞
RF ambient conditions - reflection	0.71	R	$\sqrt{3}$	1	0.41	∞
Probe positioner mechanical tolerance	0.29	R	$\sqrt{3}$	1	0.17	∞
Probe position with respect to phantom shell	2.33	R	$\sqrt{3}$	1	1.35	∞
Post processing (k = 2)	2.00	N	2	1	1.15	∞
System validation source						
Deviation of experimental source from numerical source	5.50	N	1	0.84	5.50	∞
Input power and SAR drift measurement	0.46	R	$\sqrt{3}$	1	0.27	∞
Other source contribution	2.01	R	$\sqrt{3}$	1	1.16	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.06	R	$\sqrt{3}$	1	1.19	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	3.34	R	$\sqrt{3}$	0.71	1.37	∞
Liquid conductivity (measured)	0.66	N	1	0.26	0.47	9
Liquid permittivity (Temperature uncertainty)	0.79	R	$\sqrt{3}$	0.71	0.12	∞
Liquid permittivity (measured)	2.00	N	1	0.26	0.52	9
Combined standard uncertainty			RSS		9.23	
Coverage factor k (95 % confidence level)			1.96			1355108
Expanded uncertainty					18.1	

Table 12 Example of evaluating uncertainty of system validation using a dipole antenna(3,500 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	10.19	N	2	1	5.10	∞
Isotropy (axial isotropy)	4.70	R	$\sqrt{3}$	1	2.71	∞
Boundary effect	0.17	R	$\sqrt{3}$	1	0.10	∞
Linearity (k = 2)	1.50	R	2	1	0.75	∞
Detection limits (k = 2)	1.00	N	2	1	0.58	∞
Modulation response	0.00	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.30	N	1	1	0.30	∞
Response time	0.00	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.00	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	1.17	R	$\sqrt{3}$	1	0.68	∞
RF ambient conditions - reflection	0.71	R	$\sqrt{3}$	1	0.41	∞
Probe positioner mechanical tolerance	0.72	R	$\sqrt{3}$	1	0.42	∞
Probe position with respect to phantom shell	5.76	R	$\sqrt{3}$	1	3.33	∞
Post processing (k = 2)	2.00	N	2	1	1.15	∞
System validation source						
Deviation of experimental source from numerical source	5.50	N	1	0.84	5.50	∞
Input power and SAR drift measurement	0.69	R	$\sqrt{3}$	1	0.40	∞
Other source contribution	2.01	R	$\sqrt{3}$	1	1.16	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.06	R	$\sqrt{3}$	1	1.19	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	3.09	R	$\sqrt{3}$	0.71	1.27	∞
Liquid conductivity (measured)	1.22	N	1	0.26	0.87	9
Liquid permittivity (Temperature uncertainty)	0.92	R	$\sqrt{3}$	0.71	0.14	∞
Liquid permittivity (measured)	2.29	N	1	0.26	0.60	9
Combined standard uncertainty		RSS			9.13	
Coverage factor k (95 % confidence level)		1.96				111206
Expanded uncertainty					17.9	

Table 13 Example of evaluating uncertainty of system validation using a dipole antenna(5,200 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	9.05	N	2	1	4.53	∞
Isotropy (axial isotropy)	4.70	R	$\sqrt{3}$	1	2.71	∞
Boundary effect	2.50	R	$\sqrt{3}$	1	1.44	∞
Linearity (k = 2)	1.50	R	2	1	0.75	∞
Detection limits (k = 2)	1.00	N	2	1	0.58	∞
Modulation response	0.00	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.30	N	1	1	0.30	∞
Response time	0.00	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.00	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	1.17	R	$\sqrt{3}$	1	0.68	∞
RF ambient conditions - reflection	0.71	R	$\sqrt{3}$	1	0.41	∞
Probe positioner mechanical tolerance	0.80	R	$\sqrt{3}$	1	0.46	∞
Probe position with respect to phantom shell	6.39	R	$\sqrt{3}$	1	3.69	∞
Post processing (k = 2)	2.00	N	2	1	1.15	∞
System validation source						
Deviation of experimental source from numerical source	5.50	N	1	0.84	5.50	∞
Input power and SAR drift measurement	0.93	R	$\sqrt{3}$	1	0.54	∞
Other source contribution	2.01	R	$\sqrt{3}$	1	1.16	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.06	R	$\sqrt{3}$	1	1.19	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	3.33	R	$\sqrt{3}$	0.71	1.37	∞
Liquid conductivity (measured)	1.09	N	1	0.26	0.77	9
Liquid permittivity (Temperature uncertainty)	0.68	R	$\sqrt{3}$	0.71	0.10	∞
Liquid permittivity (measured)	2.60	N	1	0.26	0.68	9
Combined standard uncertainty		RSS			9.11	
Coverage factor k (95 % confidence level)		1.96				172509
Expanded uncertainty					17.8	

Table 14 Sources of uncertainty and standard uncertainty in system validation using a dipole antenna

Frequency (MHz)	733	835	900	1450	1624	1767.5	1950	2018	2450	2585	3500	5200
Probe calibration (%)	3.84	4.06	3.71	3.63	4.56	4.06	3.84	4.03	4.06	6.08	5.10	4.53
Probe isotropy (%)	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71
Boundary effect (%)	0.31	0.29	0.47	0.12	0.21	0.31	0.51	0.70	1.55	0.80	0.10	1.44
Deviation of experimental source from numerical source (%)	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50
Expanded uncertainty (%)	14.9	15.0	14.9	14.9	15.8	15.4	15.3	15.7	16.0	18.1	17.9	17.9

Table 14 summarizes the major sources of uncertainty. In this evaluation, uncertainties directly related to frequency, such as probe calibration and boundary effect, became greater at high frequencies, which require more precision than low frequencies. Also, for probe isotropy and differences between the numerical model and actual product, values in the calibration certificate, and so on were cited, but these are constant values regardless of the frequency, thus, for example, there could be differences if evaluated at each frequency. As a result, expanded uncertainty was within 20 % overall.

4.3 Determination of SAR Reference values of standard dipoles [7]

As described earlier, in system validation of SAR measurement equipment, its operating performance is verified by measurements using a standard antenna described in the document of standards and so on as a standard radiation source. When performing these tests, for example, when a standard antenna is positioned directly below a flat phantom, the reflection coefficient ($|S_{11}|$) shall be −20 dB or less [2]–[5]. Standards such as IEC62209−1 describe electrical characteristics of the phantom liquid, standard antenna dimensions for typical frequencies, and SAR reference values determined by numerical calculations. However, in cases where the frequencies used are not described in the standard, it is necessary to determine the SAR reference value and the antenna design each time by using numerical calculation. The reason is that the element length of the standard antenna is different from the resonant length in free space, due to the existence of the phantom.

Here, description is given about the intercomparison of calculations performed in multiple institutions to determine the dipole element length and SAR reference values used in the frequencies not in the standard [7].

In Reference [7], in 5 institutions including NICT, the model in Fig. 4 was calculated by the Finite-Difference Time-Domain (FDTD) method and compared each other.

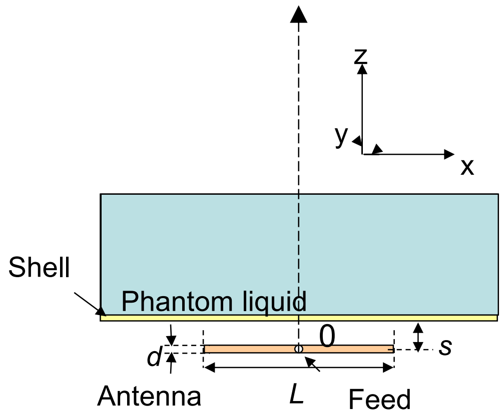

Fig. 4 Diagram of calculation model for calculation of SAR reference values in system validation of measurement system

Table 15 Calculation parameters

Frequency (MHz)	Relative permittivity	Conductivity (S/m)	L (mm)	Minimum phantom size (X,Y,Z)(mm)	Phantom shell thickness (mm)	s (mm)	d (mm)
400	44.1	0.87	312.7	800, 670, 170	6.3	15	6.35
900	41.5	0.97	149.0	360, 300, 150	2	15	3.6
2585	39.0	1.94	48.8	180, 120, 150	2	10	3.6

*For 900 MHz, cited from Reference [4]

The numerical calculation codes used were an original code in one institution, and by commercial simulators ((XFDTD (Remcom Inc.) in two institutions, and SEMCAD X (Schmidt & Partner Engineering AG) in two institutions).

For the calculation protocol, first, the values shown in Table 15 were set as calculation parameters. For 900 MHz, the values are in accordance with the standard dipole length L value and minimum phantom size provided in the IEC62209 standard. Since dielectric constants, dipole lengths, and phantom sizes of 400 MHz and 2,585 MHz are not in the standard, linear interpolation between values of the frequencies above and below was used.

Table 16 Results of comparison to IEC reference values (900 MHz)

	L (mm)	Maximum 1g-average SAR (W/kg)	Maximum 10g-average SAR (W/kg)	Local SAR (y = 0) (W/kg)	Local SAR (y = 2 cm) (W/kg)
IEC reference value [4]	149.0	10.9	7.0	16.4	5.4
Calculated value	147.8	10.8	6.8	15.9	5.2
Relative standard deviation of calculation results of each institution (%)	0.8	5.2	4.3	2.9	2.6
Difference between IEC reference value and calculation result (%)	−0.8	−1.3	−2.3	−3.0	−4.0

Table 17 Results of determining SAR standard values

Frequency (MHz)	Dimensions of standard dipole antenna		SAR standard value (1 W input)		
	Element length L (mm)	Diameter of the element d_1 (mm)	Maximum 10-g SAR (W/kg)	Local SAR at phantom surface above the feed point (W/kg)	Local SAR at phantom surface 2 cm from above the feed point (W/kg)
400	300.2	6.35	2.7	5.6	2.6
2585	49.1	3.6	24.3	117.5	6.8

Next, to confirm validity of the calculations, for the 900 MHz dipole antenna with values in Reference [4], the value of L was varied within the range of values in Table 15 ± 5 %, then at the obtained element lengths whose $|S_{11}|$ calculation results are −20 dB or less, SAR reference values were calculated and compared with the reference standard values in Reference [4].

After checking the validity of calculations, in order to also determine the dipole length for 400 MHz and 2,585 MHz in the same manner as for 900 MHz, average values of results of each institution were obtained, and the standard dipole length and SAR reference values were determined. Only the dipole element conductor was modeled in calculations, and the balun and so on were not considered. Also, the existence of a side wall of the phantom shell does not affect the SAR peak value at the bottom. Accordingly, only the bottom of the phantom shell is modeled as shown in Fig. 4, with the minimum phantom size of rectangular-shaped phantom liquid. The dielectric constants of the phantom shell are ε_r = 3.7, and tan δ = 0. NET input power supplied to the antenna was 1 W, with reflection power subtracted from incident power. With the calculation conditions described above, first, the standard dipole length L was determined at each institution. Next, a measurement system's system validation test at that dipole length L was used to obtain SAR reference values (the four types below).

- Maximum 1g-average SAR
- Maximum 10g-average SAR
- Local SAR at phantom surface above the feed point (W/kg)
- Local SAR at phantom surface 2 cm from above the feed point (W/kg)

Table 16 shows results of comparison between the average of the calculation results of each institution and the reference values in the standard at 900 MHz. These calculated results were approximately 4 % different from the values provided in the standard in maximum [4], thus for example, the calculation and standard values showed agreement comparable to the results in Reference [8] where similar calculations were performed. Each institution's data variability was around 5 % at maximum.

Next, the average value of the 400 MHz and 2,585 MHz standard dipole length L was 300.2 mm at 400 MHz, and 49.1 mm at 2,585 MHz. Table 17 shows determined SAR reference values. Variability of the results was a maximum 5.4 % at 400 MHz, and a maximum 7.2 % at 2,585 MHz. Comparing these to the 11.5 % of typical values of combined standard uncertainty in Reference [3], considering that each institution has different calculation parameters other than those specified in Table 15, good agreement was obtained generally.

Table 18 Type-A uncertainty evaluation parameters of SAR measurements

	Head	Body-worn
Frequency (MHz)	835, 1950	
Phantom used	Standard head phantom (specific anthropomorphic mannequin: SAM)	Flat phantom
Number of tested devices	6	9
Positions of device	4 (right/left and cheek/tilt)	3 (distance from bottom to terminal: 0, 5, 15 mm)
Number of measurement repetitions	5	
Number of measurers	2	
Communication protocol	W-CDMA	

5 Example of uncertainty evaluation of SAR measurement of wireless mobile devices

As described earlier, for SAR measurement of wireless mobile devices, there are measurement at the head using the standard head phantom (SAM), and body-worn measurements using a flat phantom. Measurement procedures for each are detailed in References [2]–[5].

Most sources of uncertainty in SAR measurements are the same as described in the previous section on system validation. However, instead of a standard antenna, it is necessary to evaluate sources of uncertainty caused by the wireless mobile terminal being tested. Thus this paper first describes an example of results for type-A evaluation of uncertainty in positioning device in SAR measurement shown in Table 18. Next, an example of evaluation of uncertainty of wireless mobile terminal (head or body-worn) measurements based on the IEC62209 standard is presented.

First, Table 17 shows evaluation conditions of device positioning uncertainty. Here, three separation distances of handset settings for body-worn measurement are selected, however, it should be noted that the international standard specifies that the separation distance should be at the position specified in the manual and so on. In this paper, measurements were also taken at different separation distances from those specified in manuals of the terminals, in order to investigate uncertainty of positioning.

In the evaluation of uncertainty attributed to the device positioning described above, for head SAR, standard uncertainty was 3.35 % at 835 MHz, and 3.61 % at 1,950 MHz. For body-worn devices, some differences were seen dependent on the distance from the bottom to the terminal, but the dependency was negligible, and the maximums were 3.11 % at 835 MHz, and 3.90 % at 1,950 MHz.

Next, as examples of evaluation of measured uncertainty using type-A evaluation uncertainty described above, Tables 19 to 22 show evaluation examples of uncertainty of measurement of wireless mobile terminal. Most of evaluation items are the same as in system validation, thus only the evaluating method of test sample (test terminal) related items is shown.

- Test sample positioning

There is uncertainty of the positioning of the test sample at the phantom. This paper used the type-A evaluation results of Table 7.

- Device holder uncertainty

The difference between measurement results with/without device holder. For head evaluation, this paper used values in IEC62209−1 [4]. For body-worn evaluation, Styrofoam was used instead of a device holder, therefore the uncertainty value was considered to be 0.

- SAR drift measurement

Compare SAR at the start of measurement with that at the end of measurement, and evaluate drift of the SAR value. Here, 5.0 % was used as is the typical value in IEC62209−1 [4]. A rectangular probability distribution was used.

- SAR scaling

For a terminal using multiple modulation methods in the same frequency band, from measurement results at a modulation (mod_x), use extrapolation to obtain SAR at another modulation (mod_y) that satisfies conditions such as the same number of carrier frequencies. As this paper does not perform SAR scaling, the uncertainty value was set as 0.

Table 19 Example of evaluation of measured uncertainty of wireless mobile terminal in SAR test (Head, 835 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration	8.11	N	2	1	4.06	∞
Isotropy (probe isotropy and hemispherical isotropy)	7.56	R	$\sqrt{3}$	$\sqrt{0.5}$	4.36	∞
Boundary effect	0.5	R	$\sqrt{3}$	1	0.29	∞
Linearity	1.5	R	$\sqrt{3}$	1	0.75	∞
Detection limits	1	R	$\sqrt{3}$	1	0.58	∞
Modulation response	0	R	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.3	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.09	R	$\sqrt{3}$	1	0.05	∞
RF ambient conditions - reflection	0.41	R	$\sqrt{3}$	1	0.24	∞
Probe positioner mechanical tolerance	0.14	R	$\sqrt{3}$	1	0.08	∞
Probe position with respect to phantom shell	1.11	R	$\sqrt{3}$	1	0.64	∞
Post processing	2	R	$\sqrt{3}$	1	1.15	∞
Test sample related						
Test sample positioning	3.35	N	1	1	3.35	239
Device Holder Uncertainty	5	N	1	1	5.00	7
SAR Drift Measurement	0.46	R	$\sqrt{3}$	1	0.27	∞
SAR Scaling	0	R	$\sqrt{3}$	1	0.00	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	1.34	R	$\sqrt{3}$	1	0.77	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0.00	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	1.51	R	$\sqrt{3}$	0.71	0.62	∞
Liquid conductivity (measured)	0.86	N	1	0.26	0.61	9
Liquid permittivity (Temperature uncertainty)	0.07	R	$\sqrt{3}$	0.71	0.01	∞
Liquid permittivity (measured)	1.28	N	1	0.26	0.33	9
Combined standard uncertainty		RSS			8.7	
Coverage factor *k* (95 % confidence level)		2.00				64
Expanded uncertainty					17.4	

Table 20 Example of evaluation of measured uncertainty of wireless mobile terminal in SAR test (Head, 1,950 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration	7.68	N	2	1	3.84	∞
Isotropy (probe isotropy and hemispherical isotropy)	7.69	R	$\sqrt{3}$	$\sqrt{0.5}$	4.36	∞
Boundary effect	7.76	R	$\sqrt{3}$	1	0.51	∞
Linearity	7.56	R	$\sqrt{3}$	1	0.75	∞
Detection limits	0.89	R	$\sqrt{3}$	1	0.58	∞
Modulation response	1.5	R	$\sqrt{3}$	1	0.00	∞
Readout electronics	1	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.3	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0	R	$\sqrt{3}$	1	0.13	∞
RF ambient conditions - reflection	0	R	$\sqrt{3}$	1	0.56	∞
Probe positioner mechanical tolerance	0.23	R	$\sqrt{3}$	1	0.12	∞
Probe position with respect to phantom shell	0.97	R	$\sqrt{3}$	1	0.96	∞
Post processing	0.21	R	$\sqrt{3}$	1	1.15	∞
Test sample related						
Test sample positioning	3.61	N	1	1	3.61	239
Device Holder Uncertainty	5.00	N	1	1	5.00	7
SAR Drift Measurement	0.46	R	$\sqrt{3}$	1	0.27	∞
SAR Scaling	0	R	$\sqrt{3}$	1	0.00	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	2.53	R	$\sqrt{3}$	0.71	1.04	∞
Liquid conductivity (measured)	0.95	N	1	0.26	0.67	9
Liquid permittivity (Temperature uncertainty)	0.47	R	$\sqrt{3}$	0.71	0.07	∞
Liquid permittivity (measured)	1.99	N	1	0.26	0.52	9
Combined standard uncertainty		RSS			8.90	
Coverage factor *k* (95 % confidence level)					1.99	69
Expanded uncertainty					17.7	

Table 21 Example of evaluation of measured uncertainty of wireless mobile terminal in SAR test (Body-worn, 835 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom ν_i or ν_{eff}
Measurement system						
Probe calibration	8.11	N	2	1	4.06	∞
Isotropy (probe isotropy)	4.70	R	$\sqrt{3}$	$\sqrt{0.5}$	2.71	∞
Boundary effect	0.5	R	$\sqrt{3}$	1	0.29	∞
Linearity	1.5	R	$\sqrt{3}$	1	0.75	∞
Detection limits	1	R	$\sqrt{3}$	1	0.58	∞
Modulation response	0	R	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.3	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.09	R	$\sqrt{3}$	1	0.05	∞
RF ambient conditions - reflection	0.41	R	$\sqrt{3}$	1	0.24	∞
Probe positioner mechanical tolerance	0.14	R	$\sqrt{3}$	1	0.08	∞
Probe position with respect to phantom shell	1.11	R	$\sqrt{3}$	1	0.64	∞
Post processing	2	R	$\sqrt{3}$	1	1.15	∞
Test sample related						
Test sample positioning	3.11	N	1	1	3.11	269
Device Holder Uncertainty※	0.0	N	1	1	0.0	7
SAR Drift Measurement	0.46	R	$\sqrt{3}$	1	0.27	∞
SAR Scaling	0.0	R	$\sqrt{3}$	1	0.0	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	1.34	R	$\sqrt{3}$	1	0.77	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	1.514	R	$\sqrt{3}$	0.71	0.62	∞
Liquid conductivity (measured)	0.86	N	1	0.26	0.61	9
Liquid permittivity (Temperature uncertainty)	0.07	R	$\sqrt{3}$	0.71	0.01	∞
Liquid permittivity (measured)	1.28	N	1	0.26	0.33	9
Combined standard uncertainty		RSS			6.2	
Coverage factor *k* (95 % confidence level)		1.96				3778
Expanded uncertainty					12.1	

Table 22 Example of evaluation of measured uncertainty of wireless mobile terminal in SAR test (Body-worn, 1,950 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration	7.68	N	2	1	3.84	∞
Isotropy (probe isotropy)	4.70	R	$\sqrt{3}$	$\sqrt{0.5}$	2.71	∞
Boundary effect	7.76	R	$\sqrt{3}$	1	0.51	∞
Linearity	7.56	R	$\sqrt{3}$	1	0.75	∞
Detection limits	0.89	R	$\sqrt{3}$	1	0.58	∞
Modulation response	1.5	R	$\sqrt{3}$	1	0.00	∞
Readout electronics	1	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0.3	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0	R	$\sqrt{3}$	1	0.13	∞
RF ambient conditions - reflection	0	R	$\sqrt{3}$	1	0.56	∞
Probe positioner mechanical tolerance	0.23	R	$\sqrt{3}$	1	0.12	∞
Probe position with respect to phantom shell	0.97	R	$\sqrt{3}$	1	0.96	∞
Post processing	0.21	R	$\sqrt{3}$	1	1.15	∞
Test sample related						
Test sample positioning	3.90	N	1	1	3.90	2659
Device Holder Uncertainty	0.0	N	1	1	0.0	7
SAR Drift Measurement	0.46	R	$\sqrt{3}$	1	0.3	∞
SAR Scaling	0.0	R	$\sqrt{3}$	1	0.0	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	2.53	R	$\sqrt{3}$	0.71	1.04	∞
Liquid conductivity (measured)	0.95	N	1	0.26	0.67	9
Liquid permittivity (Temperature uncertainty)	0.47	R	$\sqrt{3}$	0.71	0.07	∞
Liquid permittivity (measured)	1.99	N	1	0.26	0.52	9
Combined standard uncertainty		RSS			6.7	
Coverage factor *k* (95 % confidence level)		1.96				1947
Expanded uncertainty					13.1	

Table 23 Example of evaluation of standard uncertainty of wireless mobile terminal in SAR test

	Head		Body-worn	
Frequency (MHz)	835	1950	835	1950
Probe calibration (%)	4.13	3.88	4.13	3.88
Probe isotropy (%)	4.36	4.36	2.71	2.71
Test sample positioning (%)	3.35	3.61	3.11	3.90
Holder uncertainty (%)	5.00	5.00	0.00	0.00
Expanded uncertainty (%)	17.4	17.7	12.1	13.1

Also, Table 23 shows major sources of uncertainty. As a result, firstly, it can be seen that in any measurement at any frequency, sources with large effects are probe related (calibration, isotropy) or terminal related (positioning, holder, and measurement drift). Especially, uncertainty of the test sample positioning is 6.0 % in IEC62209−1 [4], which is much larger than our result around 2 % type-A evaluation. To reduce measurement uncertainty, it is important to evaluate at each frequency using actual devices. However, in body-worn measurements, uncertainty of the holder was set as 0, consequently these measurement uncertainties are smaller than those for the head measurement uncertainty, and thus uncertainty value is similar to that of the system validation described earlier. This also requires further study using actual measurement results of device holder uncertainty in the future. For dependency on frequencies, little relation was observed in comparison of two frequencies this time.

The evaluation results of uncertainty this time were much smaller than the examples in IEC62209−1 [4] and so on, which were under 30 %. This is mainly because of 0 uncertainty of the signal modulation, such as effects of modulation response and integration time, the uncertainty of holder in body-worn measurement, and because phantom liquid dielectric constant related uncertainty is small. When modulation signal, SAR correction, SAR correction by dielectric constant, and so on are taken into account, uncertainty is expected to be similar to that in the example in the standard.

6 Example of evaluation by calculation of SAR measurement uncertainty of wireless mobile device

As described in the previous section, test sample related uncertainty is a factor that greatly affects measurements. Accordingly, evaluations such as type-A that use measurements of actual devices are indispensable. However, for example, if it is difficult to obtain the actual device, uncertainty can be estimated to a certain degree by using data of evaluations already performed, and so on. Thus here, calculations of SAR measurement uncertainty at SAR probe calibration frequencies were performed at the frequencies where type-A measurement evaluations were not performed in the previous section. Tables 24 to 33 show examples of calculations of head SAR measurement uncertainty. For test sample uncertainty, 3.90 %, which is the maximum evaluation result at 835 MHz and 1,950MHz in the previous section, was used. In this case, the difference between head measurement and body-worn measurement is that probe isotropy evaluation includes only axial isotropy, and whether or not there is holder uncertainty. For this reason, only detailed budget tables of head measurements are presented in this paper.

Tables 34 and 35 summarize uncertainty calculation results for SAR measurements. Regarding frequency characteristics, it can be seen that higher frequencies tend to have greater uncertainties for both the head and body-worn measurements. Likewise for measurements performed at 835 MHz and 1,950MHz, for all measurements and frequencies, sources with the greatest effects were probe related (calibration, isotropy) and terminal related (positioning, holder, measurement drift); as expected, it is basically important to perform evaluation using actual mobile terminal devices. Regarding dependence on frequencies, from our calculation results, uncertainty was greater at higher frequencies, but was estimate to be around 20 %. However, especially uncertainty related to the device positioning can be expected to be greater at higher frequencies. In the future, for frequencies at which actual test devices can be obtained, more detailed uncertainty evaluations will be necessary, such as type-A evaluation of positioning and device holder.

Table 24 Example of calculating measurement uncertainty of wireless mobile terminal in SAR test (Head, 900 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	7.68	N	2	1	3.84	∞
Isotropy (probe isotropy and hemispherical isotropy)	7.56	R	$\sqrt{3}$	$\sqrt{0.5}$	4.36	∞
Boundary effect	0.53	R	$\sqrt{3}$	1	0.31	∞
Linearity (k = 2)	1.5	R	2	1	0.75	∞
Detection limits (k = 2)	1	N	2	1	0.58	∞
Modulation response	0	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.3	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.09	R	$\sqrt{3}$	1	0.05	∞
RF ambient conditions - reflection	0.41	R	$\sqrt{3}$	1	0.24	∞
Probe positioner mechanical tolerance	0.13	R	$\sqrt{3}$	1	0.08	∞
Probe position with respect to phantom shell	1.03	R	$\sqrt{3}$	1	0.59	∞
Post processing (k = 2)	2	N	2	1	1.15	∞
Test sample related						
Test sample positioning	6.0	N	1	1	6.0	11
Device Holder Uncertainty	5.0	N	1	1	5.0	7
SAR Drift Measurement	0.93	R	$\sqrt{3}$	1	0.5	∞
SAR Scaling	0.0	R	$\sqrt{3}$	1	0.0	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	1.34	R	$\sqrt{3}$	1	0.77	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	2.37	R	$\sqrt{3}$	0.71	0.44	∞
Liquid conductivity (measured)	1.1	N	1	0.26	1.68	9
Liquid permittivity (Temperature uncertainty)	0.18	R	$\sqrt{3}$	0.71	0.00	∞
Liquid permittivity (measured)	1.03	N	1	0.26	0.05	9
Combined standard uncertainty		RSS			10.1	
Coverage factor k (95 % confidence level)		2.01				50
Expanded uncertainty					20.2	

Table 25 Example of calculating measurement uncertainty of wireless mobile terminal in SAR test (Head, 900 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	7.41	N	2	1	3.71	∞
Isotropy (probe isotropy and hemispherical isotropy)	7.56	R	$\sqrt{3}$	$\sqrt{0.5}$	4.36	∞
Boundary effect	0.81	R	$\sqrt{3}$	1	0.47	∞
Linearity (k = 2)	1.5	R	2	1	0.75	∞
Detection limits (k = 2)	1	N	2	1	0.58	∞
Modulation response	0	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.3	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.29	R	$\sqrt{3}$	1	0.17	∞
RF ambient conditions - reflection	1.48	R	$\sqrt{3}$	1	0.85	∞
Probe positioner mechanical tolerance	0.17	R	$\sqrt{3}$	1	0.10	∞
Probe position with respect to phantom shell	1.4	R	$\sqrt{3}$	1	0.81	∞
Post processing (k = 2)	2	N	2	1	1.15	∞
Test sample related						
Test sample positioning	6.0	N	1	1	6.0	11
Device Holder Uncertainty	5.0	N	1	1	5.0	7
SAR Drift Measurement	0.23	R	$\sqrt{3}$	1	0.13	∞
SAR Scaling	0.0	R	$\sqrt{3}$	1	0.0	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	1.34	R	$\sqrt{3}$	1	0.77	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	1.49	R	$\sqrt{3}$	0.71	0.61	∞
Liquid conductivity (measured)	1.32	N	1	0.26	0.94	9
Liquid permittivity (Temperature uncertainty)	0.11	R	$\sqrt{3}$	0.71	0.02	∞
Liquid permittivity (measured)	1.28	N	1	0.26	0.33	9
Combined standard uncertainty		RSS			10.0	
Coverage factor k (95 % confidence level)		2.01				48
Expanded uncertainty					20.1	

Table 26 Example of calculating measurement uncertainty of wireless mobile terminal in SAR test (Head, 1,450 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	7.26	N	2	1	3.63	∞
Isotropy (probe isotropy and hemispherical isotropy)	7.56	R	$\sqrt{3}$	$\sqrt{0.5}$	4.36	∞
Boundary effect	0.2	R	$\sqrt{3}$	1	0.12	∞
Linearity (k = 2)	1.5	R	2	1	0.75	∞
Detection limits (k = 2)	1	N	2	1	0.58	∞
Modulation response	0	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.3	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.23	R	$\sqrt{3}$	1	0.13	∞
RF ambient conditions - reflection	0.97	R	$\sqrt{3}$	1	0.56	∞
Probe positioner mechanical tolerance	0.19	R	$\sqrt{3}$	1	0.11	∞
Probe position with respect to phantom shell	1.52	R	$\sqrt{3}$	1	0.88	∞
Post processing	2	R	$\sqrt{3}$	1	1.15	∞
Test sample related						
Test sample positioning	6.0	N	1	1	6.0	11
Device Holder Uncertainty	5.0	N	1	1	5.0	7
SAR Drift Measurement	0.69	R	$\sqrt{3}$	1	0.4	∞
SAR Scaling	0.0	R	$\sqrt{3}$	1	0.0	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0	∞
Liquid conductivity (Temperature uncertainty)	1.49	R	$\sqrt{3}$	0.71	0.36	∞
Liquid conductivity (measured)	1.32	N	1	0.26	0.58	9
Liquid permittivity (Temperature uncertainty)	0.11	R	$\sqrt{3}$	0.71	0.02	∞
Liquid permittivity (measured)	1.28	N	1	0.26	0.40	9
Combined standard uncertainty		RSS			9.9	
Coverage factor k (95 % confidence level)		2.01				47
Expanded uncertainty					20.0	

Table 27 Example of calculating measurement uncertainty of wireless mobile terminal in SAR test (Head, 1,624 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	9.12	N	2	1	4.56	∞
Isotropy (probe isotropy and hemispherical isotropy)	7.56	R	$\sqrt{3}$	$\sqrt{0.5}$	4.36	∞
Boundary effect	0.36	R	$\sqrt{3}$	1	0.21	∞
Linearity (k = 2)	1.5	R	2	1	0.75	∞
Detection limits (k = 2)	1	N	2	1	0.58	∞
Modulation response	0	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.3	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.23	R	$\sqrt{3}$	1	0.13	∞
RF ambient conditions - reflection	0.97	R	$\sqrt{3}$	1	0.56	∞
Probe positioner mechanical tolerance	0.2	R	$\sqrt{3}$	1	0.12	∞
Probe position with respect to phantom shell	1.62	R	$\sqrt{3}$	1	0.94	∞
Post processing	2	R	$\sqrt{3}$	1	1.15	∞
Test sample related						
Test sample positioning	6.0	N	1	1	6.0	11
Device Holder Uncertainty	5.0	N	1	1	5.0	7
SAR Drift Measurement	0.53	R	$\sqrt{3}$	1	0.3	∞
SAR Scaling	0.0	R	$\sqrt{3}$	1	0.0	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0	∞
Liquid conductivity (Temperature uncertainty)	1.70	R	$\sqrt{3}$	0.71	0.70	∞
Liquid conductivity (measured)	0.77	N	1	0.26	0.55	9
Liquid permittivity (Temperature uncertainty)	0.40	R	$\sqrt{3}$	0.71	0.06	∞
Liquid permittivity (measured)	1.64	N	1	0.26	0.43	9
Combined standard uncertainty		RSS			10.3	
Coverage factor k (95 % confidence level)		2.00				55
Expanded uncertainty					20.7	

Table 28 Example of calculating measurement uncertainty of wireless mobile terminal in SAR test (Head, 1,767.5 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	8.24	N	2	1	4.12	∞
Isotropy (probe isotropy and hemispherical isotropy)	7.56	R	$\sqrt{3}$	$\sqrt{0.5}$	4.36	∞
Boundary effect	0.53	R	$\sqrt{3}$	1	0.31	∞
Linearity	1.5	R	$\sqrt{3}$	1	0.75	∞
Detection limits (k = 2)	1	N	2	1	0.58	∞
Modulation response	0	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.3	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.23	R	$\sqrt{3}$	1	0.13	∞
RF ambient conditions - reflection	0.97	R	$\sqrt{3}$	1	0.56	∞
Probe positioner mechanical tolerance	0.21	R	$\sqrt{3}$	1	0.12	∞
Probe position with respect to phantom shell	1.65	R	$\sqrt{3}$	1	0.95	∞
Post processing	2	R	$\sqrt{3}$	1	1.15	∞
Test sample related						
Test sample positioning	6.0	N	1	1	6.0	11
Device Holder Uncertainty	5.0	N	1	1	5.0	7
SAR Drift Measurement	0.23	R	$\sqrt{3}$	1	0.1	∞
SAR Scaling	0.0	R	$\sqrt{3}$	1	0.0	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	1.82	R	$\sqrt{3}$	0.71	0.75	∞
Liquid conductivity (measured)	0.72	N	1	0.26	0.51	9
Liquid permittivity (Temperature uncertainty)	0.48	R	$\sqrt{3}$	0.71	0.07	∞
Liquid permittivity (measured)	1.70	N	1	0.26	0.44	9
Combined standard uncertainty		RSS			10.1	
Coverage factor k (95 % confidence level)		2.01				51
Expanded uncertainty					20.3	

Table 29 Example of calculating measurement uncertainty of wireless mobile terminal in SAR test (Head, 2,018 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %, (10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	8.11	N	2	1	4.06	∞
Isotropy (probe isotropy and hemispherical isotropy)	7.56	R	$\sqrt{3}$	$\sqrt{0.5}$	4.36	∞
Boundary effect	1.21	R	$\sqrt{3}$	1	0.70	∞
Linearity (k = 2)	1.5	R	2	1	0.75	∞
Detection limits (k = 2)	1	N	2	1	0.58	∞
Modulation response	0	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.3	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.3	R	$\sqrt{3}$	1	0.17	∞
RF ambient conditions - reflection	0.48	R	$\sqrt{3}$	1	0.28	∞
Probe positioner mechanical tolerance	0.27	R	$\sqrt{3}$	1	0.16	∞
Probe position with respect to phantom shell	2.14	R	$\sqrt{3}$	1	1.24	∞
Post processing	2	R	$\sqrt{3}$	1	1.15	∞
Test sample related						
Test sample positioning	6.0	N	1	1	6.0	11
Device Holder Uncertainty	5.0	N	1	1	5.0	7
SAR Drift Measurement	0.69	R	$\sqrt{3}$	1	0.4	∞
SAR Scaling	0.0	R	$\sqrt{3}$	1	0.0	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	3.47	R	$\sqrt{3}$	0.71	1.42	∞
Liquid conductivity (measured)	1.42	N	1	0.26	1.01	9
Liquid permittivity (Temperature uncertainty)	0.47	R	$\sqrt{3}$	0.71	0.07	∞
Liquid permittivity (measured)	2.12	N	1	0.26	0.55	9
Combined standard uncertainty		RSS			10.3	
Coverage factor k (95 % confidence level)		2.01				54
Expanded uncertainty					20.6	

Table 30 Example of calculating measurement uncertainty of wireless mobile terminal in SAR test (Head, 2,450 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %,(10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	8.05	N	2	1	4.03	∞
Isotropy (probe isotropy and hemispherical isotropy)	7.56	R	$\sqrt{3}$	$\sqrt{0.5}$	4.36	∞
Boundary effect	2.68	R	$\sqrt{3}$	1	1.55	∞
Linearity (k = 2)	1.5	R	2	1	0.75	∞
Detection limits (k = 2)	1	N	2	1	0.58	∞
Modulation response	0	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.3	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0.3	R	$\sqrt{3}$	1	0.17	∞
RF ambient conditions - reflection	0.48	R	$\sqrt{3}$	1	0.28	∞
Probe positioner mechanical tolerance	0.29	R	$\sqrt{3}$	1	0.17	∞
Probe position with respect to phantom shell	2.32	R	$\sqrt{3}$	1	1.34	∞
Post processing	2	R	$\sqrt{3}$	1	1.15	∞
Test sample related						
Test sample positioning	6.0	N	1	1	6.0	11
Device Holder Uncertainty	5.0	N	1	1	5.0	7
SAR Drift Measurement	0.23	R	$\sqrt{3}$	1	0.10	∞
SAR Scaling	0.0	R	$\sqrt{3}$	1	0.0	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.01	R	$\sqrt{3}$	1	1.16	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	3.46	R	$\sqrt{3}$	0.71	1.42	∞
Liquid conductivity (measured)	1.1	N	1	0.26	0.23	9
Liquid permittivity (Temperature uncertainty)	0.70	R	$\sqrt{3}$	0.71	0.11	∞
Liquid permittivity (measured)	2.14	N	1	0.26	0.56	9
Combined standard uncertainty		RSS			10.3	
Coverage factor k (95 % confidence level)		20.0				55
Expanded uncertainty					20.7	

Table 31 Example of calculating measurement uncertainty of wireless mobile terminal in SAR test (Head, 2,585 MHz Example)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %,(10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (*k* = 2)	12.15	N	2	1	6.08	∞
Isotropy (probe isotropy and hemispherical isotropy)	7.56	R	$\sqrt{3}$	$\sqrt{0.5}$	4.36	∞
Boundary effect	1.38	R	$\sqrt{3}$	1	0.80	∞
Linearity (*k* = 2)	1.5	R	2	1	0.75	∞
Detection limits (*k* = 2)	1	N	2	1	0.58	∞
Modulation response	0	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.3	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	1.17	R	$\sqrt{3}$	1	0.68	∞
RF ambient conditions - reflection	0.71	R	$\sqrt{3}$	1	0.41	∞
Probe positioner mechanical tolerance	0.29	R	$\sqrt{3}$	1	0.17	∞
Probe position with respect to phantom shell	2.33	R	$\sqrt{3}$	1	1.35	∞
Post processing	2	R	$\sqrt{3}$	1	1.15	∞
Test sample related						
Test sample positioning	6.0	N	1	1	6.0	11
Device Holder Uncertainty	5.0	N	1	1	5.0	7
SAR Drift Measurement	0.46	R	$\sqrt{3}$	1	0.3	∞
SAR Scaling	0.0	R	$\sqrt{3}$	1	0.0	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.06	R	$\sqrt{3}$	1	1.19	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	3.34	R	$\sqrt{3}$	0.71	1.37	∞
Liquid conductivity (measured)	0.66	N	1	0.26	0.14	9
Liquid permittivity (Temperature uncertainty)	0.79	R	$\sqrt{3}$	0.71	0.12	∞
Liquid permittivity (measured)	2	N	1	0.26	0.52	9
Combined standard uncertainty		RSS			11.3	
Coverage factor *k* (95 % confidence level)		1.99				78
Expanded uncertainty					22.4	

Table 32 Example of calculating measurement uncertainty of wireless mobile terminal in SAR test (Head, 3,500 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %,(10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	10.2	N	2	1	5.10	∞
Isotropy (probe isotropy and hemispherical isotropy)	7.56	R	$\sqrt{3}$	$\sqrt{0.5}$	4.36	∞
Boundary effect	0.17	R	$\sqrt{3}$	1	0.10	∞
Linearity (k = 2)	1.5	R	2	1	0.75	∞
Detection limits (k = 2)	1	N	2	1	0.58	∞
Modulation response	0	N	$\sqrt{3}$	1	0.00	∞
Readout electronics	0.3	N	1	1	0.30	∞
Response time	0	R	$\sqrt{3}$	1	0.00	∞
Integration time	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	1.17	R	$\sqrt{3}$	1	0.68	∞
RF ambient conditions - reflection	0.71	R	$\sqrt{3}$	1	0.41	∞
Probe positioner mechanical tolerance	0.72	R	$\sqrt{3}$	1	0.42	∞
Probe position with respect to phantom shell	5.76	R	$\sqrt{3}$	1	3.33	∞
Post processing	2	R	$\sqrt{3}$	1	1.15	∞
Test sample related						
Test sample positioning	6.0	N	1	1	6.0	11
Device Holder Uncertainty	5.0	N	1	1	5.0	7
SAR Drift Measurement	0.69	R	$\sqrt{3}$	1	0.4	∞
SAR Scaling	0.0	R	$\sqrt{3}$	1	0.0	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.06	R	$\sqrt{3}$	1	1.19	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	3.09	R	$\sqrt{3}$	0.71	1.27	∞
Liquid conductivity (measured)	1.22	N	1	0.26	0.26	9
Liquid permittivity (Temperature uncertainty)	0.92	R	$\sqrt{3}$	0.71	0.14	∞
Liquid permittivity (measured)	2.29	N	1	0.26	0.60	9
Combined standard uncertainty		RSS			11.1	
Coverage factor k (95 % confidence level)		1.99				74
Expanded uncertainty					22.2	

Table 33 Example of calculating measurement uncertainty of wireless mobile terminal in SAR test (Head, 5,200 MHz)

a	*b*	*c*	*d* =*f* (*c*,*g*)	*e*	*f* =*b*×*e*/*d*	*g*
Source of uncertainty	Uncertainty ± %	Probability distribution	Divisor	Sensitivity factor c_i (10 g)	Standard uncertainty ± %,(10 g)	Degrees of freedom v_i or v_{eff}
Measurement system						
Probe calibration (k = 2)	9.05	N	2	1	4.53	∞
Isotropy (probe isotropy and hemispherical isotropy)	9.10	R	$\sqrt{3}$	$\sqrt{0.5}$	4.55	∞
Boundary effect	7.56	R	$\sqrt{3}$	1	4.36	∞
Linearity (k = 2)	2.5	R	2	1	1.44	∞
Detection limits (k = 2)	1.5	N	2	1	0.75	∞
Modulation response	1	N	$\sqrt{3}$	1	0.58	∞
Readout electronics	0	N	1	1	0.00	∞
Response time	0.3	R	$\sqrt{3}$	1	0.30	∞
Integration time	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - noise	0	R	$\sqrt{3}$	1	0.00	∞
RF ambient conditions - reflection	1.17	R	$\sqrt{3}$	1	0.68	∞
Probe positioner mechanical tolerance	0.71	R	$\sqrt{3}$	1	0.41	∞
Probe position with respect to phantom shell	0.8	R	$\sqrt{3}$	1	0.46	∞
Post processing	6.39	R	$\sqrt{3}$	1	3.69	∞
Test sample related						
Test sample positioning	6.0	N	1	1	6.0	11
Device Holder Uncertainty	5.0	N	1	1	5.0	7
SAR Drift Measurement	0.93	R	$\sqrt{3}$	1	0.5	∞
SAR Scaling	0.0	R	$\sqrt{3}$	1	0.0	∞
Phantom and set-up						
Phantom uncertainty (shape and thickness uncertainty)	2.06	R	$\sqrt{3}$	1	1.19	∞
Uncertainty in SAR correction for deviations in permittivity and conductivity	0	N	1	0.84	0.00	∞
Liquid conductivity (Temperature uncertainty)	3.33	R	$\sqrt{3}$	0.71	1.37	∞
Liquid conductivity (measured)	1.09	N	1	0.26	0.77	9
Liquid permittivity (Temperature uncertainty)	0.68	R	$\sqrt{3}$	0.71	0.10	∞
Liquid permittivity (measured)	2.6	N	1	0.26	0.68	9
Combined standard uncertainty		RSS			11.1	
Coverage factor k (95 % confidence level)		1.99				73
Expanded uncertainty					22.1	

Table 34 Main sources of uncertainty and calculated values of standard uncertainty in head SAR measurements

Frequency (MHz)	733	900	1450	1624	1767.5	2018	2450	2585	3500	5200
Probe calibration (%)	3.84	3.71	3.63	4.56	4.06	4.06	4.03	4.06	6.15	5.10
Probe isotropy (%)	4.36	4.36	4.36	4.36	4.36	4.36	4.36	4.36	4.36	4.36
Test sample positioning (%)	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Holder uncertainty (%)	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Expanded uncertainty (%)	20.2	20.1	20.0	20.7	20.3	20.6	20.7	22.4	22.2	22.1

Table 35 Main sources of uncertainty and calculated values of standard uncertainty in body-worn SAR measurements

Frequency (MHz)	733	900	1450	1624	1767.5	2018	2450	2585	3500	5200
Probe calibration (%)	3.92	3.77	3.69	4.65	4.12	4.06	4.10	6.12	5.17	4.55
Probe isotropy (%)	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71	2.71
Test sample positioning (%)	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Holder uncertainty (%)	0	0	0	0	0	0	0	0	0	0
Expanded uncertainty (%)	13.2	12.9	12.8	13.9	13.3	13.7	13.9	16.4	16.1	16.0

7 Conclusions

This paper provided specific examples of SAR measurement method and uncertainty evaluation in accordance with international standards, based on our system validation results of a SAR measurement system. SAR measurement systems have different characteristics due to frequencies, such as the phantom dielectric constant, thus uncertainty sources must be evaluated at each specific frequency in general. It is also important to perform type-A evaluation using actual handsets on the market and to evaluate device holder uncertainty.

As a recent trend, more diverse terminals with a larger number of operating frequencies are becoming a problem Accordingly, high speed SAR measurement methods and methods to reduce the number of tests (test reduction) are being adopted [1][2][4]. Moreover, other than a method that uses a single probe to scan in the phantom as shown in Fig. 1, systems using multiple array sensors are being developed to measure SAR quickly. There is progress in work to standardize SAR evaluation methods using this technique. Also from Japan, including NICT, a simplification method of SAR measurement using a new shape of phantom has been proposed for standards such as IEC [9]. In addition, for methods that use a conventional single electric field probe to scan in the phantom, the need to revise measurement parameters such as special scan intervals and holder characteristics has been pointed out, in consideration of recent trends of wireless mobile terminals such as expansion of frequency bands and internal antennas becoming mainstream. To follow up these new technology trends, validation of measurement results, such as reference wave sources and uncertainty evaluation methods, must be investigated and revised continuously.

Acknowledgments

Part of this research was implemented under Ministry of Internal Affairs and Communications contracted research (Electromagnetic waves safety evaluation technology).

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