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Report on key comparison APMP.AUV.A-K5

(Final Report)

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ABSTRACT

This is the final report for key comparison APMP.AUV.A-K5 on the pressure calibration of laboratory standard microphones in the frequency range from 2 Hz to 10 kHz. Eight laboratories took part in the key comparison. National Institute of Metrology (NIM, China) and Center for Measurement Standards, Industrial Technology Research Institute (CMS-ITRI, Chinese Taipei) piloted the project. Two travelling standard microphones were circulated to the participants and results in the form of regular calibration certificates were collected throughout the project. The analysis used the results for one of the microphones only and values for both sensitivity level and sensitivity phase have been linked to the key comparison reference value (KCRV) of CCAUV.A-K5 via three linking laboratories (NIM, KRISS, NMIJ/AIST).

CONTENTS

1 INTRODUCTION

This is the final report for key comparison APMP.AUV.A-K5 on the pressure calibration of laboratory standard microphones. The results are linked back to the key comparison reference value (KCRV) of CCAUV.A-K5[1] via three linking laboratories: National Institute of Metrology, China (NIM, China), Korea Research Institute of Standards and Science (KRISS, Korea) and National Metrology Institute of Japan, AIST (NMIJ/AIST, Japan). This project was organized by the APMP Technical Committee for Acoustic, Ultrasound and Vibration. The basis of this key comparison was the calibration of laboratory standard microphones upon which primary measurement standards for sound in air are founded. Eight laboratories took part in the key comparison. National Institute of Metrology (NIM, China) and Center for Measurement Standards, Industrial Technology Research Institute (CMS-ITRI, Chinese Taipei) piloted the project. The participants are listed in Table 1.

Table 1 List of participating institutes

Participant (In order of participation)	Acronym	Country/Economy
National Institute of Metrology, China	NIM	China
National Measurement Institute, Australia	NMIA	Australia
National Metrology Institute of Malaysia	NMIM	Malaysia
Standards and Calibration Laboratory	SCL	Hong Kong, China
National Metrology Institute of Japan, AIST	NMIJ/AIST	Japan
National Institute of Metrology, Thailand	NIMT	Thailand
Center for Measurement Standards, Industrial Technology Research Institute	CMS-ITRI	Chinese Taipei
Korea Research Institute of Standards and Science	KRISS	Korea

This report is supplemented by the following Microsoft Excel spreadsheets in Table 2.

Table 2 List of Microsoft Excel spreadsheets for this report

Spreadsheet title	Spreadsheet content
APMP.AUV.A-K5 Tables of Data_Final Report.xlsx	Results and uncertainties for both microphones declared by all participants
APMP.AUV.A-K5 Uncertainty Budgets_ Final Report.xlsx	Uncertainty budgets declared by all participants

The protocol[2] specified the determination of the pressure sensitivities of two IEC type LS1P microphones according to IEC 61094-2: 2009[3], at reference environmental conditions specified therein. The microphones were circulated as travelling standards to each participant in turn, who were asked to calibrate them by their normal method (as might be offered to a customer) and report the results in their usual calibration certificate format. In addition, information was requested on the microphone parameters used to determine the sensitivity, any variation from the requirements of IEC 61094-2 together with an estimate of its likely effect on the results, and a breakdown of the declared standard uncertainty showing the components considered.

Table 3 **Scope of key comparison**

Frequency range	**Sensitivity level**	**Sensitivity phase**
2 Hz - 20 Hz (1/3-octave)	Optional	Optional
20 Hz – 10 kHz (1/12-octave)	Mandatory	Optional

Participants were asked to complete the mandatory elements, unless agreed in advance with the pilot laboratory, and were given the option to report results and link to the KCRV in the optional categories. Each laboratory was asked to determine the pressure sensitivity level of each reference microphone, and also the pressure sensitivity phase where available.

The first participant received the microphones in June 2020 and the final participant completed the measurements in August 2021.

2 DESCRIPTION OF PARTICIPANTS' MEASUREMENT SYSTEMS

Participants were asked to provide details of their methods including any aspects that deviate from IEC 61094-2. Since there are aspects of the standard that can be applied in differing ways, participants were also asked to clarify which approach has been used.

2.1 NIM

2.1.1 Method

The calibrations were performed at NIM based on the pressure reciprocity calibration technique according to IEC 61094-2: 2009. Four plane wave couplers were used with nominal lengths 5.7 mm (B&K WA-0834), 7.5 mm (B&K UA-1429), 10 mm (B&K WA-0836) and 15 mm (B&K UA-1413).

The electrical transfer impedances were measured by the microphone reciprocity calibration system with type B&K 9699, including the B&K 3560C PULSE analyzer, the B&K 5998 reciprocity apparatus and the associated measurement program *PRMP.EXE*.

The B&K 5998 reciprocity apparatus with low frequency option was used. The transmitter microphone was connected to the transmitter unit with type B&K ZE 0796. And the receiver microphone was connected to a preamplifier with type B&K 2673. The voltage ratios used to calculate the electrical transfer impedances were measured by B&K 3560C with Steady State Response analyzer.

2.1.2 Deviations from standard

None declared.

2.1.3 Declared parameters

The microphones parameters used in the calibration were shown in Table 4.

Table 4 Microphone parameters declared by NIM

	4160.2652765	**4160.2652762**
Front cavity depth (mm)	1.95	1.94
Front cavity volume (mm^3)	537	534
Equivalent volume (mm^3)	140	140
Resonance frequency (kHz)	8.46	8.58
Loss factor	1.07	1.09
Static pressure coefficient at 250 Hz(dB/kPa)	-0.016	-0.016
Temperature coefficient at 250 Hz (dB/℃)	-0.002	-0.002

The front cavity depth was measured using confocal laser scanning microscope. The front cavity volume and the equivalent volume were determined by data fitting from the results of different couplers between 250 Hz to 2 kHz. The resonance frequency was determined by the phase response at the 90° shift. The loss factor was determined by the ratio of the sensitivity at the resonance frequency to that at 250 Hz.

Values of the temperature and static pressure coefficients of the microphones used in the calculations were -0.002 dB/°C and -0.016 dB/kPa at 250 Hz respectively.

2.1.4 Calculations

The pressure sensitivity was calculated using the software *MP.EXE 4.0* in 'Standard mode'.

2.2 NMIA

2.2.1 Method

The calibrations performed at the NMIA followed the method described in IEC 61094-2 Edition 2.0: 2009-02, Electroacoustics – Measurement microphones – Part 2: *Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique* (henceforth referred to as 'the Standard').

The calibration system includes a Brüel & Kjær Type 5998 reciprocity calibration apparatus, a Brüel & Kjær Type UA 1412 microphone fixture, a Brüel & Kjær Type ZE 0796 transmitter unit and a Brüel & Kjær Type 2673-W-002 preamplifier. Version 4 of the Brüel & Kjær RMP.exe calculation package was used to process the measurement data to calculate the microphone sensitivities. The 5998 reciprocity apparatus has been modified to extend the lower frequency limit of the generator input from 10 Hz to 1 Hz, by the replacement of four electrolytic capacitors labelled as C5, C6, C33 and C34 on the transmitter PCB, with 220 µF capacitors as recommended by Brüel & Kjær.

The program RMP.exe utilizes values of several microphone parameters, supplied by the user, along with electrical measurements acquired through the reciprocity procedure to determine the sensitivity values for each microphone. These parameters are the microphone front cavity depth, resonance frequency, front cavity volume, diaphragm diameter, loss factor, and diaphragm equivalent volume. During the process to determine the microphone sensitivity, these parameters are adjusted with the aim of minimizing the differences in the calculated sensitivity of each microphone, when different couplers are used in the reciprocity apparatus. The assumption is that a microphone's pressure sensitivity should not be dependent on the volume to which it is exposed.

The front cavity depths of the intercomparison microphones were measured using a Leica DM6000 M automated microscope. The measurements of the front cavity depths correspond to the average of five measurements on each microphone performed at random locations. The resonance frequency of each microphone was measured using an electrostatic actuator, with this value used as a starting value for data fitting. Similarly, the starting value of the front cavity volume was calculated from the measured cavity depth and the nominal diaphragm diameter of the microphones. Nominal Brüel & Kjær values for data fitting procedures. The nominal values indicated above have been taken from the manufacturer's recommended parameters, such as those presented in chapter 5.8.1 of the Reciprocity Calibration Apparatus Type 9699 User Manual (December 1997, document number BE 1499-11).

The data fitting procedure minimized the differences in the calculated microphone sensitivities from reciprocity measurements using two plane-wave couplers of different volumes. The two plane-wave couplers were Brüel & Kjær Types UA 1413 and UA 1429. This process was iterative, incorporating both automated and manual fitting procedures. The combined diaphragm equivalent volume and front cavity volumes were adjusted to minimize the calculated sensitivity differences across both couplers in the low to mid-frequency range. The ratio of these volumes, while maintaining the combined total volume, was adjusted to minimize differences at higher frequencies. The resonance frequency was also varied to minimize calculated sensitivity differences across both couplers, with the loss factor determined sequentially as the ratio of the calculated sensitivity at the resonance frequency (found via interpolation), to the calculated sensitivity at 250 Hz. An automated data fitting procedure was also used to verify the process described above, and to further improve the fit.

2.2.2 Deviations from standard

None declared.

2.2.3 Declared parameters

Table 5 Microphone parameters declared by NMIA

	4160.2652765	**4160.2652762**
Front cavity depth (mm)	1.96	1.96
Front cavity volume (mm^3)	533	533
Equivalent volume (mm^3)	139	136
Resonance frequency (kHz)	8.25	8.3
Loss factor	1.01	1.01
Excess Surface Area (mm^2)	0.0	0.0
Effective Diameter (mm)	17.9	17.9

2.2.4 Calculations

As the sensitivity calculations were performed with a standard copy of Version 4 of Brüel & Kjær's RMP.exe software, the broadband solution as provided in Annex A.3 of the Standard has been used to account for viscous and thermal losses. Likewise, the environmental parameters, as provided in Annex F of the standard have been used in the calculation software. The calculations of microphone sensitivity have also incorporated radial wave motion corrections corresponding to the Bessel shape profile of the diaphragm velocity distribution as provided by Rasmussen[4]. Environmental corrections were applied based on the equations provided by Rasmussen[5].

Capillary tube corrections were not applied in the calculations, where the vents in the Brüel & Kjær couplers were blocked by a needle bung.

2.3 NMIM

2.3.1 Method

The calibration is performed according to IEC 61094-2: 2009 using Brüel & Kjær 9699 Reciprocity Calibration System.

2.3.2 Deviations from standard

None declared.

2.3.3 Declared parameters

Table 6 Microphone parameters declared by NMIM

	4160.2652765	**4160.2652762**
Front cavity depth (mm)	1.97	1.97
Front cavity volume (mm^3)	542	544
Equivalent volume (mm^3)	135	130
Resonance frequency (kHz)	8.2	8.2
Loss factor	1.05	1.05
Static pressure coefficient at 250 Hz(dB/kPa)	-0.015	-0.015
Temperature coefficient at 250Hz (dB/°C)	-0.002	-0.002

2.3.4 Calculations

A Brüel & Kjær's RMP.exe software with pressure sensitivity calculation using MP.EXE.

2.4 SCL

2.4.1 Method

In the International Standard IEC 61094-2: 2009, it defines the electrical transfer impedance for a system of two acoustically coupled microphones as the quotient of the open circuit voltage of the receiver microphone and the input current through the electrical terminals of the transmitter microphone. The B&K Type 9699 reciprocity calibration system measures the current of the transmitter microphone in an indirect way and determines the current by measuring the voltage across a precision capacitor that is connected into series with the transmitted microphone. For this reason, the Type

9699 expressions valid for electrical transfer impedance and for microphone sensitivity are slightly different from those stated in the Standard IEC 61094-2: 2009. It simplifies both the measurement equipment and the measurement process. Measurement of current and of absolute voltage is avoided, only voltage ratios need to be measured. The reported results will not be affected.

The uncertainty component “Capillary tube dimensions” as stated in Table 1 of the Standard IEC 61094-2: 2009 hasn’t taken into account since capillary tubes are not applied in this measurement. The reported results will not be affected and its associated uncertainties will be smaller as compared with capillary tubes are applied.

2.4.2 Deviations from standard

None declared.

2.4.3 Declared parameters

The values of the front cavity volume, cavity depth, and microphone acoustic impedance parameters used in the calculation, where appropriate.

Table 7 Microphone parameters declared by SCL

	4160.2652765	**4160.2652762**
Front cavity depth (mm)	1.990	1.990
Front cavity volume (mm^3)	542.0	542.0
Equivalent volume (mm^3)	133.6	128.7
Resonance frequency (kHz)	8.2	8.20
Loss factor	1.05	1.05
Excess Surface Area (mm^2)	0.0	0.0
Effective Diameter (mm)	17.9	17.9
Static pressure coefficient (dB/kPa)	-0.0156	-0.0149
Temperature coefficient (dB/℃)	-0.003	-0.003
RH correction	UNK	UNK

2.4.4 Calculations

None declared.

2.5 NMIJ/AIST

2.5.1 Method

The pressure sensitivity was determined in compliance with IEC 61094-2: 2009, using a reciprocity calibration system developed by NMIJ. In this system, the signal generation was made by a PXI waveform generator, PXI-5406 and the signal processing were executed by a PXI modulus and chassis were manufactured by National Instruments Co. Signal to noise ratio was improved by the synchronous waveform averaging method. The insert voltage technique was used to cancel the effect of the gain and impedance of an electrical circuit. The calibration was performed with the aid of LABVIEW.

Brüel & Kjær type UA1429 plane-wave (short) coupler was used for the reciprocity calibration, and a long coupler type UA1413 was also used for determining the equivalent volume of the microphones under test. Both couplers were filled with air. No grease was used to the contacting surfaces between the microphones and the couplers. The capillary tube was blocked by a needle bung DA5563. The capillary tube correction was not applied.

All the measurements were conducted within a room whose temperature and humidity were controlled (23.0 °C±0.5 °C and 50 %±5 %, respectively). Modulus and phase of pressure sensitivity were corrected to the value under the reference environmental conditions by using K. Rasmussen's method[6]. For modulus of pressure sensitivity below 250 Hz, it was corrected with reference to the technical paper by R. Kosobrodof[7]. Below 250 Hz, pressure and temperature dependency of the phase were not corrected because there were no reliable pressure and temperature coefficients.

2.5.2 Deviations from standard

None declared.

2.5.3 Declared parameters

Microphone parameters were determined as follows: The resonance frequency and loss factor were taken from Brüel & Kjær nominal values. Front depth was measured using a microscope calibrated by an ISO 17025 accredited calibration laboratory. Equivalent volume was calculated as an averaged value from 125 Hz to 2 kHz.

Table 8 Microphone parameters declared by NMIJ/AIST

	4160.2652765	**4160.2652762**
Front cavity depth (mm)	1.95	1.96
Front cavity volume (mm^3)	536	538
Equivalent volume (mm^3)	141	129
Resonance frequency (kHz)	8.2	8.2
Loss factor	1.05	1.05

2.5.4 Calculations

None declared.

2.6 NIMT

2.6.1 Method

The calibration was performed at the NIMT based on the pressure reciprocity calibration technique according to IEC 61094-2: 2009, using the pressure reciprocity calibration system Type B&K 9699.

The calibration system consists of B&K type 5998 reciprocity calibration apparatus, B&K type UA-1412 microphone fixture, B&K type ZE-0796 transmitter unit, B&K 2673-T preamplifier, B&K WB-3532 pump unit and B&K WA-1636 stabilization tank. The B&K type UA-1429 short plane-wave coupler and B&K type UA-1413 long plane-wave coupler is used for this calibration. Each coupler is supplied with a Needle Bung type DA-5563 and were filled with air.

All the measurement was conducted in the laboratory that control the ambient condition at (101.325±1.5) kPa for pressure, (23±1) °C for temperature and (50±15)% for relative humidity. The ambient pressure was controlled by using B&K WB-3532 pump unit and keep stabilized pressure by using B&K WA-1636 stabilization tank.

2.6.2 Deviations from standard

None declared.

2.6.3 Declared parameters

The following values was applied during the calculation of the pressure sensitivity of the standard microphone. The front cavity depth was measured using CNC 3D measuring machine by Dimension laboratory of NIMT.

Table 9 Microphone parameters declared by NIMT

	4160.2652765	**4160.2652762**
Front cavity depth (mm)	1.903	1.979
Front cavity volume (mm^3)	524.7	544.0
Equivalent volume (mm^3)	151.9	124.0
Resonance frequency (kHz)	8.2	8.3
Loss factor	1.0	1.0
Effective Diameter (mm)	17.9	17.9

2.6.4 Calculations

The pressure sensitivity of microphone was calculated by using the MP.EXE version 4.00. The program follows the specifications given in IEC 61094-2: 2009. The pressure sensitivity were calculated at reference environmental conditions and at the actual environmental conditions during the measurements.

2.7 CMS-ITRI

2.7.1 Method

This calibration was carried out according to Instrument Calibration Technique for Microphone Sound Pressure Sensitivity Calibration System — Reciprocity Method.

Take two reference microphones and one microphone to be calibrated by selecting two microphones as a group to carry out the calibration, one being as the transmitting microphone and the other as the receiving microphone during calibration. Place the microphones separately into the cavity coupler and measuring the ratio of voltage attenuation, then will obtain three individual sets of sensitivity equation to solve the sound pressure sensitivity of microphone by reciprocity method.

The measured value of microphone sound pressure sensitivity is at ambient condition: 23.0 °C for temperature and 101.325 kPa for ambient pressure.

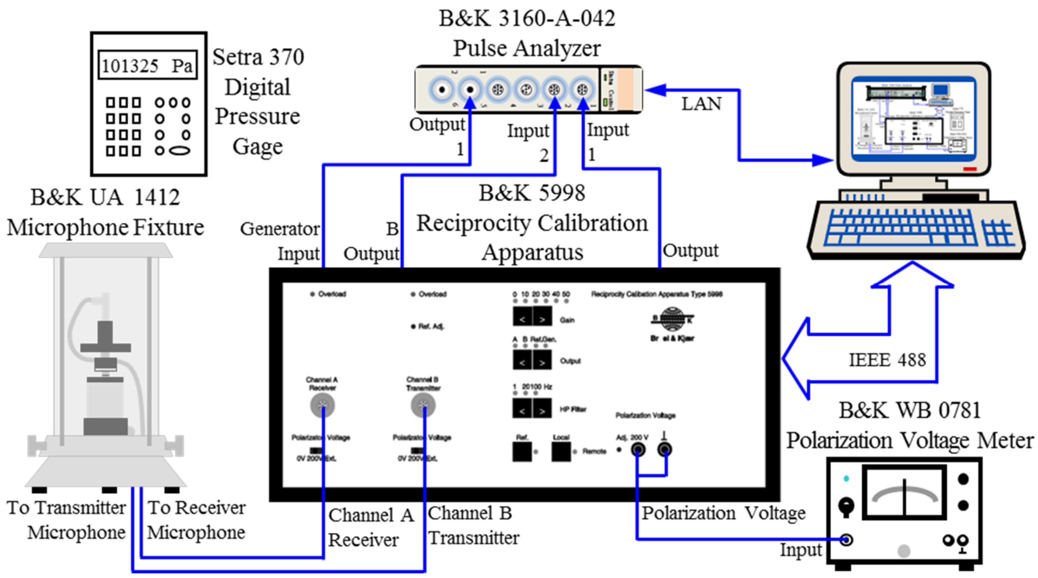

Figure 1 Microphone sensitivity calibration system - Reciprocity Method block diagram

2.7.2 Deviations from standard

None declared.

2.7.3 Declared parameters

Table 10 Microphone parameters declared by CMS-ITRI

	4160.2652765	**4160.2652762**
Front cavity depth (mm)	1.95	1.96
Front cavity volume (mm^3)	532.6	531.6
Equivalent volume (mm^3)	143.8	140.7
Resonance frequency (kHz)	8.2	8.2
Loss factor	1.05	1.05
Excess Surface Area (mm^2)	-	-
Effective Diameter (mm)	17.9	17.9
Static pressure coefficient at 250 Hz(dB/kPa)	-0.016	-0.016
Temperature coefficient at 250Hz (dB/°C)	-0.002	-0.002
RH correction	-	-

2.7.4 Calculations

None declared.

2.8 KRISS

2.8.1 Method

The calibration is performed by a reciprocity calibration according to IEC 61094-2 by using the Brüel & Kjær reciprocity calibration unit, type 5998. The microphones are coupled in pairs with two plane-wave couplers with nominal length of 7.5 mm and 15 mm, filled with air at all frequencies. A capillary tube was blocked by a needle and no capillary corrections were applied.

2.8.2 Deviations from standard

None declared.

2.8.3 Declared parameters

The front cavity depths of the microphones are measured by the Video Measuring Scope, Nikon, VMH-300N. The equivalent volume is determined by fitting the final results for the two couplers at the frequency of about 250 Hz. The nominal value of resonance frequency and the loss factor are applied.

Table 11 Microphone parameters declared by KRISS

	4160.2652765	**4160.2652762**
Front cavity depth (mm)	1.967	1.965
Front cavity volume (mm^3)	539.6	539.3
Equivalent volume (mm^3)	134.5	129.1
Resonance frequency (kHz)	8.2	8.2
Loss factor	1.05	1.05
Static pressure coefficient at 250 Hz(dB/kPa)	-0.015	-0.015
Temperature coefficient at 250Hz (dB/K)	-0.0025	-0.0025

2.8.4 Calculations

The microphone pressure sensitivities are calculated by using the Brüel & Kjær Sensitivity Calculation Program MP.EXE, Ver. 4.00. Corrections for radial wave motion in the couplers are not applied and the difference from the heat conduction correction with Geber's full solution is included in the uncertainty budget.

3 STABILITY OF TRAVELLING STANDARDS

Two Brüel & Kjær type 4160 microphones were selected for this project. Both microphones were more than 10 years old with a history of stability. The two microphones were calibrated regularly at NIM prior to circulation to establish their suitability for the key comparison.

The stability of the microphones was monitored throughout the project by regular calibration at NIM. A full calibration of each microphone was conducted, before and after circulation to pairs of participants. The results, referred to their mean value, are presented for the sensitivity level and sensitivity phase respectively. As is shown in Figure 2 and Figure 3, it gives an initial impression of the stability of microphone 4160 2652765.

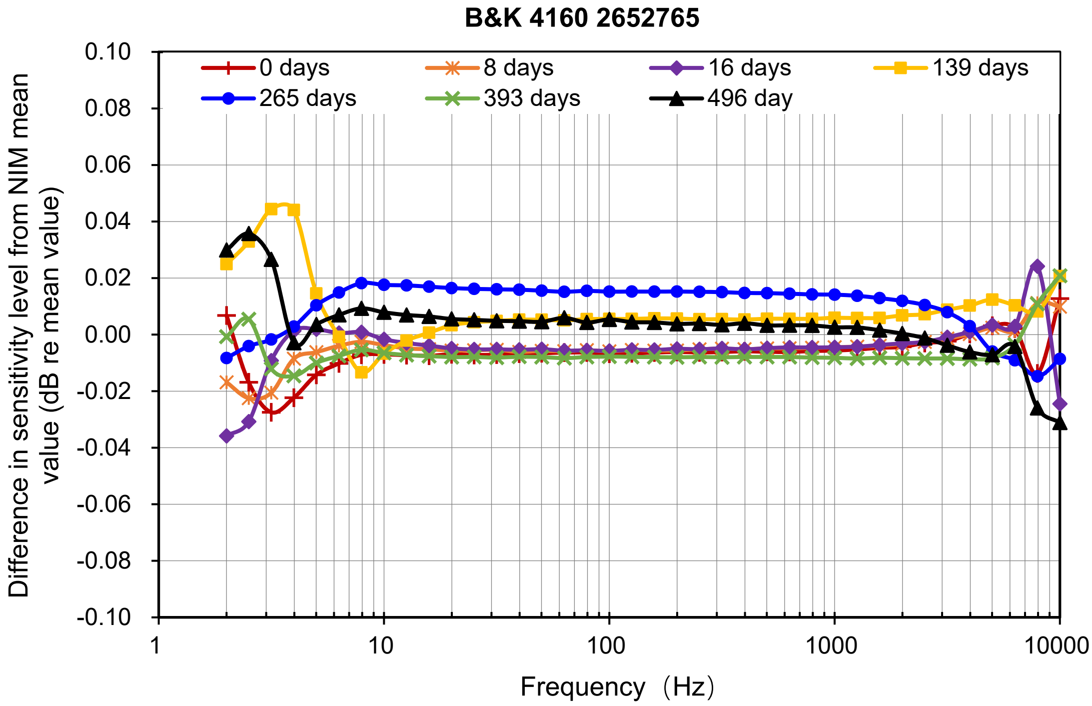

Figure 2 Stability of microphone 4160 2652765 in terms of the maximum positive and negative differences from the mean value of sensitivity level throughout the key comparison

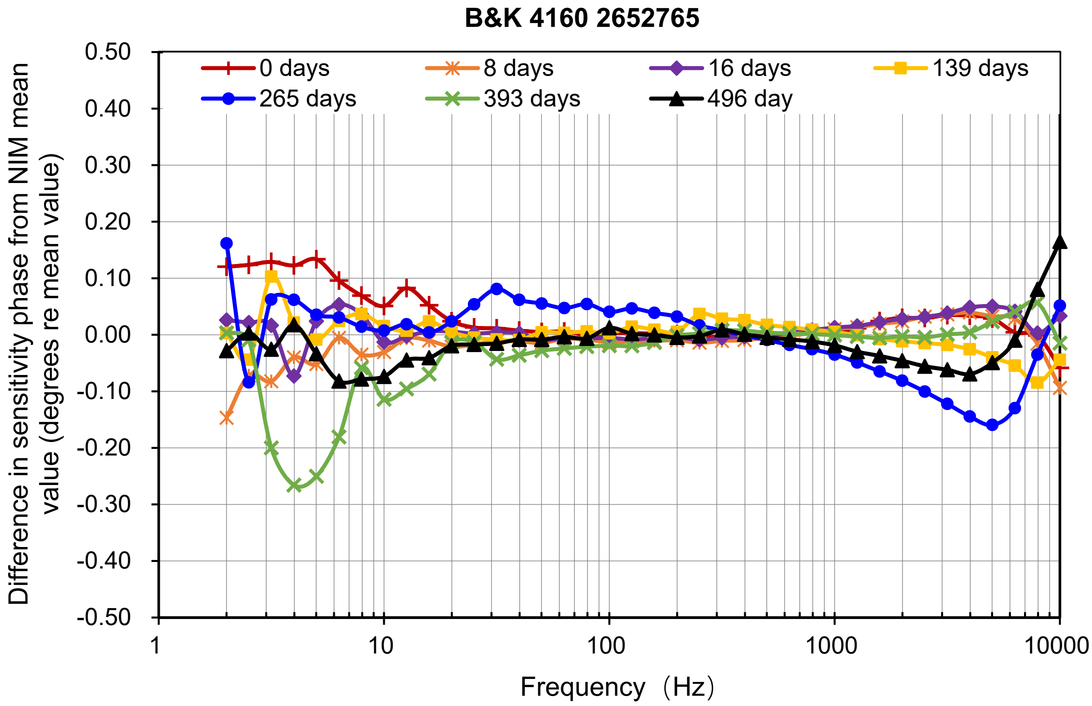

Figure 3 Stability of microphone 4160 2652765 in terms of the maximum positive and negative differences from the mean value of sensitivity phase throughout the key comparison

For microphone 4160 2652765, the absolute values of the difference in sensitivity level and sensitivity phase from NIM mean value are typically less than 0.03 dB and 0.20 degrees at frequencies from 6.31 Hz to 7940 Hz respectively in Figure 2 and Figure 3. The standard deviation of these NIM results falls below the uncertainty allocated in

NIM's uncertainty budget.

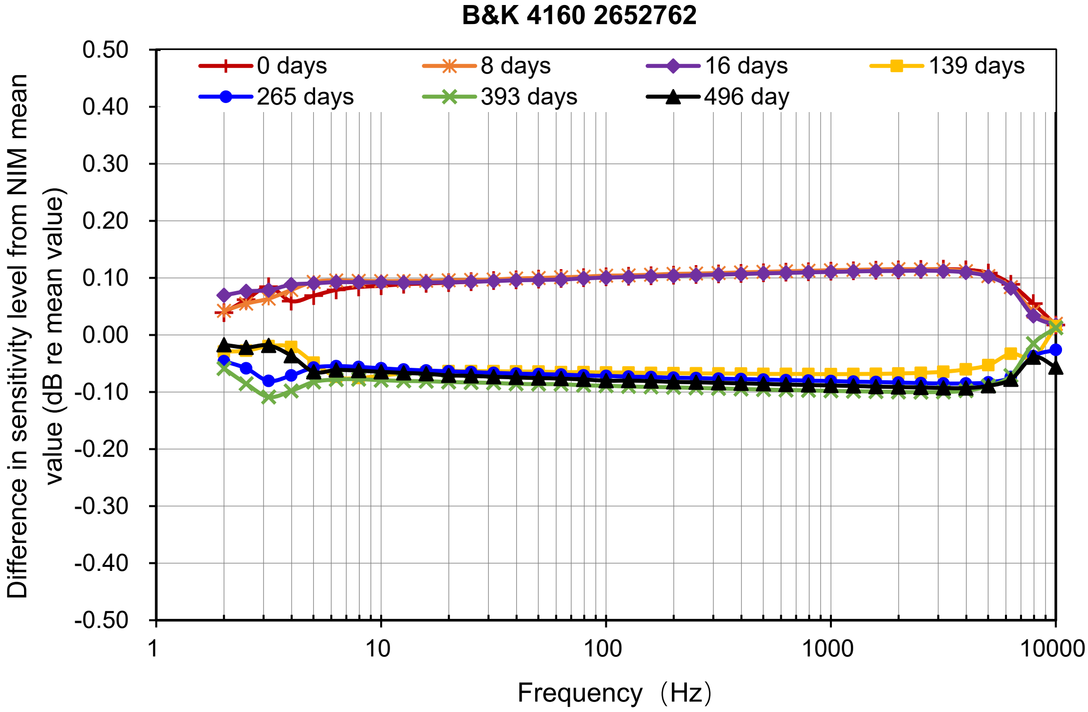

Figure 4 Stability of microphone 4160 2652762 in terms of the maximum positive and negative differences from the mean value of sensitivity level throughout the key comparison

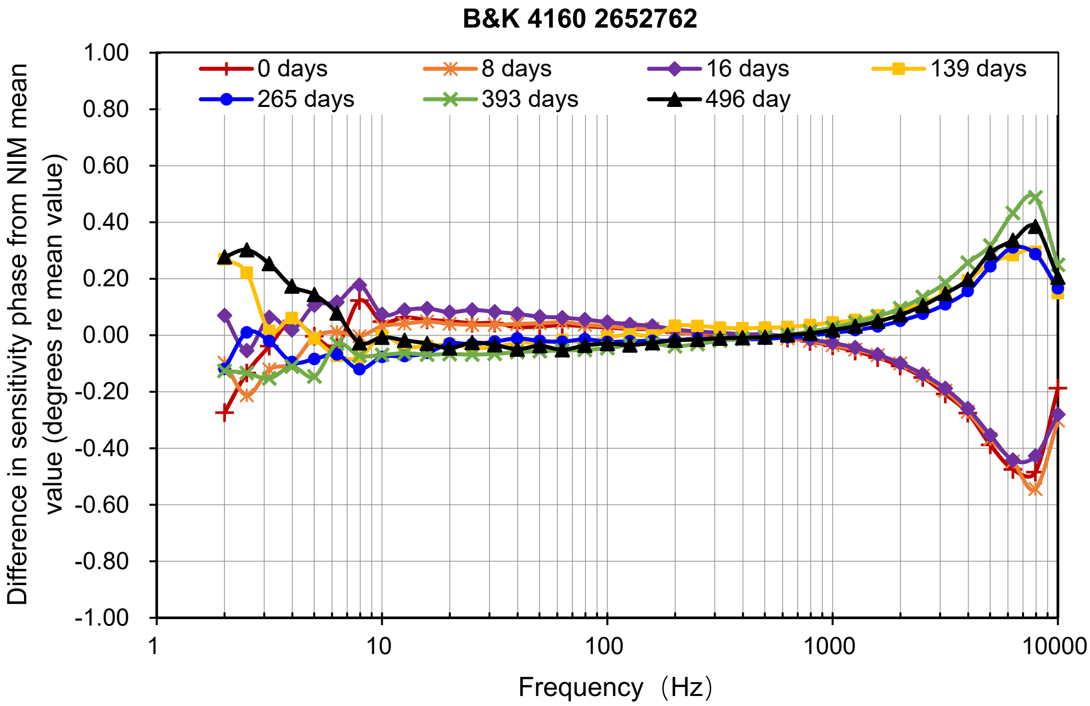

Figure 5 Stability of microphone 4160 2652762 in terms of the maximum positive and negative differences from the mean value of sensitivity phase throughout the key comparison

For microphone 4160 2652762, the absolute values of the difference in sensitivity level and sensitivity phase from NIM mean value are typically less than 0.12 dB and 0.60

degrees at frequencies from 6.31 Hz to 7940 Hz respectively in Figure 4 and Figure 5. The standard deviation of these NIM results significantly exceeds the uncertainty allocated in NIM's uncertainty budget. It can be found that the sensitivity level of microphone 4160 2652762 changed about 0.15 dB at frequencies from 6.31 Hz to 7940 Hz after circulation to the first pairs of participants (NMIA and NMIM). Figure 6 shows the details of the sensitivity level jump of microphone 4160 2652762 at 251.19 Hz. No such jump is visible in Figure 7 for microphone 4160 2652765. One laboratory (NMIA) has noted the sensitivity drift of the microphone 4160 2652762 during its period of measurements. Also, the sensitivity phase of microphone 4160 2652762 changed at frequencies above 1000 Hz and the maximum changes was about 1.00 degrees. Thus, the measurements of microphone 4160 2652762 indicate an unacceptable level of stability over the full duration of these measurements.

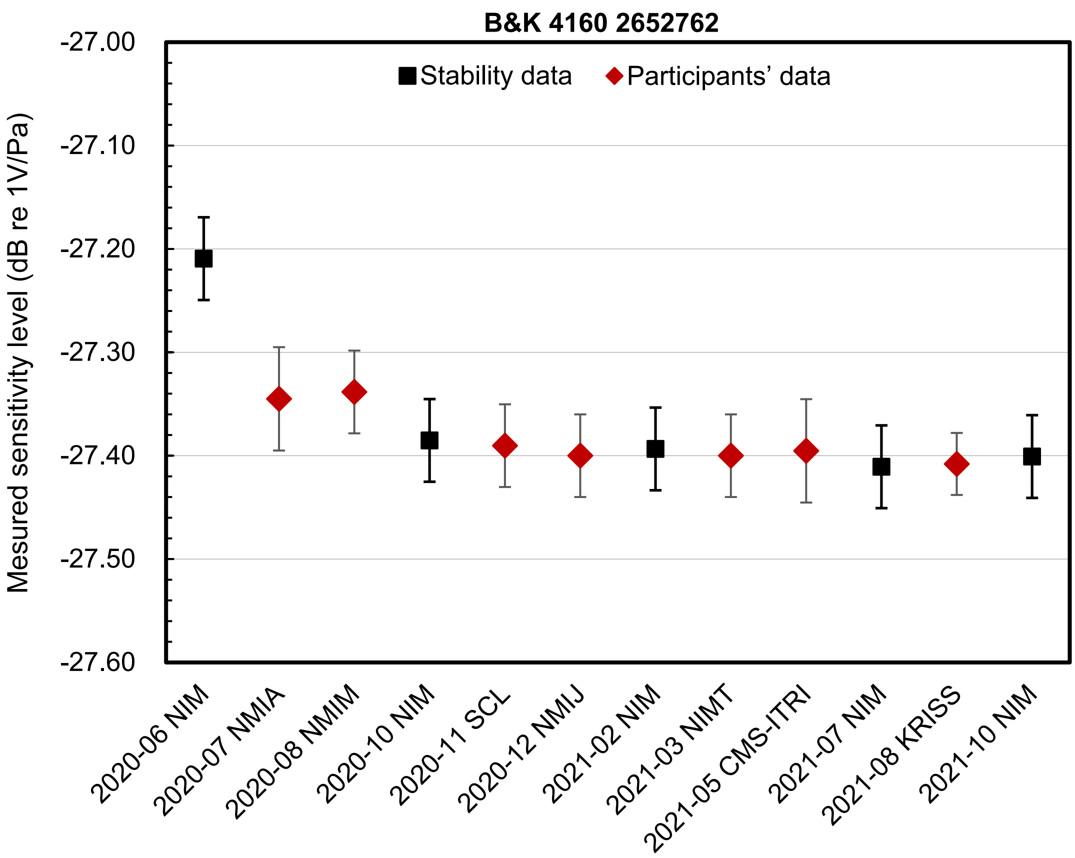

Figure 6 Stability of 4160 2652762 at 251.19 Hz during APMP.AUV.A-K5

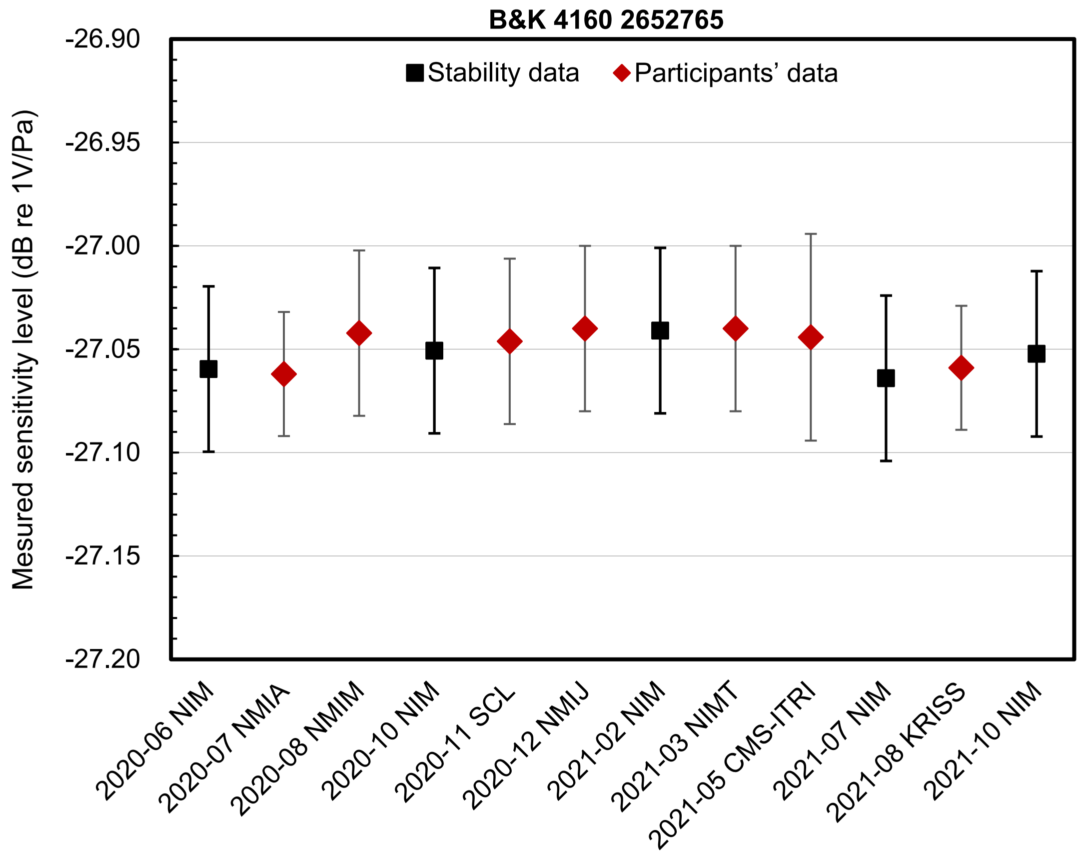

Figure 7 Stability of 4160 2652765 at 251.19 Hz during APMP.AUV.A-K5

The conclusions of the stability analysis are described as follows.

- Microphone 4160 2652765 has an acceptable stability performance.
- Microphone 4160 2652762 does not have an acceptable level of stability for the obvious jump in sensitivity level at frequencies from 6.31 Hz to 7940 Hz and sensitivity phase at frequencies above 1000 Hz during the circulation of the first pairs participants.
- Microphone 4160 2652762 shows good stability after the circulation of the first pairs participants.

It was therefore recommended in the key comparison that:

- Microphone 4160 2652765 has been shown to be stable throughout the key comparison and would present a suitable basis for linking results to the KCRV by itself.
- Using a single microphone would allow a less complicated analysis and smaller overall uncertainties in the linking to the KCRV.
- The results for microphone 4160 2652762 are presented in this report, but are not analyzed further.

4 RESULTS AND ANALYSIS OF THE APMP.AUV.A-K5 COMPARISON DATA

Tables of declared results and uncertainties for both microphones are provided in Microsoft Excel spreadsheet 'APMP.AUV.A-K5 Tables of Data_Final Report.xlsx'.

Tables of declared participant uncertainty budgets are provided in Microsoft Excel spreadsheet 'APMP.AUV.A-K5 Uncertainty Budgets_Final Report.xlsx'.

As pilot laboratory, NIM was tasked with identifying anomalous results and providing the participants concerned with the opportunity to review their data. CIPM document CIPM MRA-G-11[8] states that:

"*If, on examination of the complete set of results, the pilot institute finds results that appear to be anomalous, the corresponding participating institutes are invited to check their results for numerical errors but without being informed of the magnitude or sign of the apparent anomaly. If no numerical error is found, the result stands and the complete set is sent in a report to all participants according to Section 8.2.*"

Following the analysis of the NIM stability measurements, it was decided to exclude microphone 4160 2652762 entirely from the calculations for linking the results to the KCRV and for identifying anomalous results.

The approach taken by NIM was as follows (applied independently for each frequency for microphone 4160 2652765 only):

1) Using the data from all the laboratories, evaluate the weighted mean and its associated standard uncertainty (allowing for the actual number of data elements where some laboratories did not submit data at all frequencies). The weighted mean y and the standard uncertainty $u(y)$ associated with y are given by:

$$y = \frac{\sum_{i=1}^{M}\left(\frac{y_i}{u^2(y_i)}\right)}{\sum_{i=1}^{M}\left(\frac{1}{u^2(y_i)}\right)}. \tag{1}$$

$$\frac{1}{u(y)} = \left[\sum_{i=1}^{M}\left(\frac{1}{u^2(y_i)}\right)\right]^{\frac{1}{2}} \tag{2}$$

where y_i represents the measurement result of the ith laboratory and $u(y_i)$ is the declared uncertainty associated with the measurement result, M is the number of the laboratories participated in the key comparison.

2) A chi-squared test was applied to test the consistency of the data with the

weighted mean.

The observed chi-squared value is given by:

$$\chi^2_{obs} = \sum_{i=1}^{N} \frac{\left(y_i - y\right)^2}{u^2\left(y_i\right)} \qquad (3)$$

The number of degrees of freedom is given by:

$$\nu = N - 1 \qquad (4)$$

where N represents the number of the laboratories included in the chi-squared test.

These values of χ^2_{obs} were compared with the value of $\chi^2_{0.05}$ for ν degrees of freedom, and if

$$\chi^2_{obs} \geq \chi^2(\nu)_{0.05} \qquad (5)$$

then the data was considered inconsistent.

3) If the test is passed, include the data for all the laboratories in the analysis to evaluate Degrees of Equivalence (DoEs) based on linking to the CCAUV.A-K5 key comparison.

4) If the test is not passed, determine a largest subset such that the data for the laboratories in that subset is consistent with the weighted mean of the data. Include the data for only those laboratories contained in the largest consistent subset in the analysis to calculate estimates of the sensitivity level and sensitivity phase. These estimates then provide the basis for evaluating DoEs based on linking to the CCAUV.A-K5 key comparison. (In this case the calculation of the DoEs is different according to whether the laboratory is contained or not in the largest consistent subset.)

The above analysis indicated that the measurement results of the sensitivity level provided by all participating laboratories passed the chi-squared test. For sensitivity phase, however, the chi-squared test was not passed for the complete data set at high frequencies. It was necessary that NMIJ/AIST (for frequencies between 5623.413 Hz and 10000.000 Hz) were excluded from the calculation of the weighted mean for the chi-squared test to pass. The corrections to the sensitivity phase results from NMIJ/AIST and the corresponding data analysis were provided in Annex A.

The data for the DoEs of the linking laboratories were used to link to CIPM comparison CCAUV.A-K5, with the linking laboratories NIM, KRISS and NMIJ/AIST.

Tables of calculated weighted mean of the sensitivity level and sensitivity phase for each microphone are provided in Microsoft Excel spreadsheet ‘APMP.AUV.A-K5 Tables of Data_Final Report.xlsx’.

For illustration, Figure 8(*a*) and Figure 8(*b*) show each laboratory's results as a difference from the weighted mean of the sensitivity level and sensitivity phase for microphone 2652765 respectively.

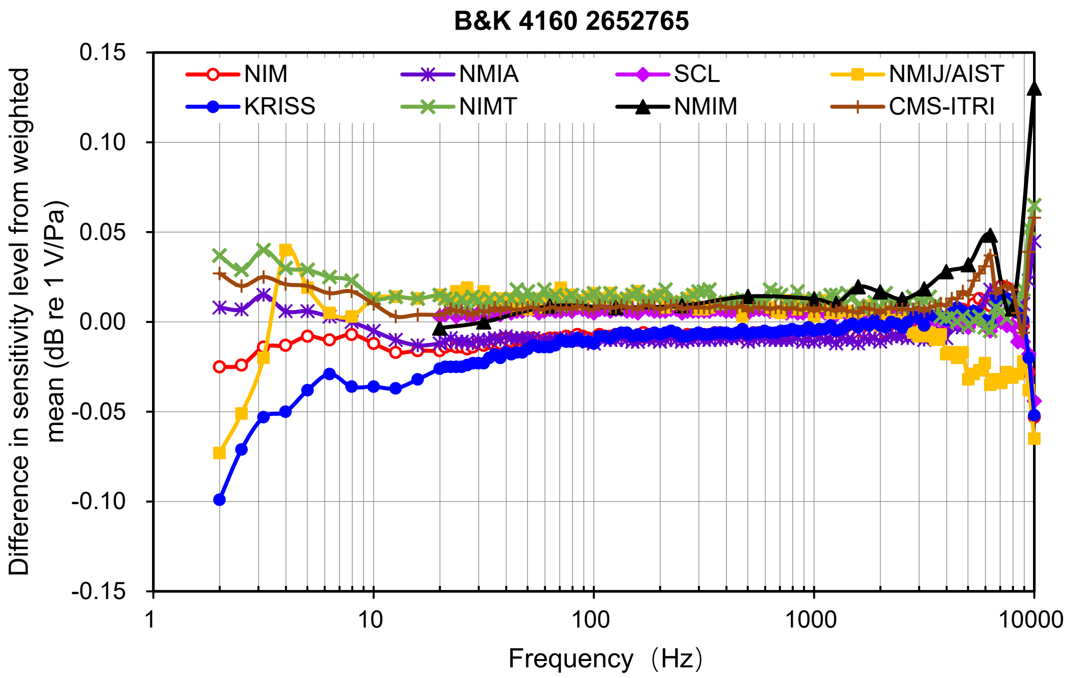

Figure 8(*a*) Combined sensitivity level results of all participating laboratories, for microphone 4160 2652765, shown as a difference from the weighted mean of the sensitivity level results

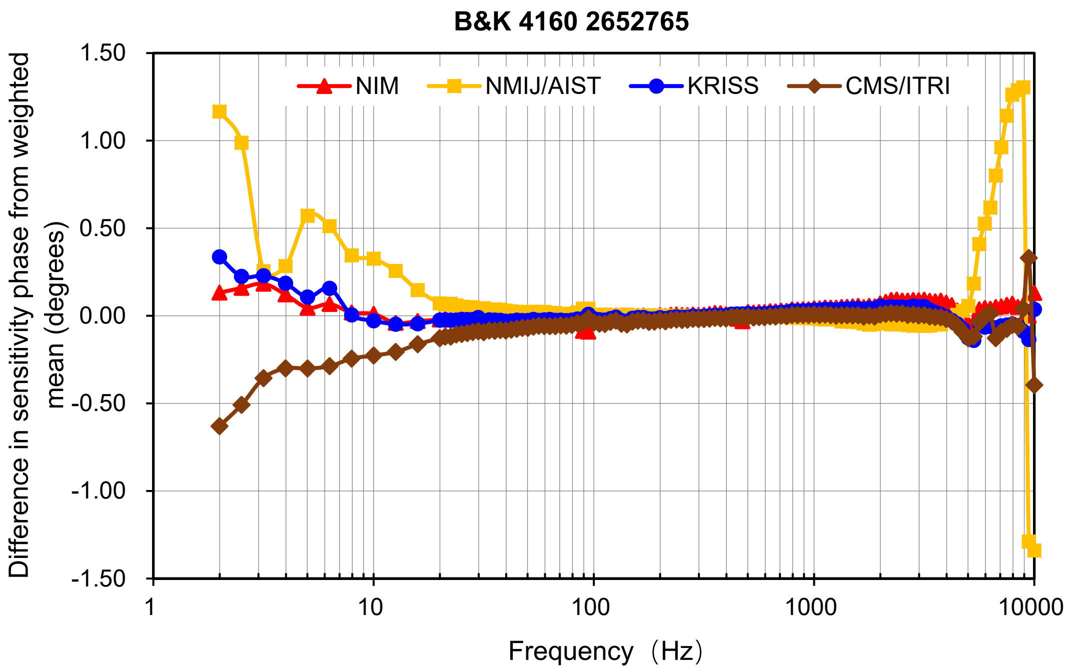

Figure 8(*b*) Combined sensitivity phase results of all participating laboratories, for microphone 4160 2652765, shown as a difference from the weighted mean of the sensitivity phase results

For microphone 4160 2652762, the unweighted mean of all measurement results is used to calculate the estimated sensitivity level and phase. Figure 9(*a*) and Figure 9(*b*) show each laboratory's results as a difference from the unweighted mean of the sensitivity level and sensitivity phase respectively. This microphone was not used in the linking calculations and the results are shown for illustration only.

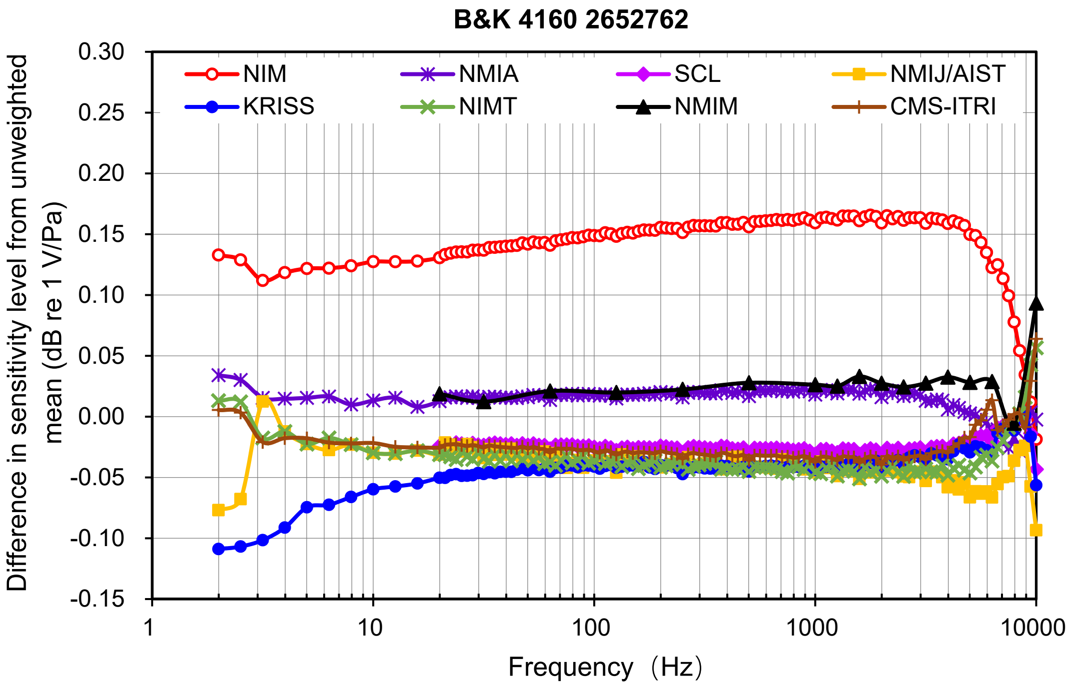

Figure 9(*a*) Combined sensitivity level results of all participating laboratories, for microphone 4160 2652762, shown as a difference from the unweighted mean of the sensitivity level results

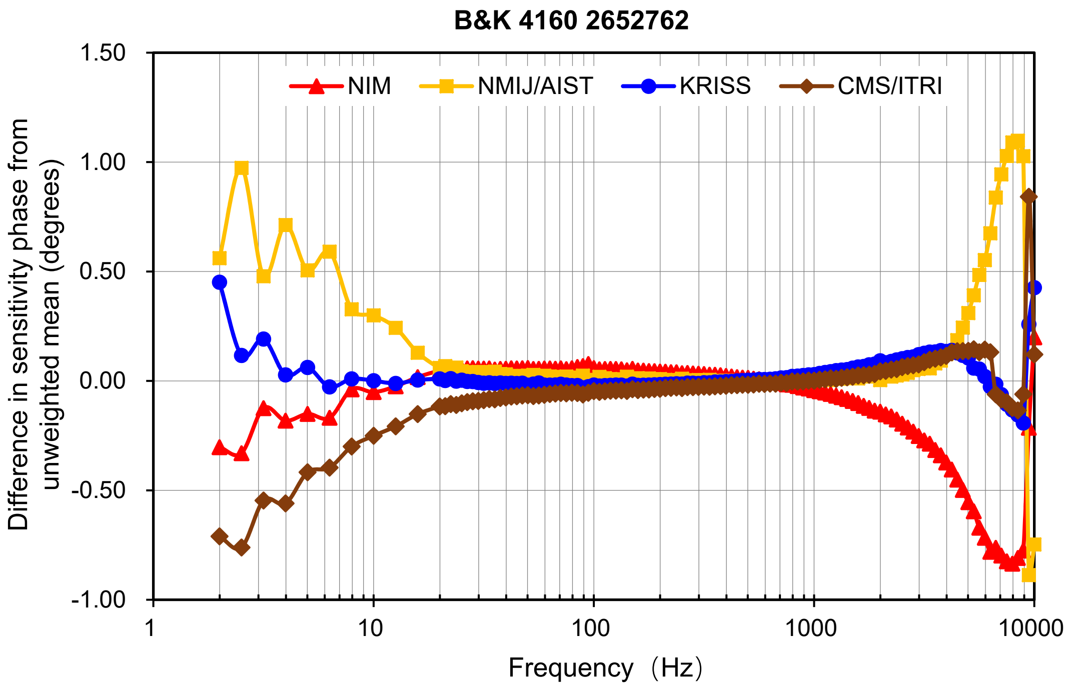

Figure 9(*b*) Combined sensitivity phase results of all participating laboratories, for microphone 4160 2652762, shown as a difference from the unweighted mean of the sensitivity phase results

NIM, KRISS and NMIJ/AIST are the three laboratories that link APMP.AUV.A-K5 back to CCAUV.A-K5. The link analysis relies to some extent on the assumption that the performance of the laboratories remains constant between the two key comparisons. As a check that this assumption is valid, the performance of the three linking laboratories has been compared with the weighted mean of the stable microphone in each key comparison. It is reasonable to expect the weighted mean values to be roughly equivalent and the linking laboratories' results to remain approximately the same in relation to those weighted mean values.

For sensitivity phase in CCAUV.A-K5, the KRISS data at frequencies between 1.995 Hz and 19.953 Hz and the NMIJ/AIST data at 6309.573 Hz were excluded from the calculation of the weighted mean for the chi-squared test to pass. The expanded uncertainty of DoEs for KRISS didn't include zero at frequencies between 21.135 Hz and 39.811 Hz. And the expanded uncertainty of DoEs for NMIJ/AIST didn't include zero at frequencies between 6309.573 Hz and 7943.282 Hz. For sensitivity phase in APMP.AUV.A-K5, the NMIJ/AIST data at frequencies between 5623.413 Hz and 10000.000 Hz were excluded from the calculation of the weighted mean. For sensitivity phase linking analysis, KRISS at frequencies between 1.995 Hz and 39.811 Hz and NMIJ/AIST at frequencies between 5623.413 Hz and 10000.000 Hz were not the linking laboratories.

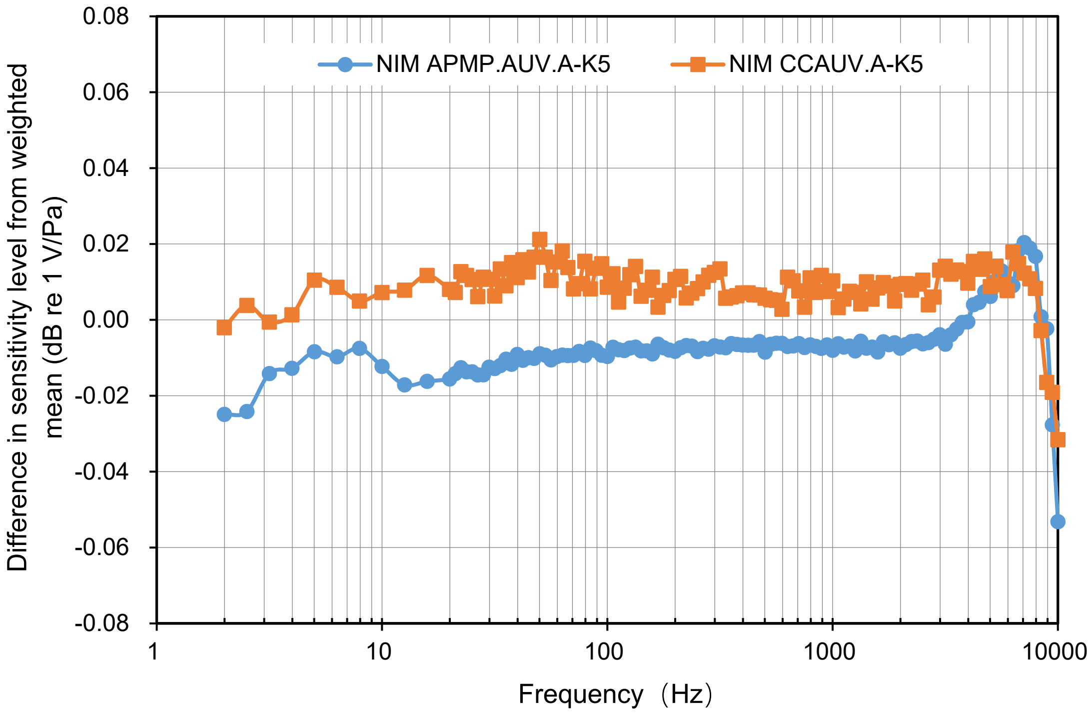

Figure 10(*a*) The NIM sensitivity level results for CCAUV.A-K5 and APMP.AUV.A-K5 in relation to the weighted mean used to calculate estimates of the sensitivity level for each key comparison.

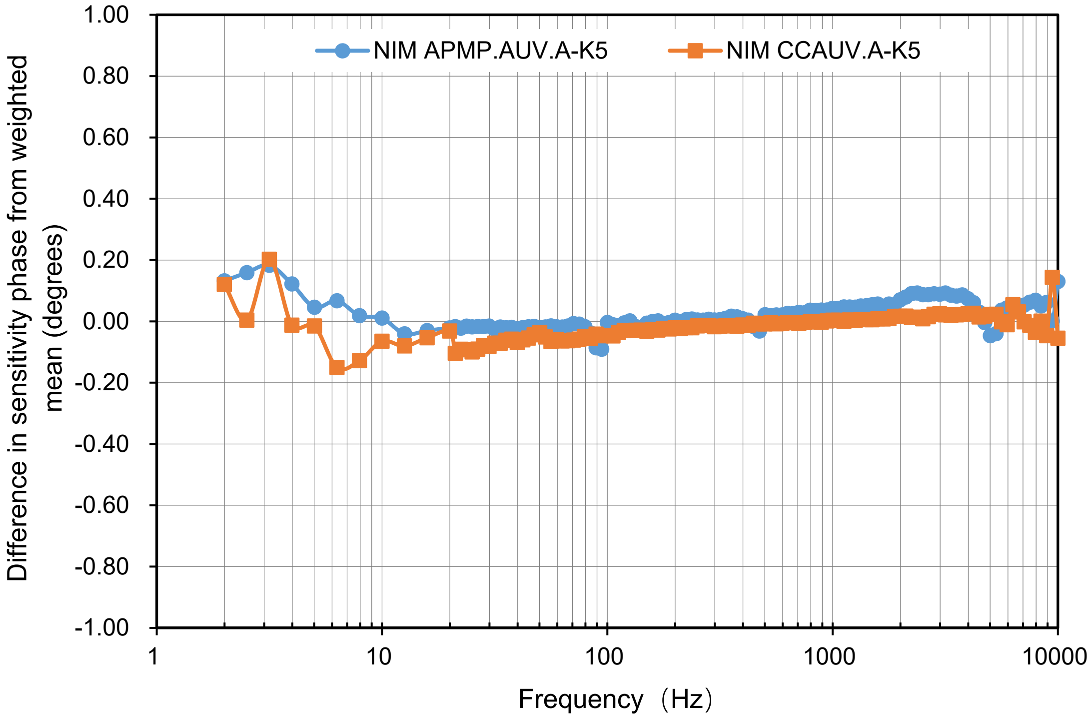

Figure 10(*b*) **The NIM sensitivity phase results for CCAUV.A-K5 and APMP.AUV.A-K5 in relation to the weighted mean used to calculate estimates of the sensitivity phase for each key comparison.**

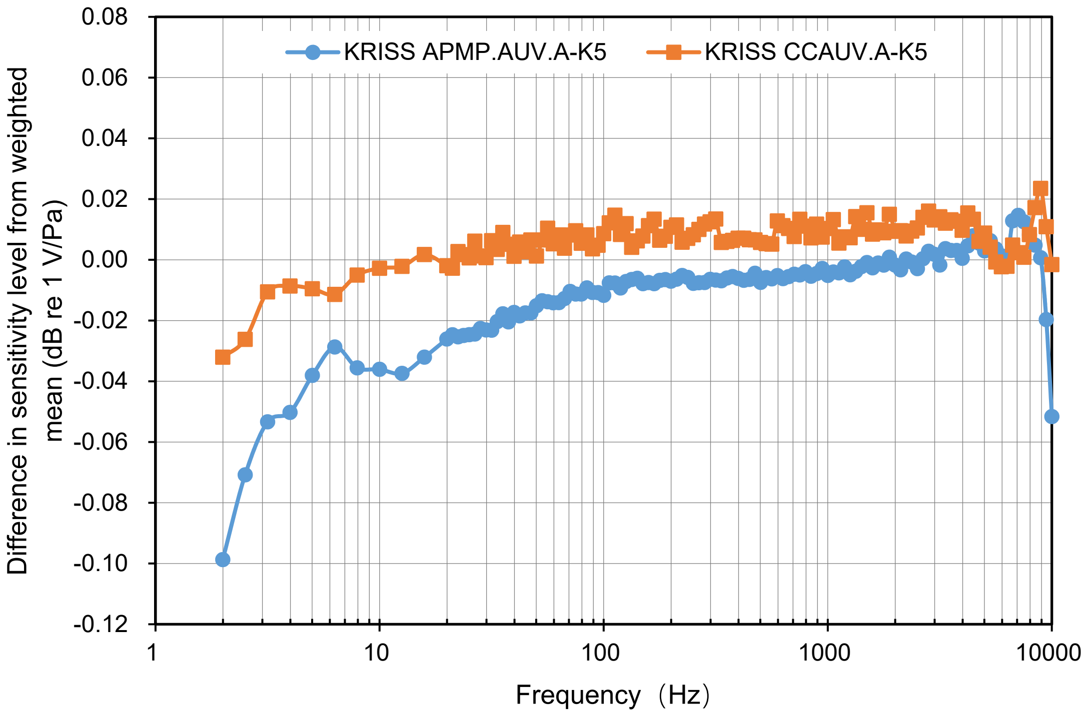

Figure 11(*a*) **The KRISS sensitivity level results for CCAUV.A-K5 and APMP.AUV.A-K5 in relation to the weighted mean used to calculate estimates of the sensitivity level for each key comparison.**

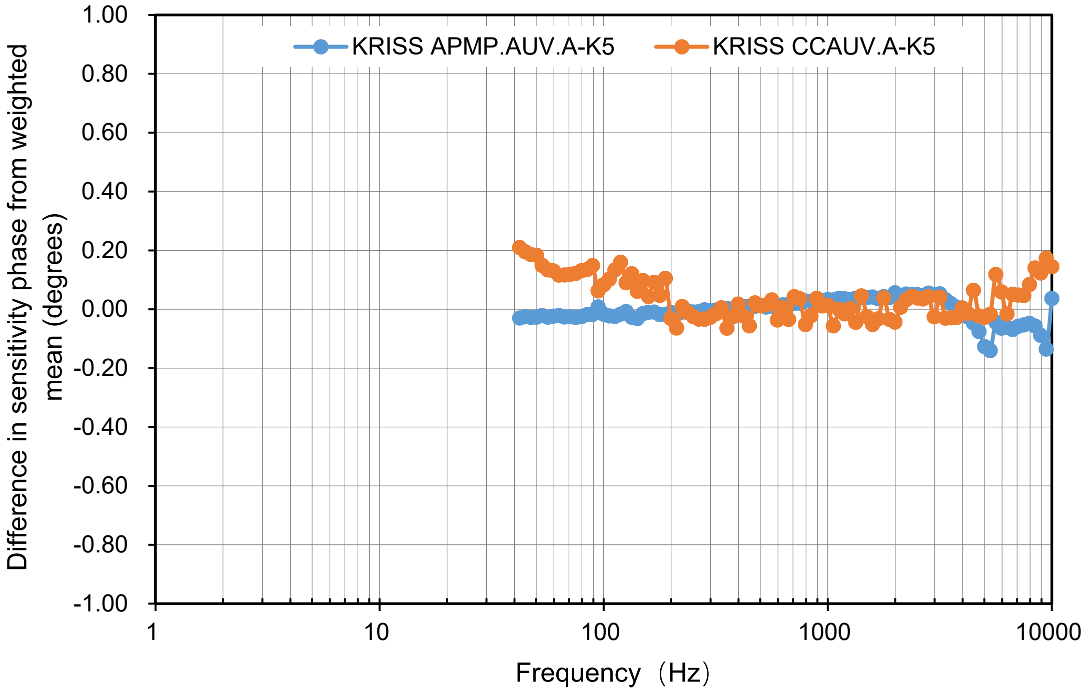

Figure 11(*b*) The KRISS sensitivity phase results for CCAUV.A-K5 and APMP.AUV.A-K5 in relation to the weighted mean used to calculate estimates of the sensitivity phase for each key comparison.

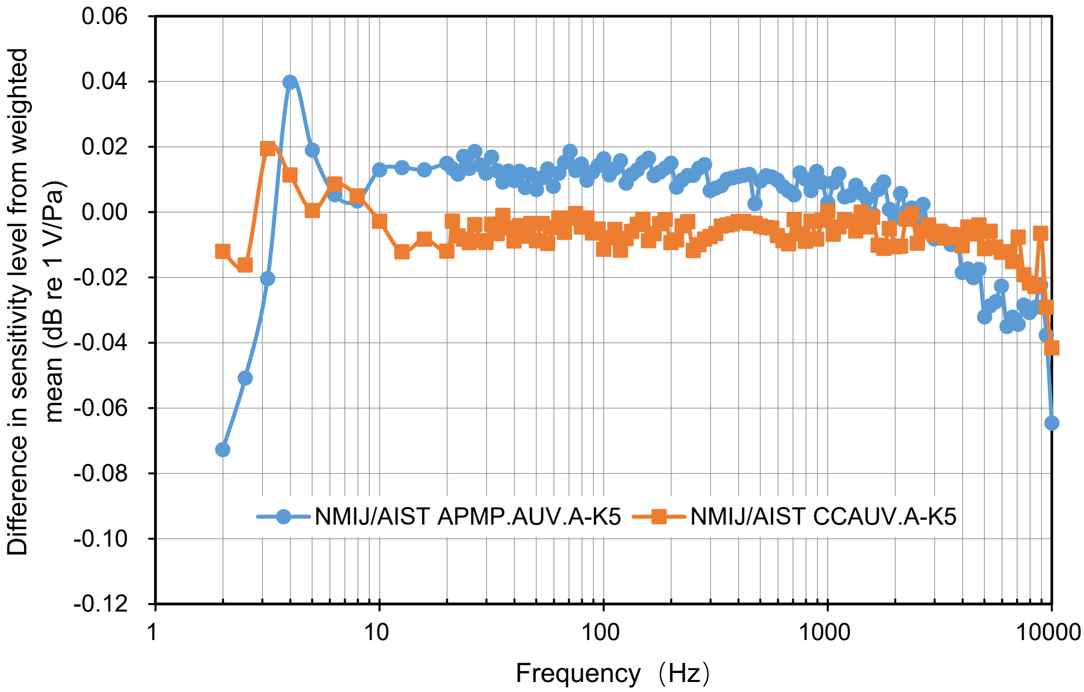

Figure 12(*a*) The NMIJ/AIST sensitivity level results for CCAUV.A-K5 and APMP.AUV.A-K5 in relation to the weighted mean used to calculate estimates of the sensitivity level for each key comparison.

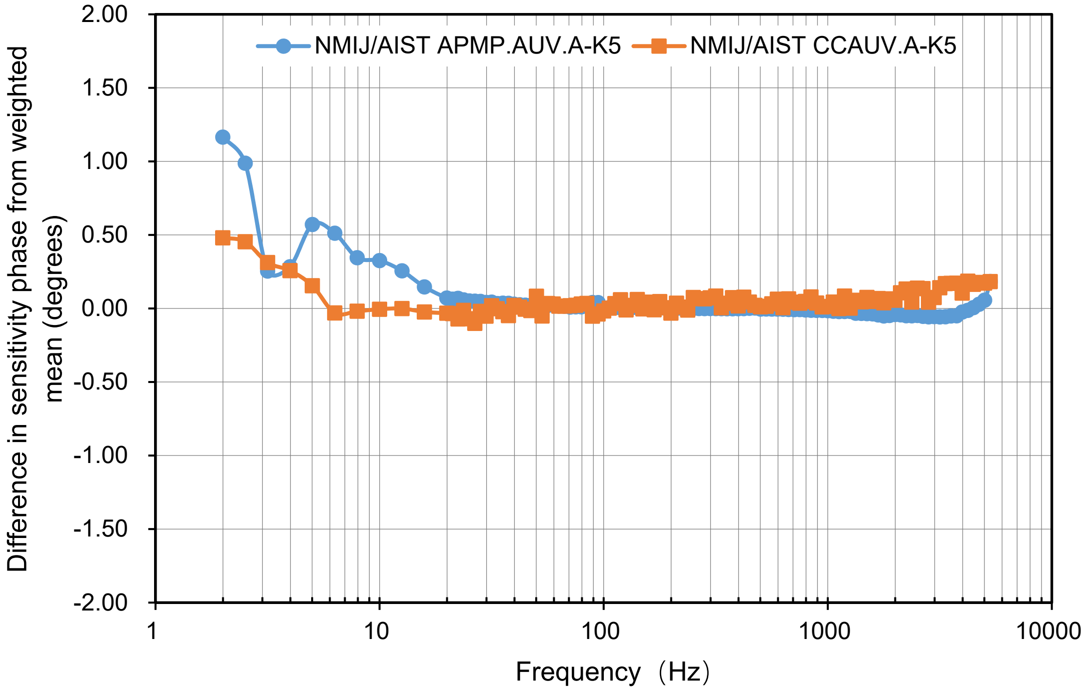

Figure 12(*b*) The NMIJ/AIST sensitivity phase results for CCAUV.A-K5 and APMP.AUV.A-K5 in relation to the weighted mean used to calculate estimates of the sensitivity phase for each key comparison.

Figure 10(*a*) and Figure 10(*b*) show the NIM results relative to the weighted mean of the results used to calculate estimates of the sensitivity level and sensitivity phase in each of the two key comparisons. Both NIM's results of sensitivity level and sensitivity phase show a good degree of consistency between the two key comparisons. Also, the results presented in Figure 11(*a*) to Figure 12(*b*) above provide a qualitative indication that the performance of the other two linking laboratories is satisfactory in the given frequency range.

5 LINKING TO THE KCRV ESTABLISHED IN CCAUV.A-K5

The main goal of the RMO comparison is to establish the DoEs for the participating laboratories through the linking laboratory taking part in CIPM and in RMO comparison[8]. In APMP.AUV.A-K5 comparison, there are three linking laboratories, including NIM, KRISS and NMIJ/AIST, which were all included in the CCAUV.A-K5. For sensitivity level, NIM, KRISS and NMIJ/AIST are all the linking laboratories. For sensitivity phase, KRISS is not the linking laboratory at frequencies between 1.995 Hz and 39.811 Hz and NMIJ/AIST is not the linking laboratory at frequencies between 5623.413 Hz and 10000.000 Hz.

Based on the stability analysis, only the microphone 4160 2652765 can be used in the linking analysis. The linking procedure is described below[9-12].

Suppose that N laboratories identified by indices i=1, …, N participated in CCAUV.A-K5, where l=i=1, …, L denotes the linking laboratories participated in both the comparisons CCAUV.A-K5 and APMP.AUV.A-K5, the measured results x_1, $u(x_1)$, x_2, $u(x_2)$, … , x_N, $u(x_N)$ denote the measurement results and associated standard uncertainties of the sensitivity level (or phase) provided by the participants used to calculate the KCRV in CCAUV.A-K5. The KCRV used in the following linking procedure is given in the final report of CCAUV.A-K5.

Suppose that M laboratories identified by indices j=1, …, M participated in APMP.AUV.A-K5, where l=j=1, …, L denote the linking laboratories participated in both the comparisons CCAUV.A-K5 and APMP.AUV.A-K5, the measured results y_1, $u(y_1)$, y_2, $u(y_2)$, … , y_M, $u(y_M)$ denote the measurement results and associated standard uncertainties of the sensitivity level (or phase) provided by the participants used to calculate the weighted mean in APMP.AUV.A-K5.

Let x_L and y_L denote the weighted mean of the measured results provided by the linking laboratories in CCAUV.A-K5 and APMP.AUV.A-K5:

$$x_L = \sum_{i=1}^{L} \frac{x_i}{u^2(x_i)} \Bigg/ \sum_{i=1}^{L} \frac{1}{u^2(x_i)} \tag{6}$$

$$u^2(x_L) = \frac{1}{\sum_{i=1}^{L} \frac{1}{u^2(x_i)}} \tag{7}$$

$$y_L = \sum_{j=1}^{L} \frac{y_j}{u^2(y_j)} \Bigg/ \sum_{j=1}^{L} \frac{1}{u^2(y_j)} \tag{8}$$

$$u^2(y_L) = \frac{1}{\sum_{j=1}^{L} \frac{1}{u^2(y_j)}} \tag{9}$$

Let δ_L be the difference between the weighted mean of the measured results provided by the linking laboratories in CCAUV.A-K5 and APMP.AUV.A-K5:

$$\delta_L = x_L - y_L \tag{10}$$

$$u^2(\delta_L) = u^2(x_L) + u^2(y_L) - 2u^2(x_L)u^2(y_L) \sum_{l=1}^{L} \frac{u(x_l, y_l)}{u^2(x_l)u^2(y_l)} \tag{11}$$

In (11), the correlation of the two measurement results x_l and y_l needs to be considered. The two measurement results of a linking laboratory in CCAUV.A-K5 and APMP.AUV.A-K5 are expected to be correlated since the same measurement procedure is usually applied in the laboratory. Such correlations typically arise from the same systematic effects presented in CCAUV.A-K5 and APMP.AUV.A-K5 measurements.

And the two measurement results of different laboratories in CCAUV.A-K5 and APMP.AUV.A-K5 are expected to be uncorrelated. Thus, (11) can be expressed by:

$$u^2(\delta_L) = u^2(x_L) + u^2(y_L) - 2u^2(x_L)u^2(y_L)\sum_{l=1}^{L}\frac{u_S{}^2(x_l)}{u^2(x_l)u^2(y_l)} \tag{12}$$

where $u_S(x_l)$=$u_S(y_l)$ is the systematic uncertainty components of the linking laboratory l and:

$$u\left(x_l, y_l\right) = u_S{}^2(x_l) = u_S{}^2(y_l) \tag{13}$$

Let z_1, $u(z_1)$, z_2, $u(z_2)$, … , z_M, $u(z_M)$ denote the transformed measurement results of the participants in APMP.AUV.A-K5 with the difference δ_L for linking:

$$z_j = y_j + \delta_L \tag{14}$$

$$u^2(z_j) = u^2(y_j) + u^2(\delta_L) + 2u(y_j, \delta_L) \tag{15}$$

where

$$u(y_j, \delta_L) = \begin{cases} u^2(x_L)\dfrac{u_S{}^2(y_j)}{u^2(x_j)} - u^2(y_L) & j = 1 \cdots L \\ 0 \quad otherwise \end{cases} \tag{16}$$

Let d_j and d_{ji} denote the components of the DoEs for the transformed measurement results of the participants in APMP.AUV.A-K5 compared with the KCRV and the measurement results of each participant in CCAUV.A-K5 respectively:

$$d_j = z_j - x \tag{17}$$

$$u^2(d_j) = u^2(z_j) + u^2(x) - 2u(z_j, x) \tag{18}$$

where x is the KCRV established in CCAUV.A-K5 and

$$u(z_j, x) = \begin{cases} u^2(x) + u^2(x)\dfrac{u_S{}^2(y_j)}{u^2(x_j)} - \displaystyle\sum_{l=1}^{L}\frac{u^2(x)}{u^2(x_l)}\frac{u^2(y_L)}{u^2(y_l)}u_S^2(y_l) & j = 1 \cdots L \\ u^2(x) - \displaystyle\sum_{l=1}^{L}\frac{u^2(x)}{u^2(x_l)}\frac{u^2(y_L)}{u^2(y_l)}u_S^2(y_l) \quad otherwise \end{cases} \tag{19}$$

$$d_{ji} = z_j - x_i \tag{20}$$

$$u^2(d_{ji}) = u^2(z_j) + u^2(x_i) - 2u(z_j, x_i) \tag{21}$$

where

$$u(z_j, x_i) = \begin{cases} u^2(x_L) + u_S^2(y_j) - u^2(y_L)\dfrac{u_S^2(x_i)}{u^2(y_j)} & j = i \in [1, L] \\ u^2(x_L) - u^2(y_L)\dfrac{u_S^2(x_i)}{u^2(y_j)} & j \neq i,\ i \in [1, L], j \in [1, L] \\ 0 \quad otherwise & \end{cases} \tag{22}$$

For sensitivity phase, the KRISS data at frequencies between 1.9953 Hz and 19.9526 Hz and the NMIJ/AIST data at 6309.5734 Hz were excluded from the calculation of the KCRV in CCAUV.A-K5 and the calculation of δ_L in APMP.AUV.A-K5. Then, (16) and (19) for KRISS and NMIJ/AIST can be expressed by:

$$u(y_j, \delta_L) = 0 \tag{23}$$

$$u(z_j, x) = u^2(x) - \sum_{l=1}^{L} \frac{u^2(x)}{u^2(x_l)} \frac{u^2(y_L)}{u^2(y_l)} u_S^2(y_l) \tag{24}$$

In addition, for sensitivity phase, except for NMIJ/AIST data at 6309.5734 Hz, the KRISS data at frequencies between 21.1349 Hz and 39.8107 Hz and the NMIJ/AIST data between 5623.4133 Hz and 10000.000 Hz were included in the calculation of the KCRV in CCAUV.A-K5 and excluded from the calculation of δ_L in APMP.AUV.A-K5. So, (16) and (19) for KRISS and NMIJ/AIST can be expressed by:

$$u(y_j, \delta_L) = 0 \tag{25}$$

$$u(z_j, x) = u^2(x) + u^2(x)\frac{u_S{}^2(y_j)}{u^2(x_j)} - \sum_{l=1}^{L} \frac{u^2(x)}{u^2(x_l)} \frac{u^2(y_L)}{u^2(y_l)} u_S^2(y_l) \tag{26}$$

6 DEGREES OF EQUIVALENCE AND UNCERTAINTIES

The DoEs have been calculated using measurements made with microphone 4160 2652765 only, and linked to the KCRV established in CCAUV.A-K5 by the method described above.

The graphs of results shown below for each laboratory display the DoEs for each frequency with uncertainty bars corresponding to coverage factor k=2.

For linking laboratories NIM, KRISS and NMIJ/AIST, the DoEs in CCAUV.A-K5 are shown directly below the DoEs in APMP.AUV.A-K5 for comparison. The similarity of the DoEs for the three linking laboratories across the two key comparisons in the related frequency ranges illustrates the high degree of correlation for these results and lends extra confidence to the linking process.

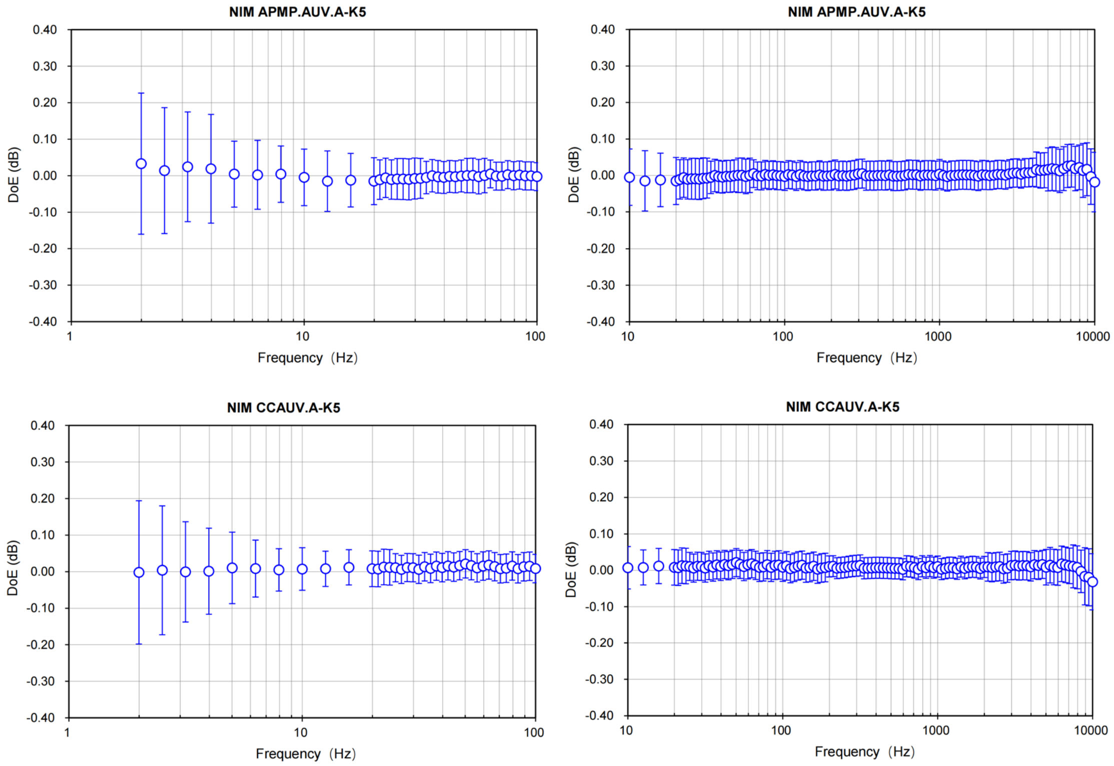

Figure 13(*a*) Degrees of Equivalence for NIM sensitivity level measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5 and CCAUV.A-K5

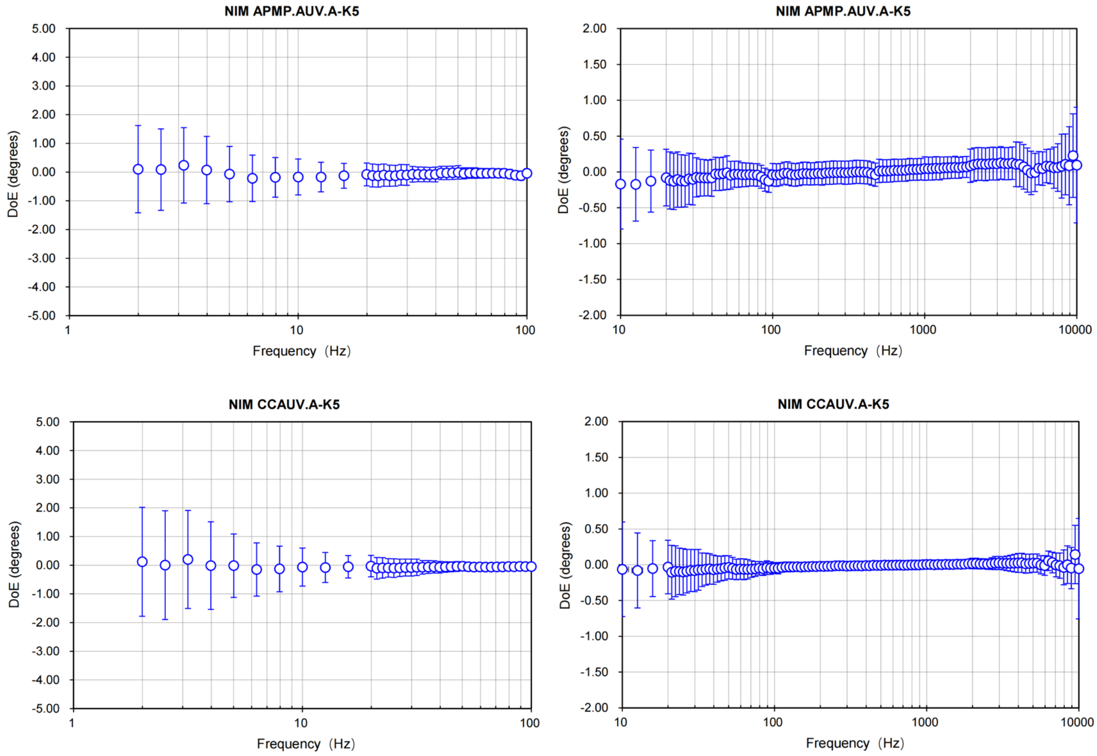

Figure 13(*b*) Degrees of Equivalence for NIM sensitivity phase measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5 and CCAUV.A-K5

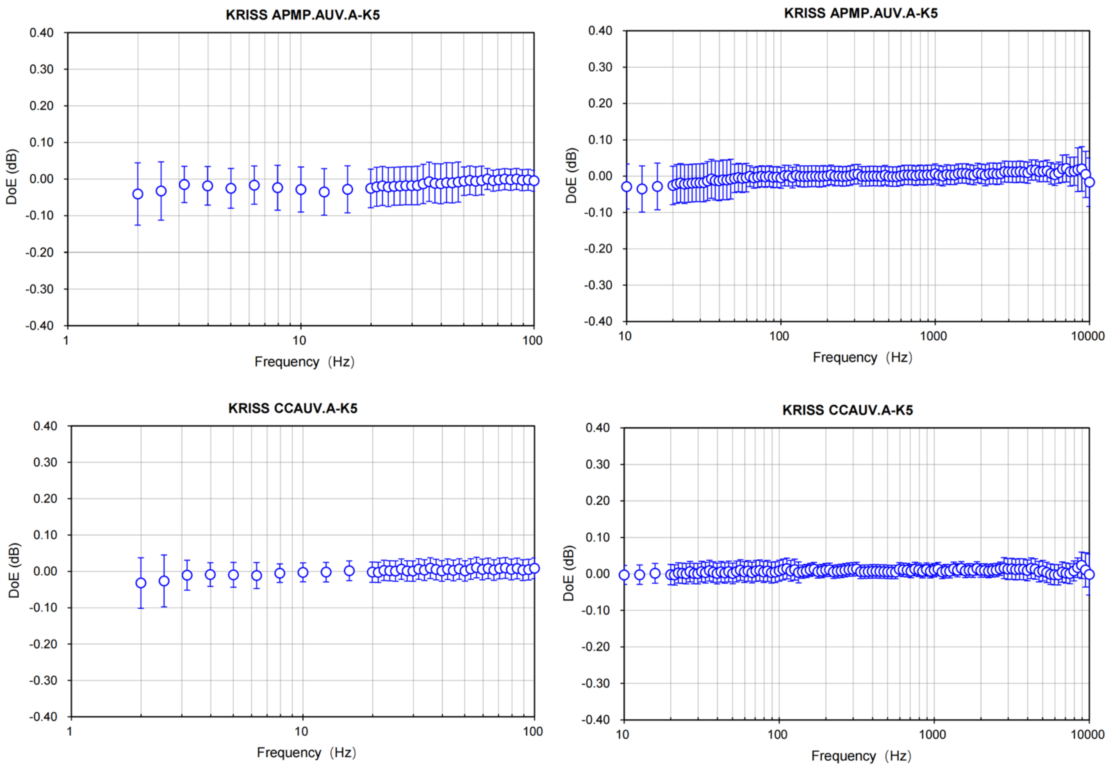

Figure 14(*a*) Degrees of Equivalence for KRISS sensitivity level measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5 and CCAUV.A-K5

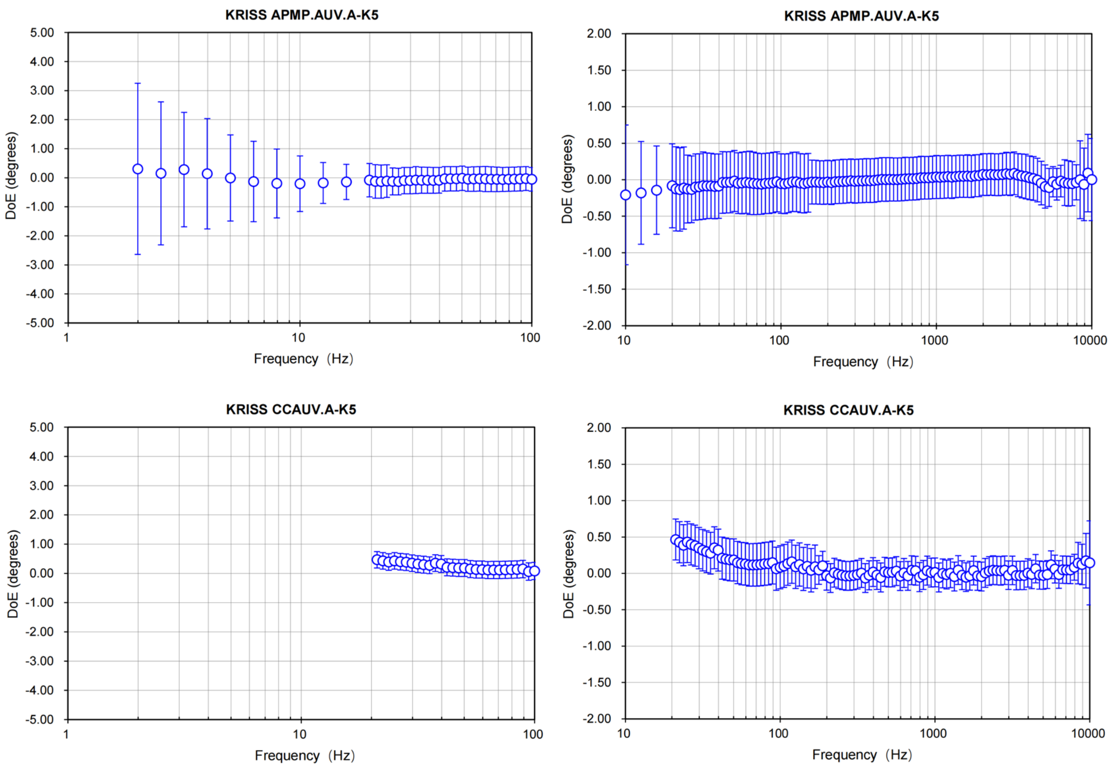

Figure 14(*b*) Degrees of Equivalence for KRISS sensitivity phase measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5 and CCAUV.A-K5

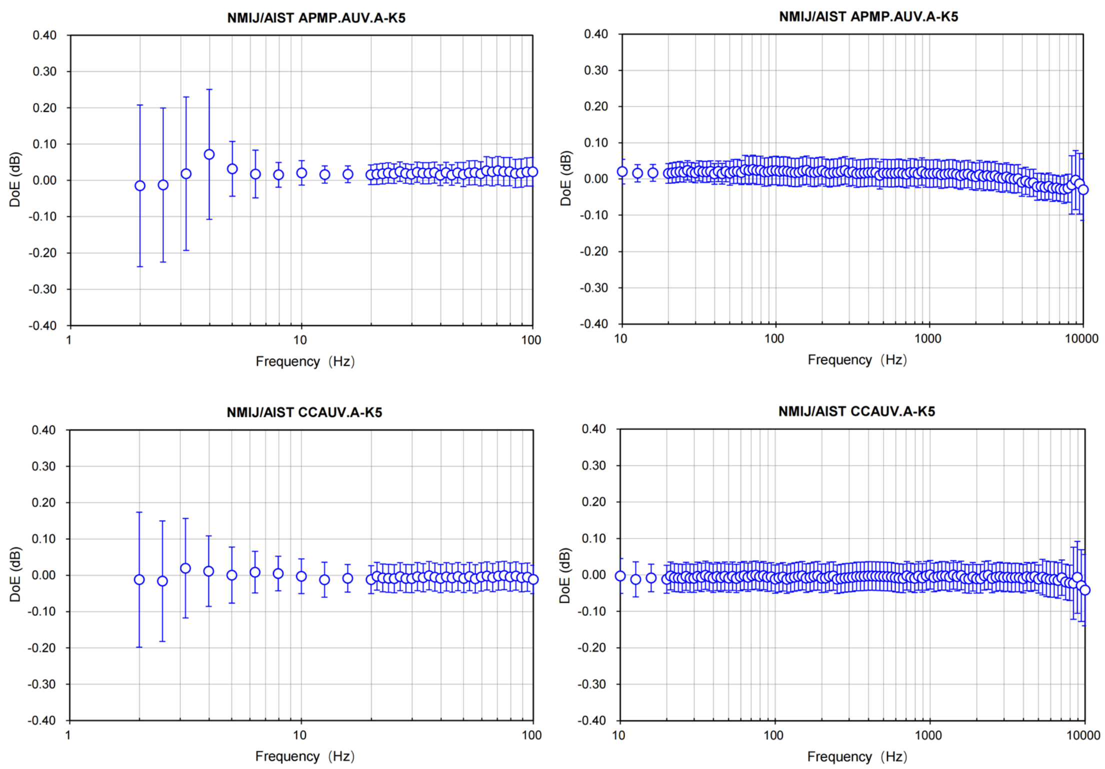

Figure 15(*a*) Degrees of Equivalence for NMIJ/AIST sensitivity level measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5 and CCAUV.A-K5

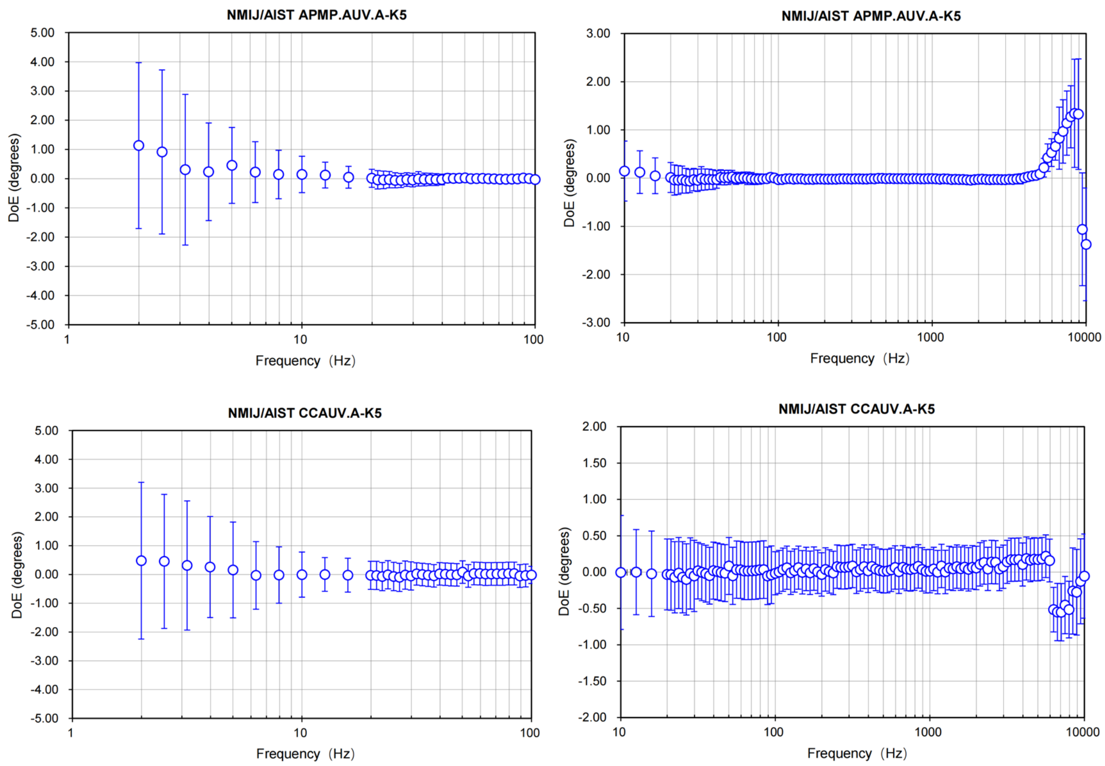

Figure 15(*b*) Degrees of Equivalence for NMIJ/AIST sensitivity phase measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5 and CCAUV.A-K5

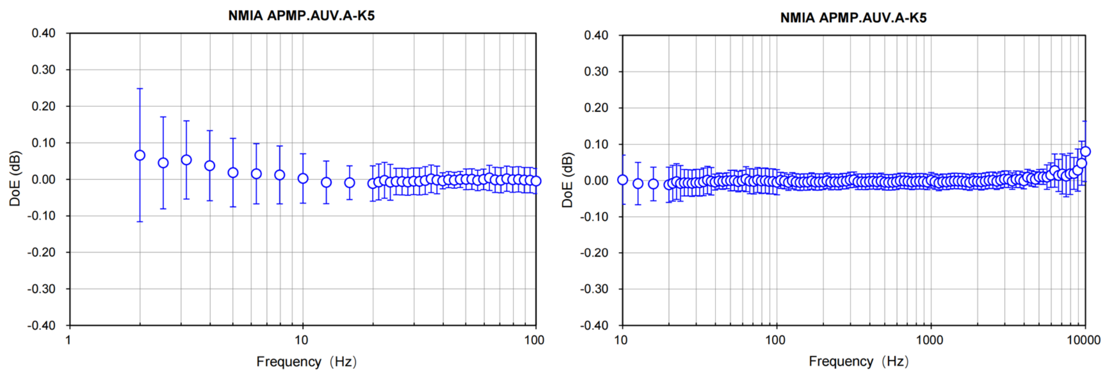

Figure 16 Degrees of Equivalence for NMIA sensitivity level measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5

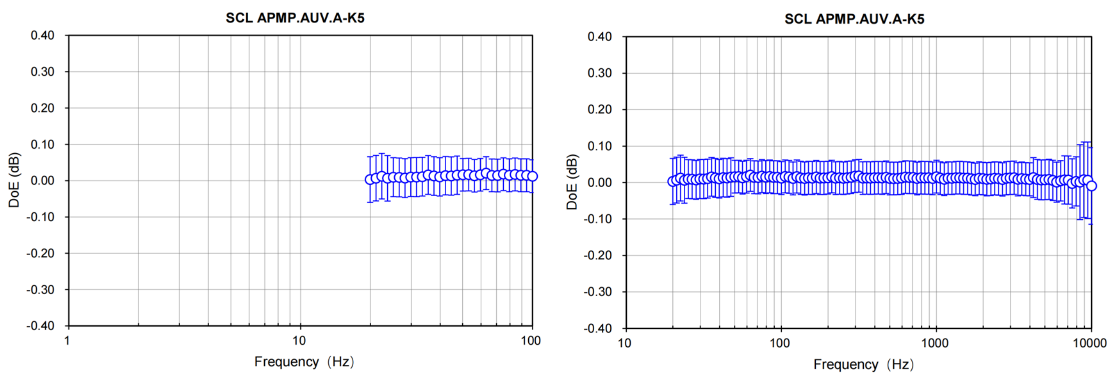

Figure 17 Degrees of Equivalence for SCL sensitivity level measurements with uncertainties for a coverage factor *k*=2 for APMP.AUV.A-K5

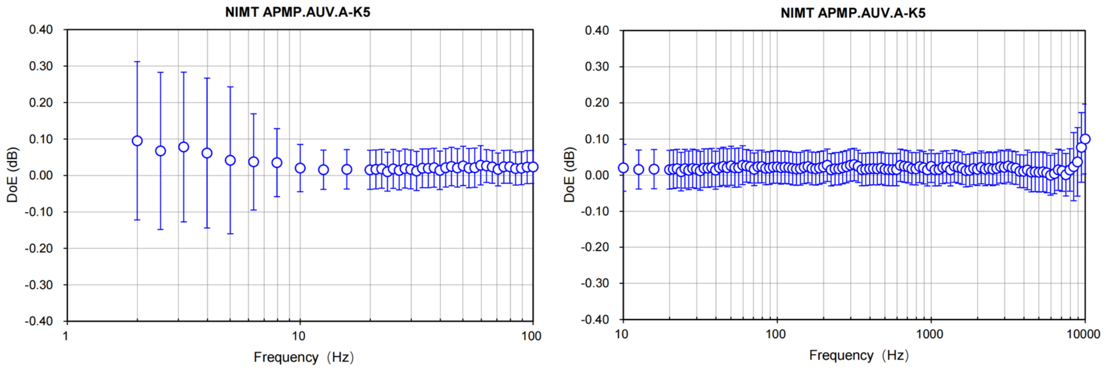

Figure 18 Degrees of Equivalence for NIMT sensitivity level measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5

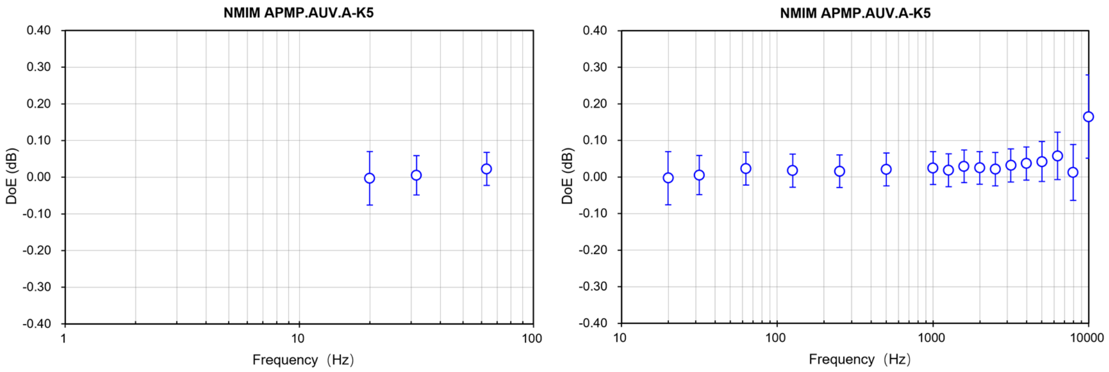

Figure 19 Degrees of Equivalence for NMIM sensitivity level measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5

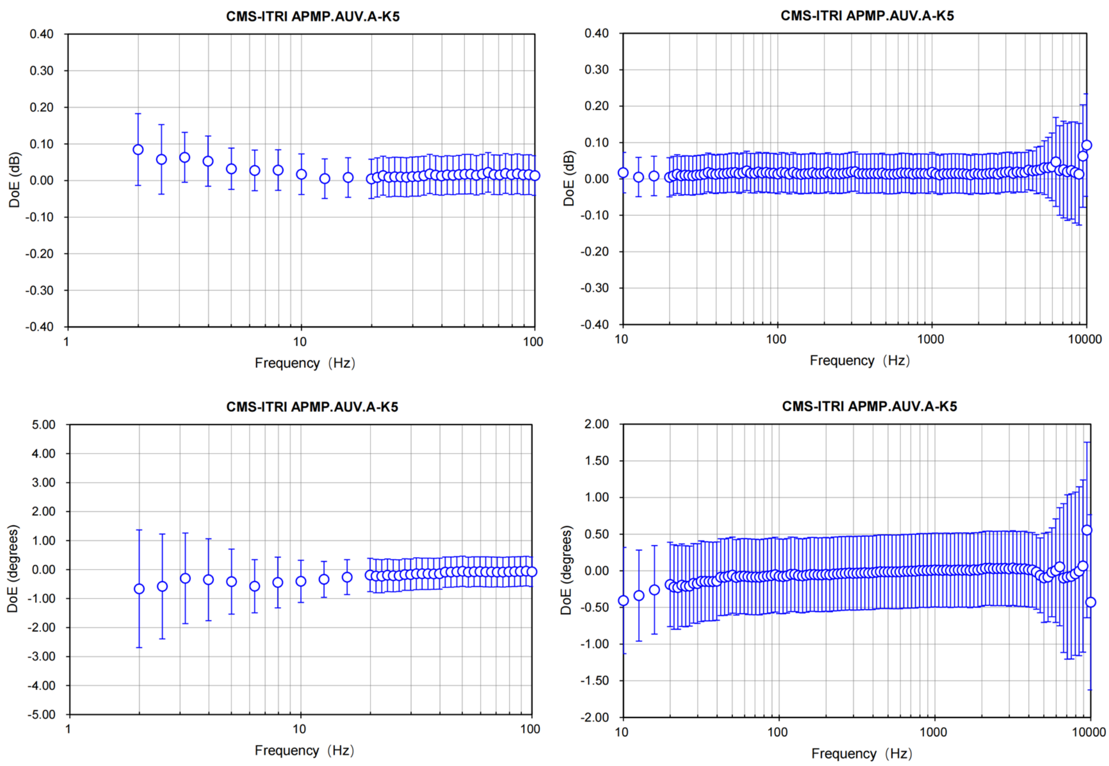

Figure 20 Degrees of Equivalence for CMS-ITRI sensitivity level and sensitivity phase measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5

7 CONCLUSION

This report describes the results for key comparison APMP.AUV.A-K5 on the pressure calibration of laboratory standard microphones in the frequency range from 2 Hz to 10 kHz. Participants provided calibrations of microphone sensitivity level and sensitivity phase.

Eight laboratories took part in the key comparison: NIM (China), NMIA (Australia), NMIM (Malaysia), SCL (Hong Kong, China), NMIJ/AIST (Japan), NIMT (Thailand), CMS-ITRI (Chinese Taipei), KRISS (Korea).

Two travelling standard microphones were circulated to the participants and results in the form of regular calibration certificates were collected throughout the project. The analysis used the results for one of the microphone only, the other had a jump in the sensitivity level at all frequencies and sensitivity phase at frequencies between 1 kHz to 10 kHz.

Values for both sensitivity level and sensitivity phase have been linked to the key comparison reference value (KCRV) of CCAUV.A-K5. The link was provided by three NMIs (NIM, KRISS and NMIJ/AIST) in sensitivity level for all measurement frequencies and in sensitivity phase for the majority of measurement frequencies. For sensitivity phase at frequencies between 1.9953 Hz and 39.8107 Hz, there were only two linking laboratories (NIM and NMIJ/AIST). For sensitivity phase at frequencies between 5623.413 Hz and 10000.000 Hz, there were only two linking laboratories (NIM and KRISS).

For sensitivity level, except for NIMT and NMIM at 10 kHz, all participants presented Degrees of Equivalence (DoEs) to the KCRV in compliance with the respective claimed expanded uncertainties in the given frequencies.

For sensitivity phase, the originally submitted data points from NMIJ/AIST at frequencies from 5623.413 Hz to 10000.000 Hz were consistently identified as being discrepant and then were confirmed to be incorrect following the circulation of Draft A report. With the corrected data from NMIJ/AIST, all participants presented Degrees of Equivalence (DoEs) to the KCRV in compliance with the respective claimed expanded uncertainties.

8 REFERENCES

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ANNEX A: CORRECTIONS TO REPORTED RESULTS

Before the circulation of the draft A report, all participating laboratories were contacted and invited to check their results for numerical errors. All participating laboratories declined to resubmit results.

During the circulation of the draft A report, NMIJ/AIST communicated the following error in the reported results. And the associated expanded uncertainties of the sensitivity phase results have been confirmed to be correct.

NMIJ: *The draft A indicates that our calibration results of sensitivity phases in a high frequency range do not align with those of other participants and have been excluded from determining the reference values for this key comparison. Following this, NMIJ rechecked all measurement data and found some errors. When calculating sensitivity phases, the correction values for heat conduction and viscous losses were not correctly applied to the sensitivity phase of the target frequency. For instance, the correction value for 1000.0 Hz was wrongly applied to 891.25 Hz. This kind of mistake impacted all frequencies between 2 Hz to 10 kHz. The attached file displays the original and revised sensitivity phase for the circulated two microphones. Additionally, the sensitivity level in the original does not require revision and has been confirmed to be correct.*

NMIJ/AIST originally declared and revised sensitivity phase results are provided in Microsoft Excel spreadsheet 'APMP.AUV.A-K5 Tables of Data_Final Report.xlsx'. And the weighted mean of the sensitivity phase and DoEs for all participating laboratories with associated uncertainties were recalculated, the results of which were shown in detail as follows and provided in Microsoft Excel spreadsheet 'APMP.AUV.A-K5 Tables of Data_Final Report.xlsx'.

A.1 ANALYSIS OF THE REVISED SENSITIVITY PHASE RESULTS

For the originally declared measurement results of the sensitivity phase provided by all participating laboratories, the chi-squared test was not passed at high frequencies. The measurement results of NMIJ/AIST at frequencies from 5623.413 Hz to 10000.000 Hz was consistently identified as being discrepant and excluded from the calculation of the weighted mean. With corrections to the reported results of NMIJ/AIST, the measurement results of the sensitivity phase provided by all participating laboratories passed the chi-squared test. And the weighted mean of the sensitivity phase has been recalculated with no data excluded. The following graphs in Figure A.1 show each laboratory's results as a difference from the estimated sensitivity phase (weighted mean) for microphone 4160 2652765.

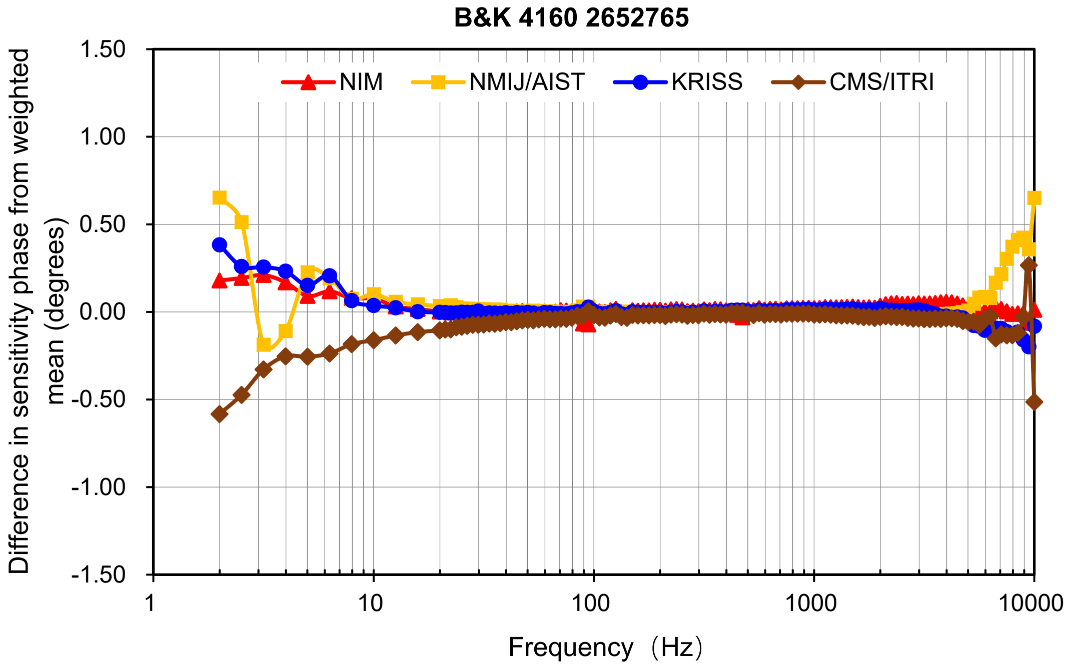

Figure A.1 Combined sensitivity phase results of all participating laboratories, for microphone 4160 2652765, shown as a difference from the estimated reference sensitivity phase (weighted mean)

A.2 LINKING TO THE KCRV ESTABLISHED IN CCAUV.A-K5

For sensitivity phase in CCAUV.A-K5, the KRISS data at frequencies between 1.995 Hz and 19.953 Hz and the NMIJ/AIST data at 6309.573 Hz were excluded from the calculation of the weighted mean for the chi-squared test to pass. The expanded uncertainty of DoEs for KRISS didn't include zero at frequencies between 21.135 Hz and 39.811 Hz. And the expanded uncertainty of DoEs for NMIJ/AIST didn't include zero at frequencies between 6309.573 Hz and 7943.282 Hz. For revised sensitivity phase in APMP.AUV.A-K5, all participating laboratories passed the chi-squared test. So, in the linking procedure, KRISS at frequencies between 1.995 Hz and 39.811 Hz and NMIJ/AIST at frequencies between 6309.573 Hz and 7943.282 Hz were excluded from the linking laboratories.

A.3 DEGREES OF EQUIVALENCE AND UNCERTAINTIES

The DoEs have been recalculated with NMIJ/AIST's revised sensitivity phase results. The graphs of results shown below for each laboratory display the recalculated DoEs for each frequency with uncertainty bars corresponding to coverage factor k=2.

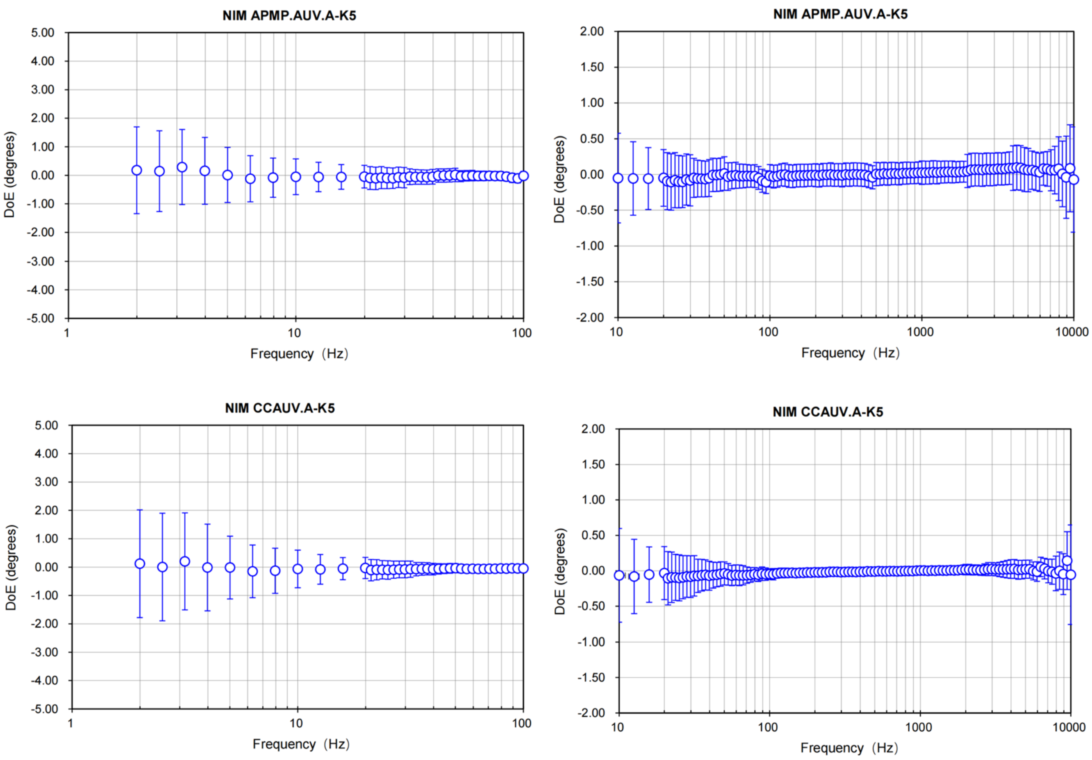

Figure A.2 Recalculated DoEs for NIM sensitivity phase measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5 and CCAUV.A-K5

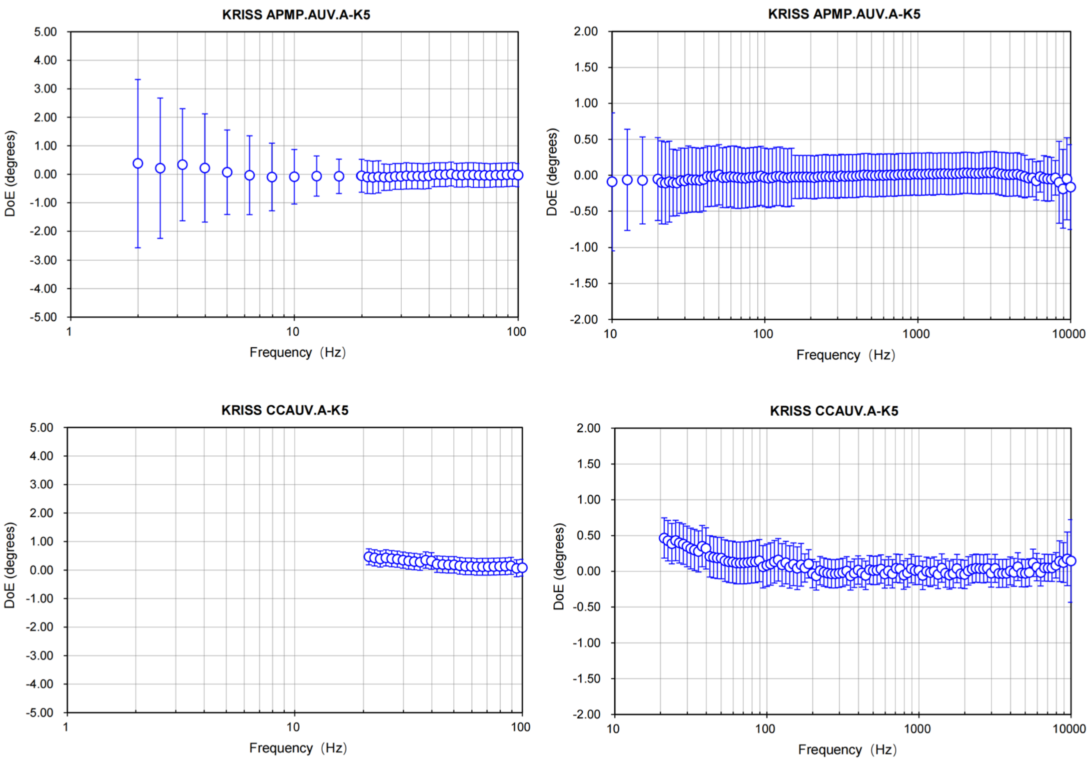

Figure A.3 Recalculated DoEs for KRISS sensitivity phase measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5 and CCAUV.A-K5

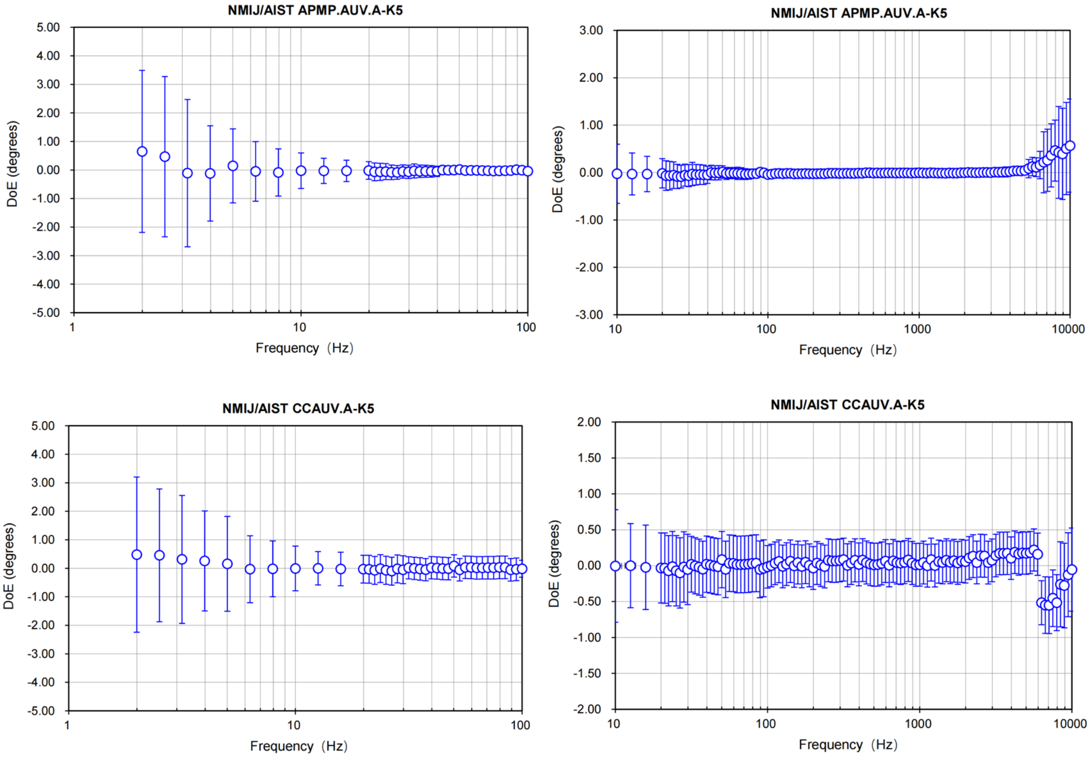

Figure A.4 Recalculated DoEs for NMIJ/AIST sensitivity phase measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5 and CCAUV.A-K5

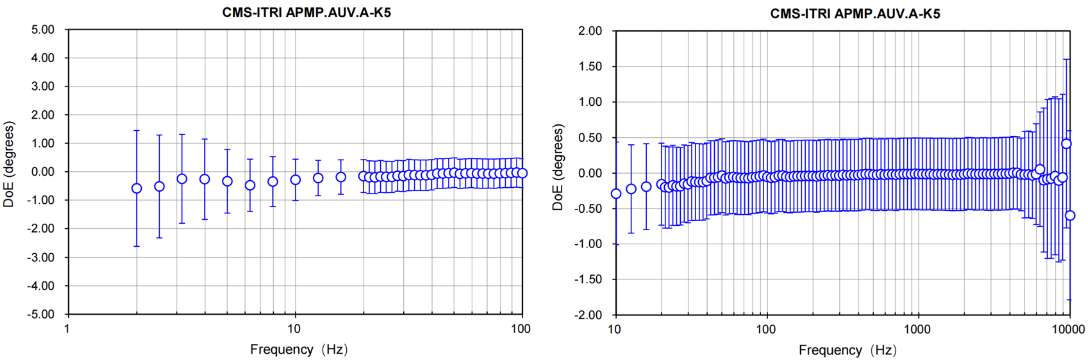

Figure A.5 Recalculated DoEs for CMS-ITRI sensitivity phase measurements with uncertainties for a coverage factor *k*=2 in APMP.AUV.A-K5