

## **FINAL REPORT: KEY COMPARISON EURAMET.AUV.A-K5**

**Authors:**

**JANINE AVISON, PETER HARRIS and STEPHEN ROBINSON (NPL)**

**Co-authors:**

<b>DOMINIQUE RODRIGUES</b>	<b>(LNE)</b>
<b>CLAUDIO GUGLIELMONE</b>	<b>(INRIM)</b>
<b>CHRISTIAN HOF</b>	<b>(METAS)</b>
<b>ENVER SADIKOGLU</b>	<b>(UME)</b>
<b>MARIN CHUSHKOV</b>	<b>(BIM)</b>
<b>SLOBODAN ZELENKA</b>	<b>(DMDM)</b>
<b>PETER ROSENKRANTZ</b>	<b>(BEV)</b>
<b>HÅKAN ANDERSSON</b>	<b>(SP-RISE)</b>
<b>THOMAS FEDTKE and CHRISTIAN KOCH</b>	<b>(PTB)</b>
<b>NIEVES MEDINA MARTIN and SALUSTIANO RUIZ</b>	<b>(CEM)</b>
<b>HANY SHAWKY</b>	<b>(NIS)</b>

**DECEMBER 2018**



## FINAL REPORT: KEY COMPARISON EURAMET.AUV.A-K5

Authors: Janine Avison, Peter Harris and Stephen Robinson (NPL)

Co-authors:

Dominique Rodrigues	(LNE)
Claudio Guglielmone	(INRIM)
Christian Hof	(METAS)
Enver Sadikoglu	(UME)
Marin Chushkov	(BIM)
Slobodan Zelenika	(DMDM)
Peter Rosenkrantz	(BEV)
Håkan Andersson	(SP-RISE)
Thomas Fedtke and Christian Koch	(PTB)
Nieves Medina Martin and Salustiano Ruiz	(CEM)
Hany Shawky	(NIS)

### ABSTRACT

This is the final report for key comparison EURAMET.AUV.A-K5 on the pressure calibration of laboratory standard microphones in the frequency range from 2 Hz to 10 kHz. Twelve national metrology institutes took part in the key comparison and the National Physical Laboratory 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 and have been linked to the CCAUV.A-K5 key comparison reference value (KCRV) via two linking laboratories (NPL and INRIM).

© NPL Management Ltd, 2018

ISSN: **1754-2936**

National Physical Laboratory  
Hampton Road, Teddington, Middlesex, TW11 0LW

Extracts from this report may be reproduced provided the source is acknowledged and the extract is not taken out of context.

Approved on behalf of NPLML by Dr Bajram Zeqiri (Science Area Leader).

## CONTENTS

<b>1</b>	<b>INTRODUCTION .....</b>	<b>2</b>
<b>2</b>	<b>DESCRIPTIONS OF PARTICIPANTS' MEASUREMENT SYSTEMS.....</b>	<b>3</b>
2.1	NPL .....	3
2.2	LNE.....	4
2.3	INRIM.....	4
2.4	METAS.....	5
2.5	UME.....	6
2.6	BIM.....	6
2.7	DMDM.....	7
2.8	BEV.....	7
2.9	SP (RISE).....	8
2.10	PTB.....	8
2.11	CEM.....	9
2.12	NIS.....	10
<b>3</b>	<b>STABILITY OF TRAVELLING STANDARDS.....</b>	<b>10</b>
<b>4</b>	<b>RESULTS AND ANALYSIS OF THE EURAMET.AUV.A-K5 COMPARISON DATA.....</b>	<b>13</b>
<b>5</b>	<b>LINKING TO THE KCRV ESTABLISHED IN CCAUV.A-K5 .....</b>	<b>22</b>
<b>6</b>	<b>DEGREES OF EQUIVALENCE AND UNCERTAINTIES.....</b>	<b>25</b>
6.1	GRAPHS OF DEGREES OF EQUIVALENCE TO THE KCRV FOR EACH PARTICIPANT .....	25
<b>7</b>	<b>CONCLUSION.....</b>	<b>32</b>
<b>8</b>	<b>ACKNOWLEDGMENTS.....</b>	<b>32</b>
<b>9</b>	<b>REFERENCES .....</b>	<b>32</b>
	<b>ANNEX A: DETAILED STABILITY ANALYSIS.....</b>	<b>34</b>
A.1	CONSISTENCY OF FITS .....	34
A.2	DRIFT PARAMETERS FOR BEST-FIT STRAIGHT LINES .....	344
A.2.1	4160 2036126 Sensitivity level .....	35
A.2.2	4160 2036126 Sensitivity phase.....	36
A.2.3	4160 811014 Sensitivity level .....	37
A.2.4	4160 811014 Sensitivity phase.....	38
	<b>ANNEX B: BEV CALCULATION REVISION.....</b>	<b>39</b>

## 1 INTRODUCTION

This is the final report for key comparison EURAMET.AUV.A-K5 on the pressure calibration of laboratory standard microphones. The results are linked back to the KCRV established by key comparison CCAUV.A-K5<sup>1</sup> via two linking laboratories: the National Physical Laboratory in the UK and INRIM in Italy. This project was organized by the Consultative Committee for Acoustics, 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. Twelve national metrology institutes took part and the National Physical Laboratory in the UK, piloted the project. The participants are listed in Table 1.

Table 1. List of participating institutes

Participant (in order of participation)	Acronym	Country	Country Code
National Physical Laboratory	NPL	United Kingdom	UK
Laboratoire National de Métrologie et d'Essais	LNE	France	FR
Istituto Nazionale di Ricerca Metrologica	INRIM	Italy	IT
Federal Institute of Metrology	METAS	Switzerland	CH
TÜBİTAK Ulusal Metroloji Enstitüsü	UME	Turkey	TR
Bulgarian Institute of Metrology	BIM	Bulgaria	BG
Directorate of Measures and Precious Metals	DMDM	Republic of Serbia	RS
Bundesamt für Eich- und Vermessungswesen	BEV	Austria	AT
SP Sveriges Tekniska Forskningsinstitut	SP (RISE) <sup>†</sup>	Sweden	SE
Physikalisch-Technische Bundesanstalt	PTB	Germany	DE
Centro Español de Metrología	CEM	Spain	ES
National Institute for Standards	NIS	Egypt	EG

<sup>†</sup> Since participating in the comparison, SP (Sveriges Tekniska Forskningsinstitut) have changed their name to RISE (Research Institutes of Sweden AB).

This report is supplemented by the following Microsoft Excel spreadsheets:

<u>Spreadsheet title</u>	<u>Spreadsheet content</u>
EURAMET.AUV-A-K5 Draft B Tables of Data.xls	Results and uncertainties for both microphones declared by participants
EURAMET_AUV_A-K5 Uncertainty Budgets Draft B.xlsx	Uncertainty budgets declared by the participants

*Protocol*

The protocol<sup>2</sup> specified the determination of the pressure sensitivities of two IEC type LS1P microphones according to IEC 61094-2 (2009)<sup>3</sup>, at standard 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 2 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

Table 2 shows the measurands and frequency ranges within the scope of this key comparison. 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 open-circuit pressure sensitivity level of each reference microphone, and also the open-circuit pressure sensitivity phase where available.

The first participant received the microphones in September 2013 and the final participant completed their measurements in March 2015.

## 2 DESCRIPTIONS 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 NPL

#### 2.1.1 Method

Traceability for the electrical transfer impedance in the NPL system comes from a set of calibrated resistors and one calibrated capacitor, which was used for measurements at frequencies below 19.95 Hz. A single coupler of length 7.5020 mm and radius 9.30135 mm was used for all measurements. The coupler was fitted with a capillary tube, but this was blocked using a wire. Sealing of the microphones in the coupler was achieved by a constant applied force and without sealant.

The measurement process was controlled using NPL's own in-house designed software. The same software also implements the calculation of acoustic transfer impedance.

#### 2.1.2 Deviations from standard

None declared.

#### 2.1.3 Declared parameters

The effective volume of the microphone's front cavity was measured using an acoustical technique and the cavity depth was measured using a depth measuring microscope. Nominal values were assumed for the acoustical impedance parameters.

#### 2.1.4 Calculations

The effects of non-radial motion inside the coupler have been accounted for using a model that assumes a Bessel-shaped diaphragm profile leading the determination of a correction for sensitivity level. However, this has not been applied for the sensitivity phase, nor has an uncertainty component been determined for the effect on phase. The effect of heat conduction in the coupler on sensitivity level and phase has been accounted for by using the "Broad-band" model of IEC 61094-2:2009 clause A.3.

The models for the temperature and pressure coefficients given in IEC 61094-2:2009 were used to correct the results to reference environment conditions. The required microphone diaphragm resonance frequency was calculated from the acoustical compliance and mass parameters.

At 50 Hz the results were interpolated from adjacent frequencies to avoid mains frequency noise. The resulting additional uncertainty component had no effect on the overall uncertainty at this frequency. This approach differs from the approach taken by NPL in the CCAUV.A-K5 key comparison, where the actual measured results at 50 Hz were presented with a larger uncertainty reflecting the impact of the mains noise.

### 2.2 LNE

#### 2.2.1 Method

Determinations of the microphone parameters were carried out by running a calibration in two different couplers. The parameters are determined by minimizing the sensitivity level differences obtained in the two different couplers.

The dimensions of the used couplers are:

Type	UA 1429	UA 1413
Diameter (mm)	18.6122	18.6047
Length (mm)	7.4996	14.9956

Measurements were made in accordance of IEC 61094-2:2009. The used coupler was the UA 1429 previously described. No capillarity tube was used and measurements were made at the local atmospheric pressure. Measurements were carried out from 1.995 Hz until 10 kHz and repeated five times.

Results are corrected to the reference environmental conditions given in IEC 61094 2:2009 using the polynomial coefficients given in the Technical Review "Properties and Calibration of Laboratory Standard Microphones", Bruël & Kjaer no. 1 2001.

#### 2.2.2 Deviations from standard

None declared.

### 2.3 INRIM

#### 2.3.1 Method



INRiM uses a Brüel & Kjær reciprocity calibration unit, type 5998.

Four plane wave couplers were used in the measurements in the frequency range 20 Hz to 10 kHz. They had a nominal radius of 18.6 mm and lengths of 4.3 mm, 5.7 mm, 7.5 mm and 10 mm. For low frequency measurements, only the coupler of length 5.7 mm was used.

### 2.3.2 Deviations from standard

None declared.

### 2.3.3 Declared parameters

The microphone parameters were estimated indirectly by data fitting. The resonance frequency was calculated from the 90 ° phase response, the equivalent volume by minimizing the differences in the 200 Hz – 2000 Hz frequency range in the sensitivity, the damping factor by minimizing the differences in the upper frequency range.

The cavity depth was measured by means of an optical microscope with a linear encoder, 8 points at 45° were measured.

### 2.3.4 Calculations

The calculation program has been realized at INRiM using the Matlab© programming language. It follows IEC 61094-2:2009. The heat conduction correction has been calculated using the broadband solution outlined in the Annex A of the standard.

## 2.4 METAS

### 2.4.1 Method

METAS uses a measurement set-up which was developed in-house around the B&K reciprocity apparatus B&K 5998. The data acquisition is performed by means of a National Instruments front-end involving an A/D- and D/A-conversion board PXI-4461. The measurement routine has been programmed in LabView. For the determination of the complex sensitivity (amplitude and phase) quasi stationary signals are analyzed by the sine-approximation method.

Pairings of laboratory standard microphones are made using different sets of couplers. For the calibration of LS1 microphones we are using a set of three sapphire couplers of nominal lengths of 4.3 mm, 5.7 mm and 10 mm. These couplers were designed by METAS – they don't have any capillary tubes. All measurements are performed in a quiet laboratory (semi-reflecting room) within the pressurized vessel (under stabilized environmental conditions being close to the standard pressure and temperature).

Geometrical data of the couplers as well as some parameters of the microphones (such as the front cavity depth) are measured by the laboratory of dimensional metrology at METAS. The remainder of the required microphone parameters are determined by fitting procedures to yield consistent results from the various couplers (front cavity volume, equivalent volume, effective diameter) or by iterative means from the resulting microphone sensitivity (loss factor, resonance frequency).

### 2.4.2 Deviations from standard

None declared.

### 2.4.3 Calculations

The analysis of the measurement data is performed by a number of scripts programmed in MatLab. Despite the complexity of the calculations (according to IEC 61094-2) the uncertainties of the relevant input quantities are propagated according to the requirements of the GUM by using the "measurement uncertainty calculator" (UncLib) developed at METAS.

## 2.5 UME

### 2.5.1 Method

The open-circuit pressure sensitivity of the microphone with the grid removed was determined by the reciprocity technique in full accordance with IEC 61094-2:2009 standard. The microphones were coupled in pairs using two air filled plane-wave couplers with nominal lengths 7.5 mm and 15 mm. Actual dimensions of the couplers were determined by using Coordinate Measuring Machine at TÜBİTAK UME Dimensional Laboratory. The main component of the equipment used is Brüel & Kjær (B&K) Type 5998 Reciprocity Calibration Apparatus. No capillary tubes were fitted to the plane-wave couplers in order to equalize the static pressure inside and outside the couplers. The receiver microphone was connected to a preamplifier B&K type 2673 with insert voltage facilities and the current through the transmitter microphone was determined by the voltage across reference impedance in series with the microphone. Voltage across reference impedance was measured by Wavetek/Datron Type 1281 Digital Multimeter. The polarising voltage applied to the microphone was  $(200.00 \pm 0.05)$  V. The variation of the polarizing voltage was monitored by HP 3458A Digital Multimeter. The polarizing voltage was measured at the port of the reciprocity calibration apparatus, instead of at the terminals of the microphone. For each microphone measurements were performed ten times using different triad of microphones. The final results declared for the comparison are average of ten measurement results. The calculation of microphone sensitivity was performed using software MP.exe ver. 4.0 developed at DTU in accordance with the IEC 61094-2 standard. All measurements were conducted in a temperature controlled room at temperature  $(23.0 \pm 3.0)$  °C and relative humidity (40 – 60) % rh. The static pressure, temperature and humidity were measured by Vaisala Combined Pressure, Humidity and Temperature Transmitter PTU300. Nominal values for the microphone cavity depth, resonance frequency and loss factor declared by manufacturer were used for the sensitivity calculation. Values for microphone equivalent and front volume were determined by data fitting of microphone sensitivities obtained for two couplers in the frequency range 250 Hz – 2000 Hz. Final sensitivity values were corrected to the reference environmental conditions.

## 2.6 BIM

### 2.6.1 Method

The PULSE based pressure reciprocity calibration system type 9699, Brüel & Kjær was used to determine the open circuit pressure sensitivity level of the microphones according to IEC 61094-2. The main units of the system used in this comparison are:

- Reciprocity calibration apparatus type 5998;
- PULSE system type 3560-C;
- Three laboratory standard microphones type 4160;
- Two air filled plane-wave couplers with nominal lengths 7,5 and 15 mm;
- DTU sensitivity calculation program "MP.EXE" to calculate and create new calibration result files;
- Data fitting of microphone sensitivities obtained for two couplers to determine the values of microphone front and equivalent volumes for minimization of reciprocity calibration uncertainty;
- The environmental conditions were measured with Testo type 452 and Testo type 525.

The open circuit pressure sensitivities were corrected to the reference environmental conditions (23 °C and 101.325 kPa) given in IEC 61094-2.

## 2.6.2 Declared parameters

- The depth of the front cavity was determined by nominal parameters according to IEC 61094-1, Cavity depth:  $(1.95 \pm 0.03)$  mm;
- The front cavity volume together with the equivalent volume was determined by acoustical method according to IEC 61094-2;
- The nominal parameters was used for Resonance frequency (8.2 kHz), Loss factor (1.05), Ps correction (-0.015 dB/kPa), Temperature correction (-0.002 dB/°C) and RH correction (not applied).

## 2.7 DMDM

### 2.7.1 Method

The condenser microphones were calibrated by Reciprocity Calibration System (B&K type 9699). The measurement data were analyzed using software MP.EXE Microphone pressure sensitivity calibration calculation program version 3.00 (September, 1999), E. Sandermann Olsen and K. Rasmussen from Technical University of Denmark. Ambient conditions in the laboratory were monitored using Vaisala PTU 303 unit.

Reciprocity technique consists in determining the sensitivity for a triplet of microphones: A, B and C. These microphones are coupled in pairs as AB, AC and BC, with a number of plane wave couplers. When microphones are coupled, the electrical and acoustical transfer impedances are determined for a given set of frequencies. From these transfer impedances the pressure sensitivity product of each pair of microphones is calculated for each plane wave coupler. For each plane wave coupler, a set of three equations, corresponding to each microphone pair, with three unknowns are solved to get the individual pressure sensitivity for each microphone.

Static pressure and temperature corrections are applied, to the measurement results, to get the pressure sensitivity product at environmental reference conditions (101.325 kPa, 23 °C, 50% HR). Pressure sensitivity is calculated according to IEC 61094-2:2009.

The front cavity depth was taken as nominal value and static pressure and temperature coefficients as well as resonance frequency and loss factor are used as given from the manufacturer's typical values. Front cavity and equivalent volumes were adjusted by a curve fitting process using the sensitivity levels obtained from a set of two plane wave couplers.

## 2.8 BEV

### 2.8.1 Method

A Brüel & Kjær 9699 reciprocity calibration system was the main part of the measurement system.

At each frequency all six possible combinations of two microphones out of three were measured with 5 different air filled plane wave couplers. The capillary tube of the couplers was closed with a needle bung DA 5563. Thus no capillary tube corrections were necessary for microphone sensitivity calculations.

The cavity depths of both microphones were calibrated by a confocal non-contact technique at the length department at BEV.

Sensitivity levels were then calculated according to EN 61094 2:2009. Below 250 Hz the acoustic transfer impedance was calculated according to formula 3 in 5.4 of EN 61094 2:2009. All other results were calculated according to formula 4 in 5.4 of EN 61094 2:2009. For low frequencies the calculations of heat conduction and viscous losses were done according to "Journal of the Acoustical Society of America 36, 1964, 1427 1434".

The correction of the speed of sound due to dispersion according to annex F.3 was omitted.

Radial wave motion corrections were applied according to “Acta Acustica 1 (1993) pp 145 151” using the Bessel function velocity distribution to describe the diaphragm velocity.

Additional heat conduction losses due to the inner thread of B&K 4160 microphones were accounted for by adding an additional surface area of 81 mm<sup>2</sup> (Annex A of EN 61094 2:2009 and “B&K Technical Review No. 1 2001, pp 14 23”).

Temperature and static pressure coefficients were calculated according to “B&K Technical Review No. 1 2001, pp 1 13”.

Bessel functions are calculated according to “International Journal of modern Physics C 23, 2012, 1250084”.

## 2.9 SP (RISE)

### 2.9.1 Method

A single coupler with nominal length 7.5 mm was used. The capillary tube holes in the coupler were blocked by blocking pins. The electrical transfer impedance was measured by a modified Reciprocity Calibration Apparatus type B&K 4143 together with a National Instruments data acquisition system. The measurement process as well as the calculations was controlled using in-house designed software.

### 2.9.2 Deviations from standard

None declared.

### 2.9.3 Declared parameters

The effective volume of the microphone’s front cavity was determined by sensitivity fitting by using two couplers with lengths 7.5 mm and 15 mm and the cavity depth was measured by using a depth measuring microscope. The equivalent volume used is the nominal given in the manual for B&K 9699 calibration system. The resonance frequency is determined from the 90° phase shift of the microphone calibration result. The loss factor is determined by the sensitivity ratio at low frequencies and resonance frequency.

### 2.9.4 Calculations

The calculations have been done according to IEC 61094-2:2009. The effect of heat conduction in the coupler has been accounted for by using the “Broad-band” model of clause A.3 in the standard. Corrections to reference environment conditions have been made according to B&K Technical Review No. 1 2001. No radial wave motion correction has been applied.

## 2.10 PTB

### 2.10.1 Method

The calibration was performed according to IEC 61094-2:2009, using three microphones coupled in pairs by air filled plane wave couplers (lengths 15 mm, 10 mm and 7.5 mm). During the measurements the couplers' vents were closed with a needle, in order to avoid capillary tube corrections and to have minimal leakage. No additional sealing was used.

The electrical transfer impedance was measured using the main unit of a Brüel & Kjaer reciprocity calibration system 5998 (modification WH 3432), transmitter unit ZE 0796 (with modification WH 3433) and pre-amp 2673 (with modification WH 3291). The complex voltage ratio was measured by means of a B&K 3110 Pulse analyzer. The devices were controlled by the B&K WT 9708 reciprocity measurement program, version 3.1.

The polarization voltage was checked by a differential voltmeter type Fluke 893A. The static pressure was measured by a calibrated barometer, Druck DPI 141, the temperature and humidity by a laboratory meter Testo 600.

The microphone front cavity depth was measured using a depth focusing microscope with a 'digimatic indicator' ID 110.

The sensitivity was calculated with the 'Calcmp2' software designed at PTB, using the broad-band solution according to Annex A.3 of IEC 61094-2:2009 for the propagation coefficient and the acoustic impedance of the plane waves in the couplers. The influence of a possible thread in the front cavity on the heat conduction losses was neglected. This simplification was accounted for in the uncertainty.

The total effective volume and the microphone impedance (equivalent volume, loss factor and resonance frequency) were determined by minimizing the differences of the sensitivity levels obtained in the three different couplers. In addition, the low-frequency sensitivity level (250 Hz) was verified by a large-volume-coupler reciprocity measurement. Radial wave motion in the plane-wave couplers was corrected according to Ref. [C.2] of the standard, using the Bessel model for the pressure distribution over the diaphragm. If possible, the sensitivity was calculated as mean value over the three couplers. In case of any (high-frequency) resonance problems or undue leakage, results from the respective couplers were excluded from the average.

The pressure and temperature coefficients for correcting the sensitivity of the microphones to reference environmental conditions were calculated according to "Rasmussen, K., The static pressure and temperature coefficients of laboratory standard microphones. *Metrologia*, 1999, 36, 265-273.

## 2.11 CEM

### 2.11.1 Method

The absolute pressure calibration of condenser microphones was performed at CEM by reciprocity, using the Brüel & Kjær reciprocity calibration apparatus type 5998. Three microphones were coupled acoustically in pairs through four air-filled plane wave couplers of four different lengths, namely 4.3 mm, 5.7 mm, 7.5 mm and 10 mm.

The front cavity depths of the microphones under calibration are measured using a depth microscope. This was done by a specialized dimensional metrology laboratory.

The calculation of the microphone sensitivity was achieved, according to the reciprocity method, by determining the electrical transfer impedance and the acoustical transfer impedance for every microphone pair. The following measurement procedure was performed at every frequency within the frequency range of interest.

- The receiver microphone was mounted on a Brüel & Kjær 2673 preamplifier.
- The transmitter microphone was mounted on a Brüel & Kjær transmitter unit ZE 0796.
- Transmitter and receiver thus assembled are connected to the reciprocity apparatus.
- The microphone pair under test, properly fitted in a plane wave coupler, was placed inside a chamber where temperature and static pressure were measured.
- The test signal, generated by a B&K 1051 signal generator, was fed to the transmitting unit through the reciprocity apparatus.
- The input and output voltages of transmitting and receiving microphones were measured by means of a voltmeter Datron 1281.

The measurement data were recorded by the software RMP.exe developed by B&K and supplied to the specific software developed by CEM in accordance with IEC 61094-2. The calculations have been performed according to the broad-band solution as show in A.3 of the UNE-EN 61094-2.

The measurements were performed in a temperature controlled room at  $21.0\text{ }^{\circ}\text{C} \pm 1.0\text{ }^{\circ}\text{C}$ , and humidity was monitored but not controlled during the measurements.

## 2.12 NIS

### 2.12.1 Method

The calibration of the laboratory microphone LS1 is realized in accordance with IEC recommendation IEC 61094-2(2009) for the three-microphone method. The measurements are made in two plane wave couplers, having the lengths 7.5 mm and 15 mm. The average value of the microphone sensitivity obtained in two couplers is taken a final result. The frequency range of calibration is 20Hz to 10 kHz. The sensitivity of the microphone is obtained from the electrical transfer impedance which was measured using the computer operated automatic Reciprocity Calibration Apparatus B&K 5998.

### 2.12.2 Deviations from standard

None declared.

### 2.12.3 Declared parameters

#### Front Cavity Depth:

The depth of the microphone front cavity is measured by an optical method using depth focusing microscope. The front cavity depth is determined from the mean of measurements.

#### Front Cavity Volume:

The microphone front cavity volume  $V_f$  is calculated using the equation as given in the technical documentation of reciprocity calibration system B&K 9699:

$$V_f = \text{Cavity depth} / 1.95 * 530$$

#### Equivalent Volume:

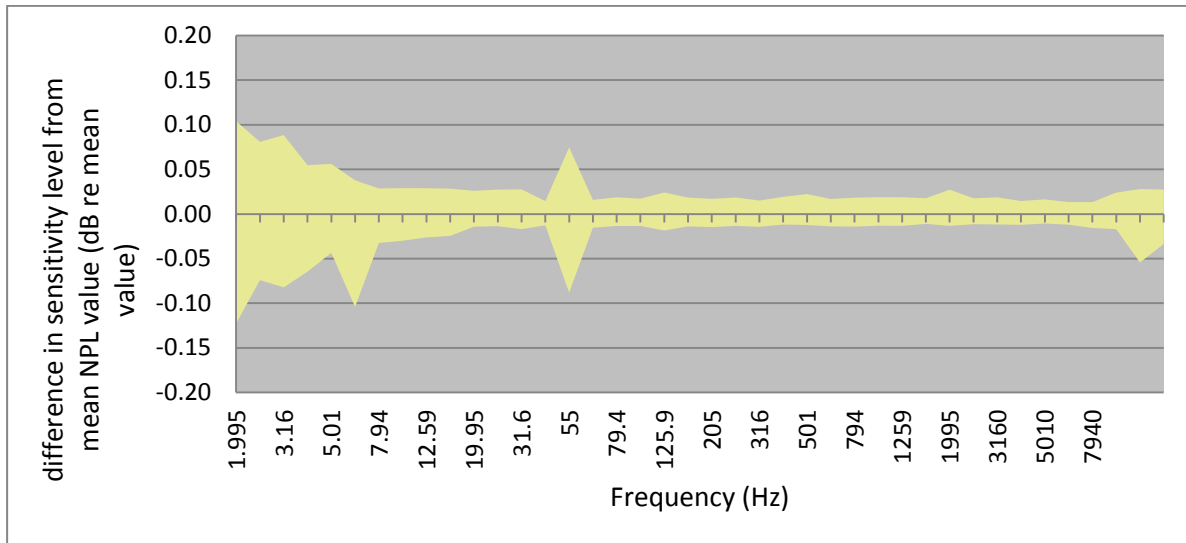
The equivalent volume is estimated by data fitting. The equivalent volume is adjusted to have the minimum difference between the measured results of the short (nominal length of 7.5 mm) and the long (nominal length 15 mm) plane wave couplers.

$$V_e = 2.935 * \text{Sensitivity [mV/Pa]}$$

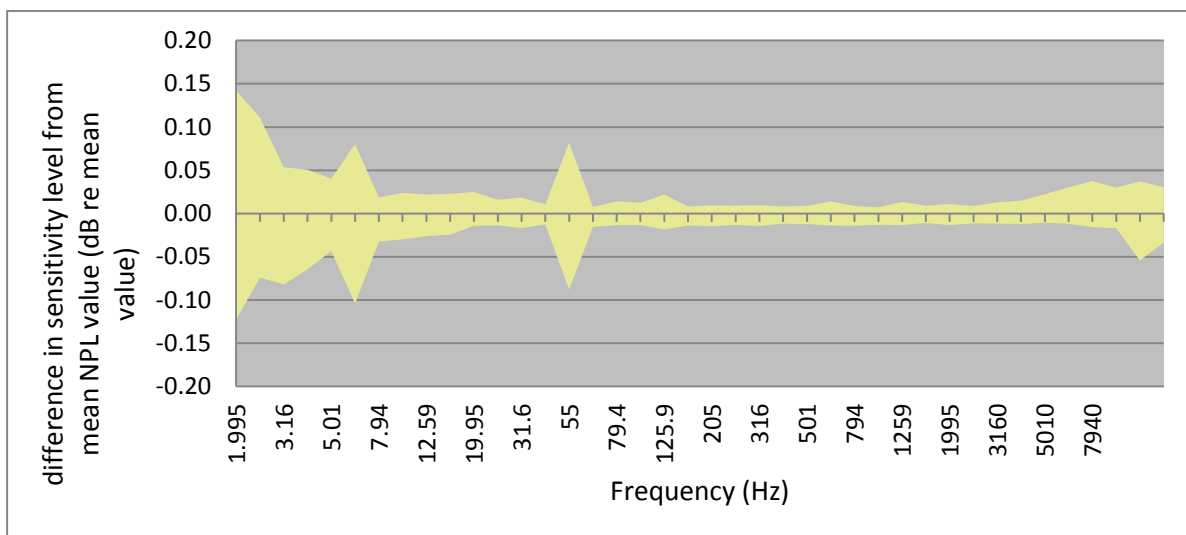
## 3 STABILITY OF TRAVELLING STANDARDS

Two Brüel and Kjær type 4160 microphones were selected for this project. Both microphones have a history of stability. Both microphones were calibrated regularly at NPL prior to circulation to establish their suitability for the key comparison. The results declared by NPL are derived from a set of measurements performed at the end of these pre-circulation measurements.

The stability of the microphones was monitored throughout the project by regular calibration at the pilot laboratory. A full calibration of each microphone was conducted, before and after circulation to pairs of participants. The spread in these NPL results is shown in Figure 1, and gives an initial impression of the stability of each microphone.



**Figure 1(a). Stability of 4160 811014 in terms of the maximum positive and negative differences from the mean value of NPL measurements throughout the key comparison**



**Figure 1(b). Stability of 4160 2036126 in terms of the maximum positive and negative differences from the mean value of NPL measurements throughout the key comparison**

The absolute value of the difference in magnitude sensitivity level from the NPL mean value is typically less than 0.03 dB for microphone serial number 811014 and less than 0.02 dB for microphone serial number 2036126 at frequencies from 6.31 Hz to 7940 Hz. The standard deviation of these NPL results is less than that allowed for in the NPL uncertainty analysis suggesting that both microphones were reasonably stable. A more detailed assessment of the behaviour of 2036126 also revealed no statistically significant drift in the sensitivity level and phase of the microphone. However the same analysis revealed a small drift in 811014 over the duration of the key comparison.

The detailed analysis applied to both microphones was as follows:

For each frequency, a weighted least squares method was used to calculate a best fit constant and a best fit straight line for the sensitivity (level and phase) of each microphone as a function of time. The data was weighted according to the pilot laboratory's type A standard uncertainty. The consistency of each fit with the data was then assessed using a chi-squared test. If the best fit constant was consistent according to the chi-squared test, as was the case with microphone 4160 2036126, the microphone

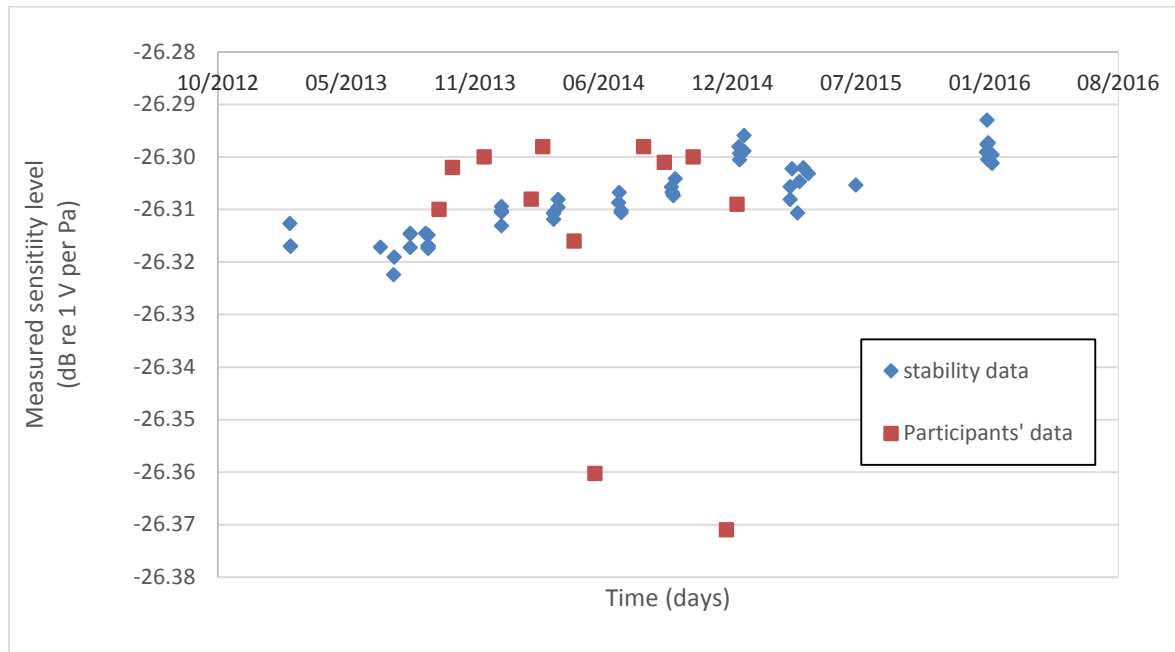
sensitivity was considered to have been stable throughout the key comparison. This analysis is described in greater detail in Annex A.

For microphone serial number 811014, however, the absolute value of the difference in magnitude sensitivity level from the NPL mean value is larger. It would be possible to apply a correction to the results to reliably account for drift, but inclusion of a second microphone would significantly complicate the analysis and the linking to CCAUV.A-K5. It was therefore agreed by consensus that measurement results for microphone serial number 811014 should be excluded altogether on the grounds that:

- For microphone 4160 811014 there is evidence of a statistically significant drift at nearly all frequencies
- Microphone 4160 2036126 has been shown to have been 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 use of a single microphone is consistent with the practice established in CCAUV.A-K5

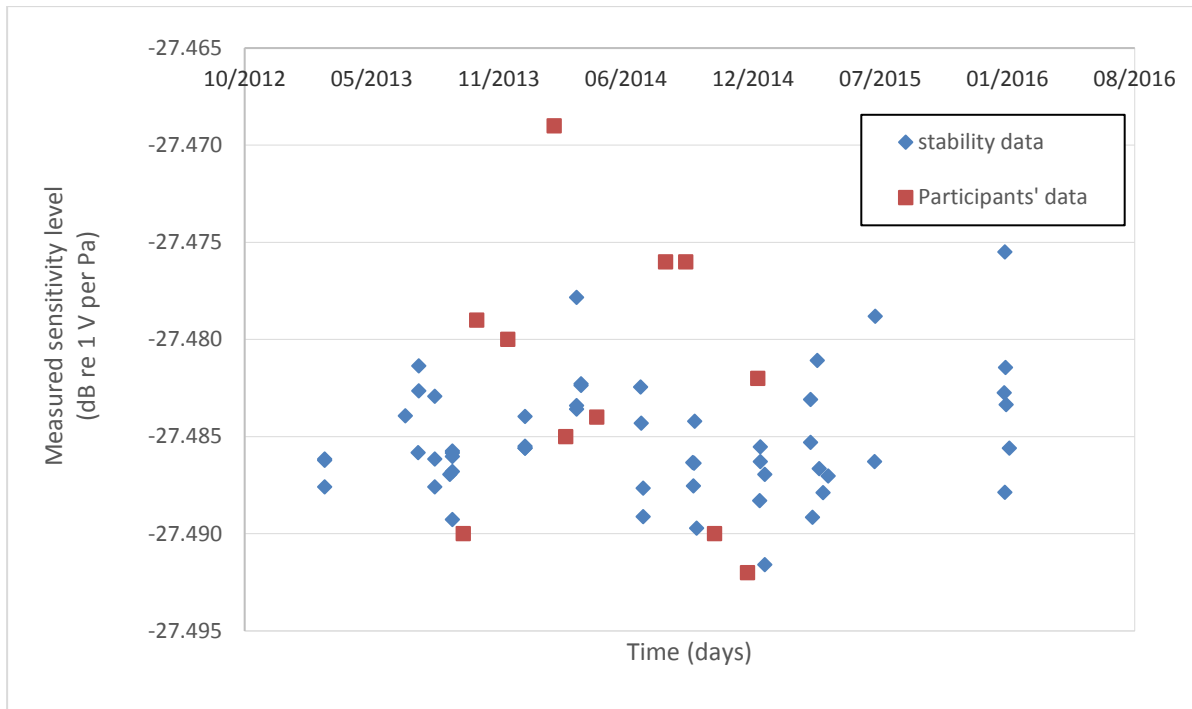
The full analysis has been performed for microphone serial number 2036126 only. The results for 4160 811014 may still be of interest, even if they are not included in the calculations for linking to the KCRV, so the participants' data has been provided for this microphone also. A discussion of the detailed statistical analysis has been provided in Annex A. A simple illustration is provided below.

Figure 2 shows the trend with time for each microphone at 251.189 Hz. A weak trend is evident in Figure 2(a) whereas in Figure 2(b) no such trend is visible. The full analysis confirmed these observations quantitatively. For reference, the corresponding results declared by the participants are also included in each graph. For 2036126 one outlier in the participants' data is not shown, to keep the vertical scale suitable for the rest of the data.



**Figure 2(a). Stability of 4160 811014 at 251.189 Hz during EURAMET.AUV.A-K5**





**Figure 2(b). Stability of 4160 2036126 at 251.189 Hz during EURAMET.AUV.A-K5**

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

Tables of declared results and uncertainties for both microphones are provided in the Microsoft Excel spreadsheet ‘EURAMET.AUV.A-K5 Draft B Tables of Data.xls’.

Tables of the declared participant uncertainty budgets are provided in Microsoft Excel spreadsheet ‘EURAMET\_AUV\_A-K5 Uncertainty Budgets Draft B.xlsx’.

As pilot laboratory, NPL was tasked with identifying anomalous results and providing the participants concerned with the opportunity to review their data. CIPM document CIPM MRA-D-05<sup>4</sup> states that:

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

Following the analysis of the NPL stability measurements, it was decided to exclude microphone 4160 811014 entirely from the calculations linking the results to the Key Comparison Reference Value (KCRV) and for identifying anomalous results.

The approach taken by NPL was as follows (applied independently for each frequency for microphone 4160 2036126 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);

- 2) Apply a chi-squared test of the consistency of the data with the weighted mean;
- 3) If the test is passed, include the data for all the laboratories in the analysis to evaluate 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 sensitivity data reported by DMDM was generally inconsistent with the data reported by the other laboratories participating in the EURAMET.AUV.A-K5 comparison. Consequently, the process outlined above was initiated. However, DMDM did not report any numerical errors and the originally reported results therefore stand. As a result this inconsistency persisted, and the sensitivity data reported by DMDM have therefore been excluded from the subsequent analysis, which utilised the data for only those laboratories in the EURAMET.AUV.A-K5 comparison deemed to be consistent.

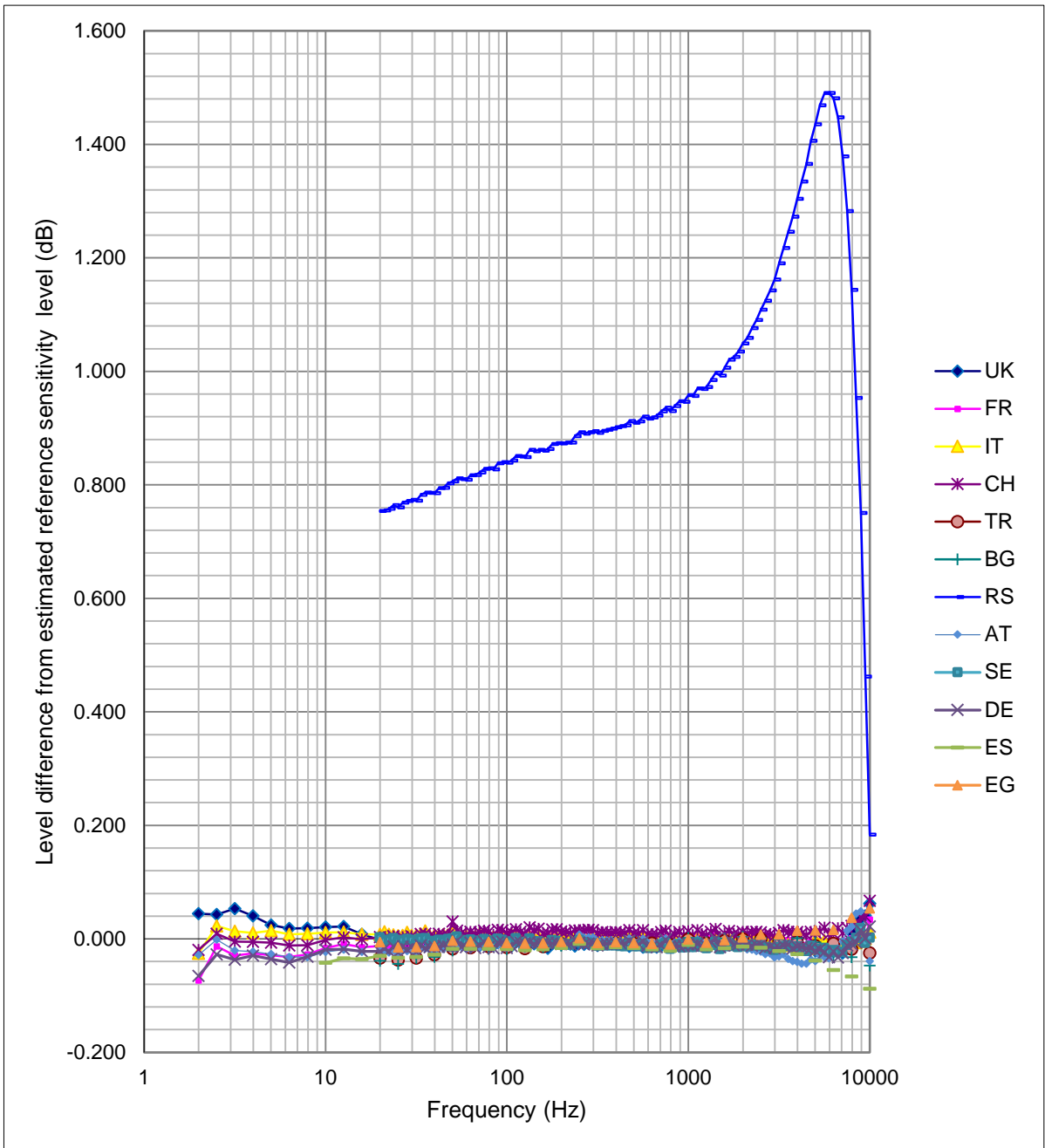
The data for the DoEs for the linking laboratories were used to link to CIPM comparison CCAUV.A-K5, the linking laboratories being NPL and INRIM. Because of the inconsistency of the results of DMDM with those of the other participants in EURAMET.AUV.A-K5, the calculation of the DoEs for DMDM was done differently from those other participants, and involved evaluating directly the deviations of the measured values reported by DMDM from the consensus values for the microphone determined in the linking analysis and the uncertainties associated with those deviations. All other participants' data were found to be consistent and were used in the calculation of DoEs based on linking to the CCAUV.A-K5 key comparison.

Tables of calculated degrees of equivalence (DoEs) for each laboratory are provided in Microsoft Excel spreadsheet '*EURAMET.AUV-A-K5 Draft B Tables of Data.xls*'.

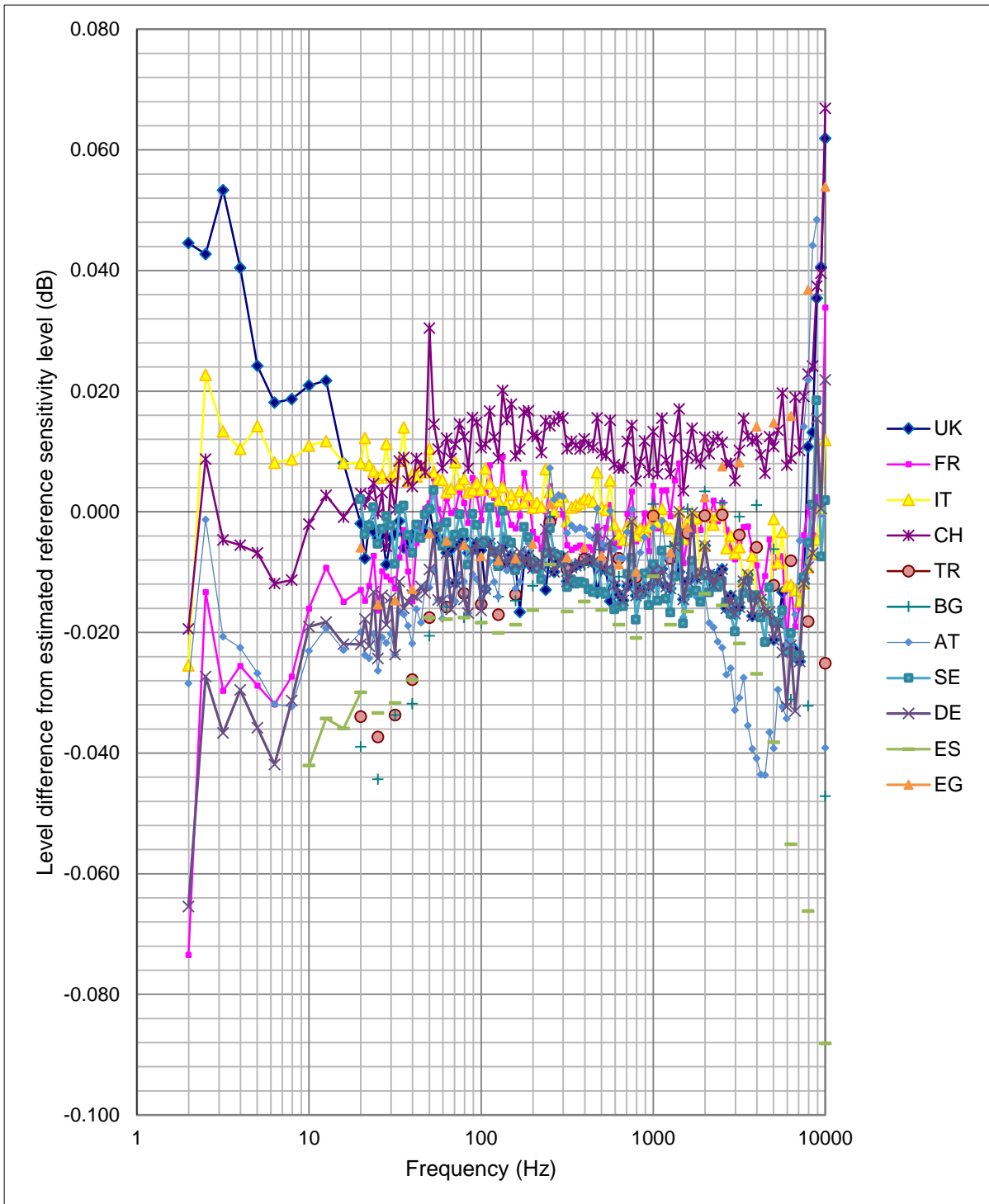
For illustration, the following graphs show each laboratory's results as a difference from the estimated sensitivity level and phase for each microphone. Figures 3(a) and 3(b) show the results for sensitivity level for microphone serial number 2036126 with and without the results of DMDM respectively. Figure 3(c) shows the results for sensitivity phase for the same microphone. For microphone serial number 2036126, the estimated sensitivity level and phase are based on an aggregation of the information about the sensitivity level and phase contained in the results reported by the laboratories participating in EURAMET.AUV.A-K5 and the information about the DoEs for the linking laboratories. See Section 5 for a detailed description of the linking and aggregation process.

The DMDM results have not been included in the calculation of the estimated sensitivity level and phase for microphone serial number 2036126.

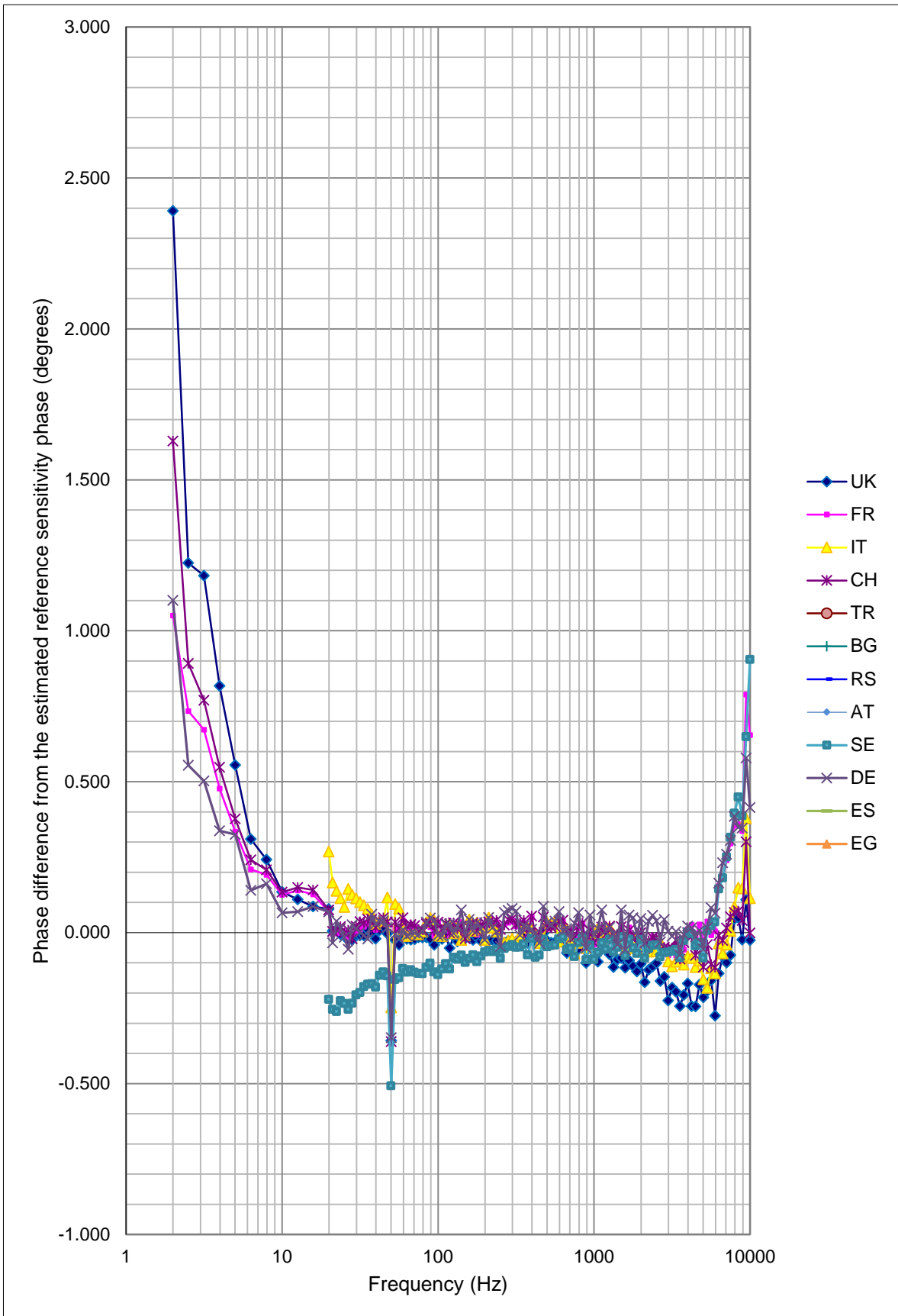
For microphone serial number 811014, the unweighted mean of all the results is used to calculate the estimated sensitivity level and phase. These results are shown in Figures 3(d) and 3(e). This microphone was not used in the linking calculations and the results are shown for illustration only.



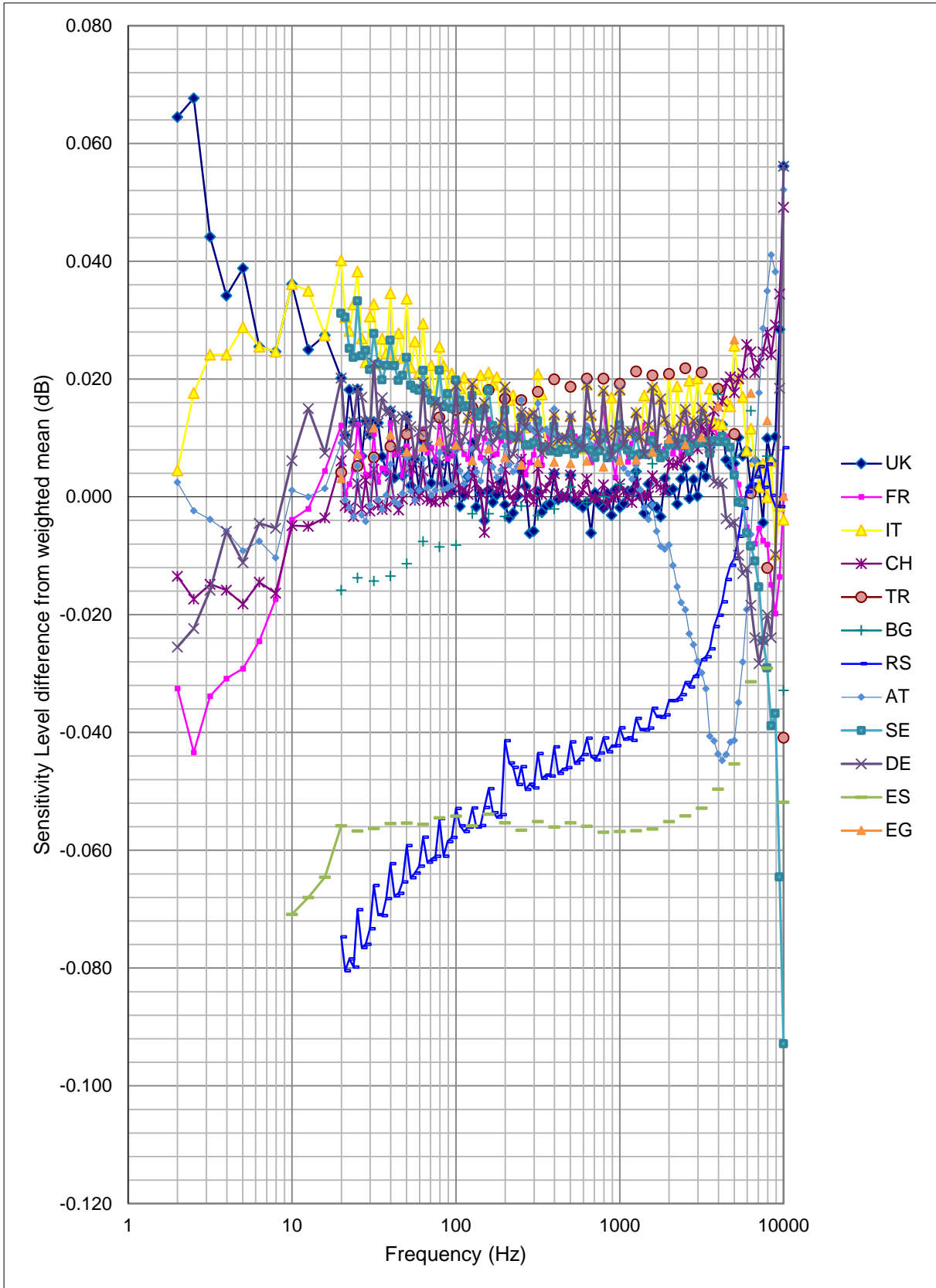
**Figure 3(a). Combined sensitivity level results of all participating laboratories, for 4160 2036126, shown as a difference from the estimated reference sensitivity level**



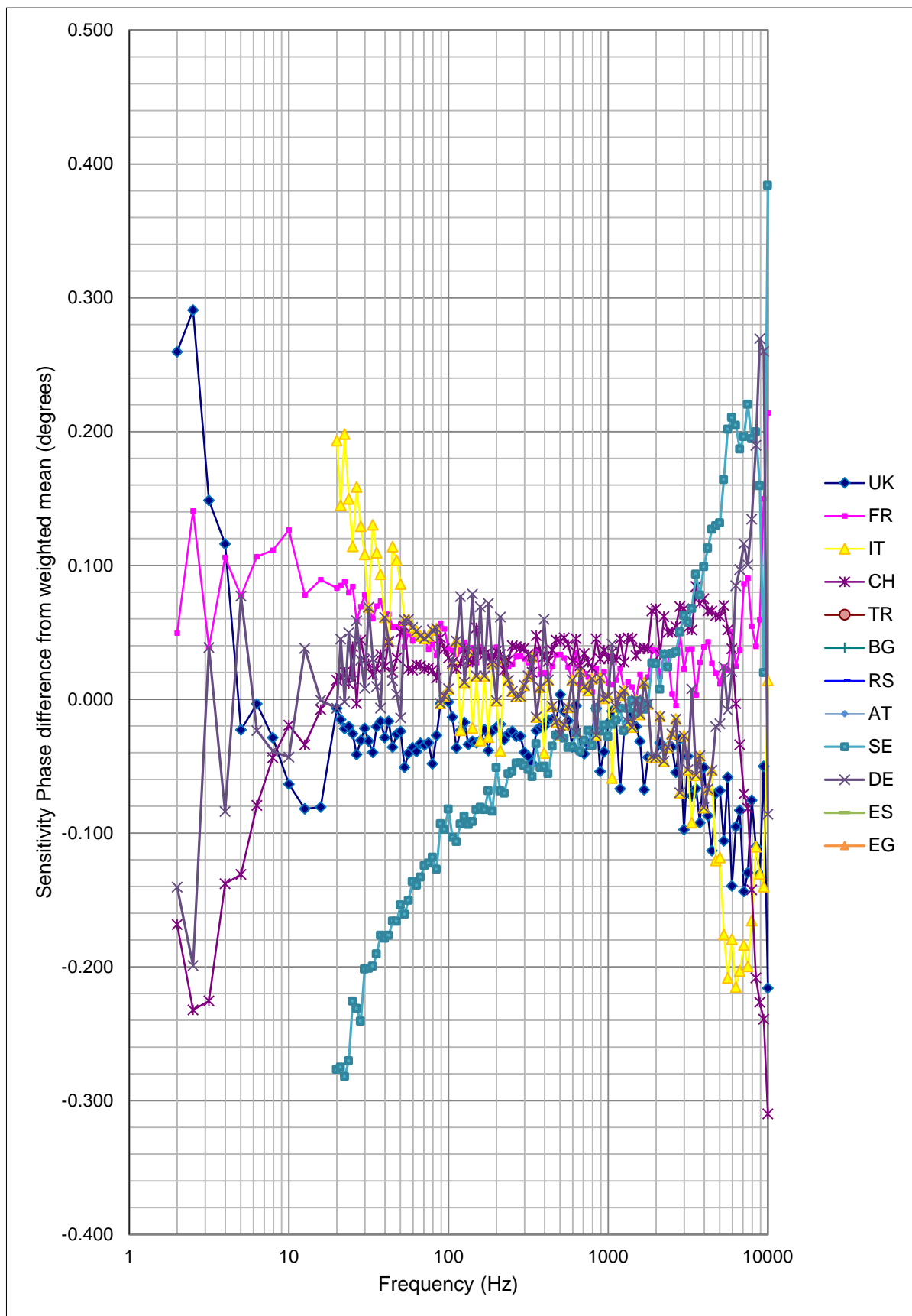
**Figure 3(b).** Combined sensitivity level results of all participating laboratories except DMDM (RS), for 4160 2036126, shown as a difference from the estimated reference sensitivity level



**Figure 3(c). Combined sensitivity phase results of all participating laboratories, for 4160 2036126, shown as a difference from the estimated reference sensitivity phase**



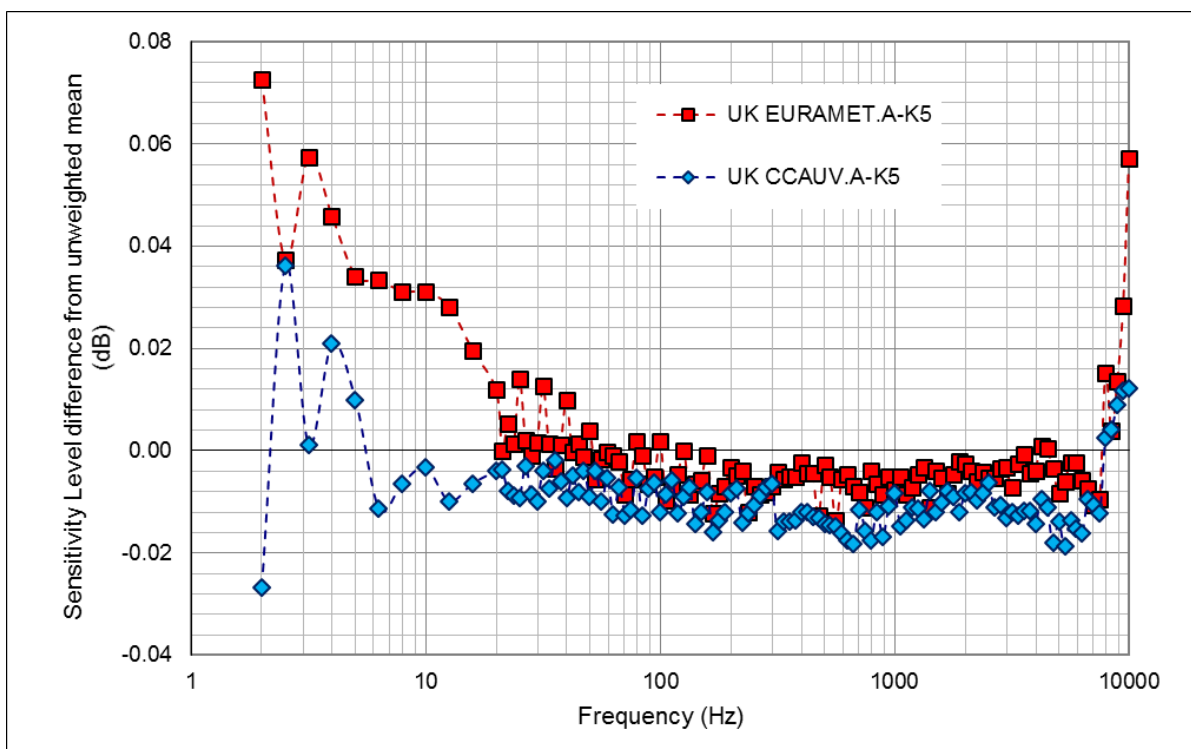
**Figure 3(d) Combined sensitivity level results of all participating laboratories, for 4160 811014, shown as a difference from the unweighted mean of all the results. (NB. These results have not been used for linking)**



**Figure 3(e) Combined sensitivity phase results of all participating laboratories, for 4160 811014, shown as a difference from the unweighted mean of all the results. (NB. These results have not been used for linking)**

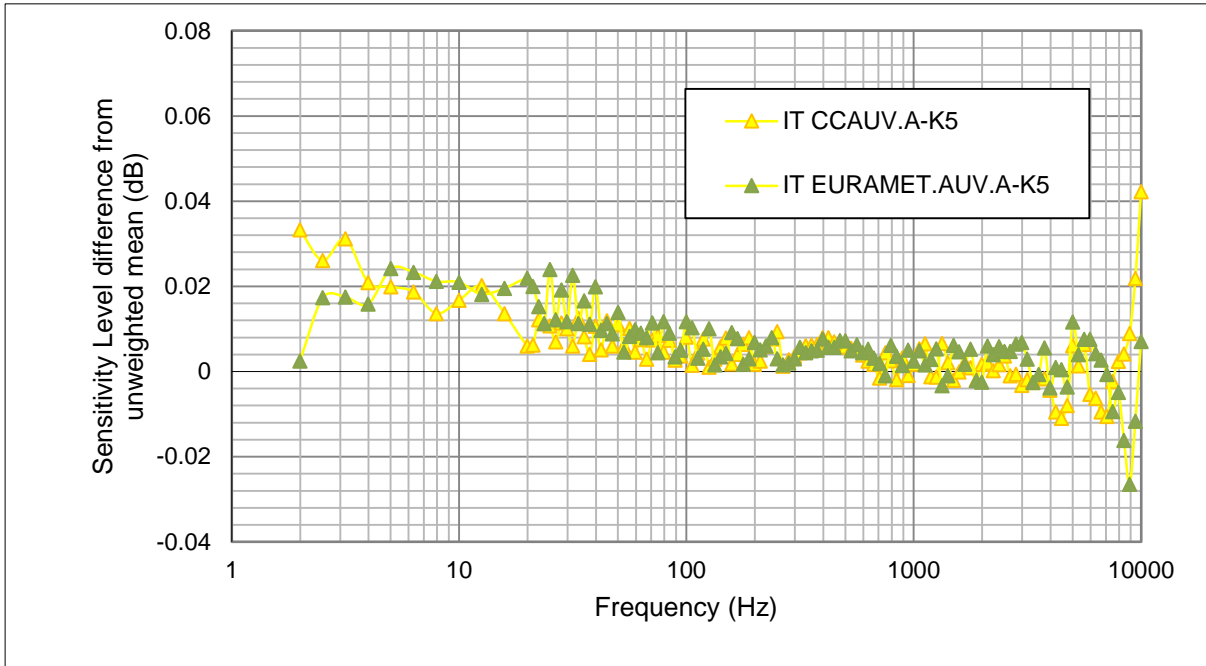
NPL and INRIM are the two laboratories that link EURAMET.AUV.A-K5 back to CCAUV.A-K5. The linking analysis relies to some extent on the assumption that the performance of the two laboratories remains constant between the two key comparisons. As a check that this assumption is valid, the performance of the two linking laboratories has been compared with the mean of all the results within each key comparison. With twelve participants contributing to each key comparison mean value (albeit different participants) it is reasonable to expect the mean values to be roughly equivalent and the linking laboratories' results to remain approximately the same in relation to those mean values.

The following graphs show the NPL and INRIM results relative to the unweighted mean of the results for each of the two key comparisons. Both laboratories' results show a good degree of consistency between the two key comparisons. This test is not based on a formal mathematical process, but the results presented in Figures 4(a) to 4(d) below provide a qualitative indication that the performance of the linking laboratories is satisfactory.

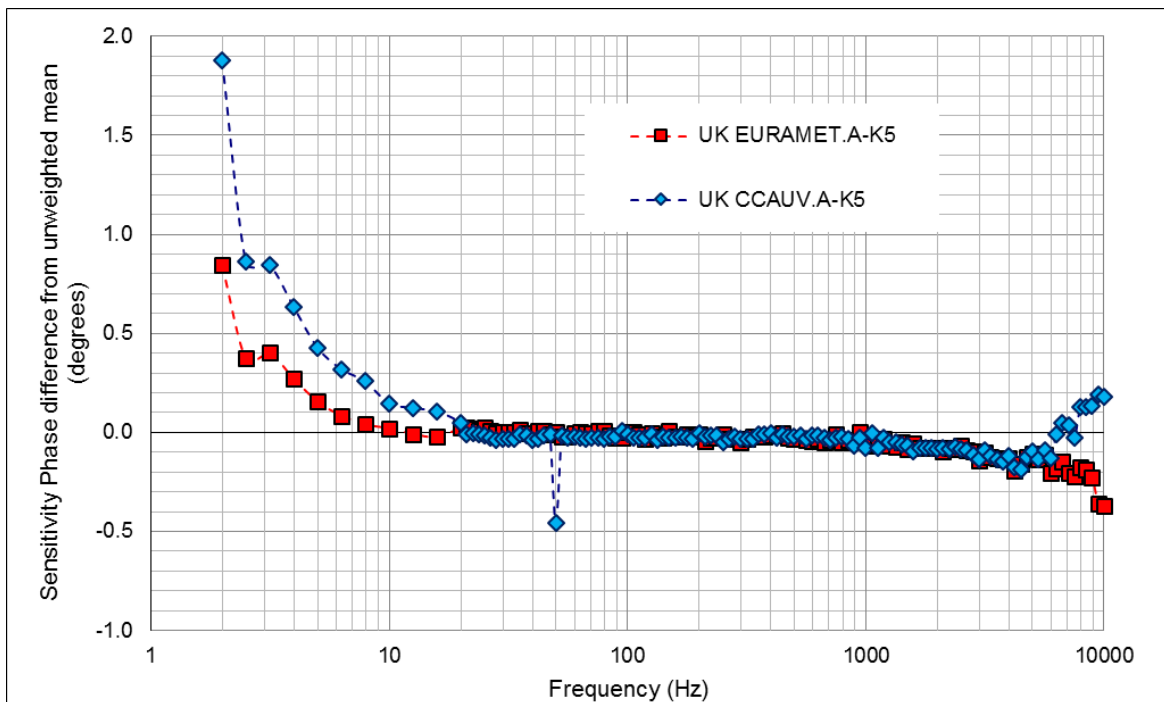


**Figure 4(a). The NPL sensitivity level results for CCAUV.A-K5 and EURAMET.AUV.A-K5 in relation to the unweighted mean of all participants' results (except DMDM) for each key comparison**

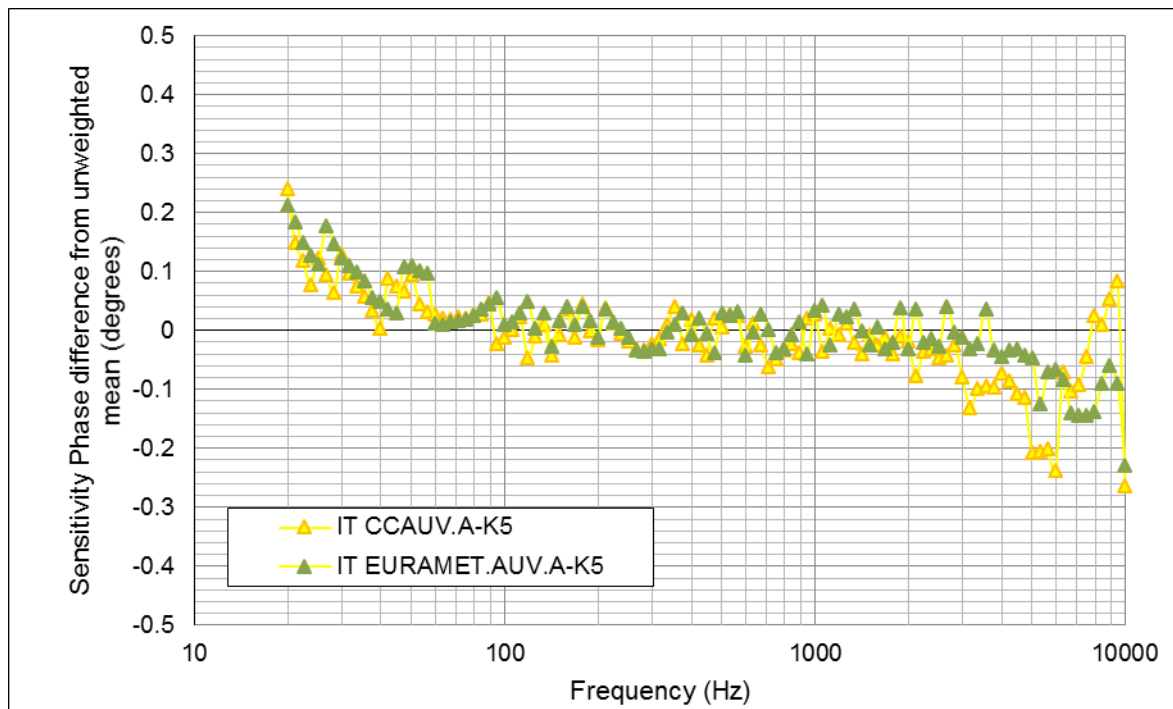




**Figure 4(b). The INRIM sensitivity level results for CCAUV.A-K5 and EURAMET.AUV.A-K5 in relation to the unweighted mean of all participants' results (except DMDM) for each key comparison**



**Figure 4(c). The NPL sensitivity phase results for CCAUV.A-K5 and EURAMET.AUV.A-K5 in relation to the unweighted mean of all participants' results (except DMDM) for each key comparison**



**Figure 4(d). The INRIM sensitivity phase results for CCAUV.A-K5 and EURAMET.AUV.A-K5 in relation to the unweighted mean of all participants' results (except DMDM) for each key comparison**

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

### Overview

The analysis approach involves the following steps:

1. Stability analysis of microphones using data provided by NPL;
2. Pre-processing of data reported by the laboratories participating in the EURAMET.AUV-K5 comparison;
3. Evaluation of degrees of equivalence for laboratories participating in the EURAMET.AUV-K5 comparison based on linking to the CCAUV.A-K5 key comparison with linking laboratories NPL and INRIM.

The results of step 1 indicated that only one of the two microphones was stable and, consequently, only the data related to the stable microphone was used in the analysis steps 1 and 2.

Step 2 involved the separate analysis of the sensitivity level and phase data reported by the laboratories participating in the EURAMET.AUV-K5 comparison without any consideration of linking to the CCAUV.A-K5 key comparison. The results of this step indicated that the sensitivity data reported by DMDM was generally inconsistent with the data reported by the other laboratories participating in the EURAMET.AUV-K5 comparison. Consequently, the sensitivity data reported by DMDM was excluded from the analysis in step 3, and degrees of equivalence for DMDM were instead calculated by considering the deviations of the measured values reported by DMDM from the reference values for the microphone determined in step 3 and the uncertainties associated with those deviations.

Step 3 involves an analysis of the data reported in the EURAMET.AUV-K5 comparison and the CCAUV.A-K5 key comparison, and the analysis is described below.

### Approach to linking

Suppose that  $N$  laboratories identified by indices  $i = 1, \dots, N$ , measure  $m$  microphones identified by indices  $k = 1, \dots, m$ , in the regional metrology organization (RMO) comparison. Furthermore, suppose there are  $L$  linking laboratories identified by indices  $l = 1, \dots, L$ , that participated also in the CC key comparison (KC).

For each frequency, the following model equations are considered for the measured data provided in the RMO comparison<sup>5</sup>

$$x_{i,k} = y_k + \Delta_i + \varepsilon_{i,k},$$

where  $x_{i,k}$  is the measured value of sensitivity level (or phase) provided by laboratory  $i$  for microphone  $k$ ,  $y_k$  is an estimate of the sensitivity level (or phase) for microphone  $k$ ,  $\Delta_i$  is an estimate of the value component of the degree of equivalence (DoE) for laboratory  $i$ , and  $\varepsilon_{i,k}$  is the error associated with  $x_{i,k}$ . Here,  $\varepsilon_{i,k}$  is assumed to be a random draw from a normal distribution with expectation zero and standard deviation  $u(x_{i,k})$ , the standard uncertainty associated with  $x_{i,k}$  reported by the laboratory. Additionally, for the linking laboratories, the following model equations are assumed for the value components of their DoEs calculated in the KC:

$$d_l = \Delta_l + \delta_l,$$

where  $d_l$  is the estimated value of the value component of the DoE for laboratory  $l$ , and  $\delta_l$  is the error associated with  $d_l$ . Here,  $\delta_l$  is assumed to be a random draw from a normal distribution with expectation zero and standard deviation  $u(d_l)$ , the standard uncertainty associated with  $d_l$  determined in the KC.

The model equations are aggregated into a single (usually overdetermined) linear system of equations represented by

$$\mathbf{x} = \mathbf{A}\mathbf{y} + \mathbf{e},$$

where the vector  $\mathbf{x}$  contains the data  $x_{i,k}$  and  $d_l$ , the vector  $\mathbf{y}$  contains the unknown parameters  $y_k$  and  $\Delta_i$ , the vector  $\mathbf{e}$  contains the errors  $\varepsilon_{i,k}$  and  $\delta_l$ , and the matrix  $\mathbf{A}$  has dimension  $(Nm + L) \times (m + N)$ . For example, for the case  $N = 4, m = 1$  and  $L = 2$ , then  $\mathbf{x} = (x_{1,1}, x_{2,1}, x_{3,1}, x_{4,1}, d_1, d_2)^T$ ,  $\mathbf{y} = (y_1, \Delta_1, \Delta_2, \Delta_3, \Delta_4)^T$  and the matrix  $\mathbf{A}$  takes the form

$$\mathbf{A} = \begin{pmatrix} 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{pmatrix}.$$

The vector  $\mathbf{e}$  has an associated covariance matrix  $\mathbf{V}$  with diagonal elements given by the variances (squared standard uncertainties) of the components of  $\mathbf{x}$ , and off-diagonal elements that are the covariances between pairs of the components of  $\mathbf{x}$ . The covariance will be non-zero for:

- The DoE for one linking laboratory and the DoE for another linking laboratory (type 1);
- The DoE for a linking laboratory and the measurements that laboratory makes within the RMO comparison (type 2);
- The DoE for a linking laboratory and the measurements that another linking laboratory makes within the RMO comparison (type 3);
- The measurements of different microphones made by the same laboratory within the RMO comparison (type 4).

For example, for the case above with  $N = 4, m = 1$  and  $L = 2$ , the matrix  $\mathbf{V}$  takes the form

$$V = \begin{pmatrix} u^2(x_{1,1}, x_{1,1}) & 0 & 0 & 0 & u(x_{1,1}, d_1) & u(x_{1,1}, d_2) \\ 0 & u^2(x_{2,1}, x_{2,1}) & 0 & 0 & u(x_{2,1}, d_1) & u(x_{2,1}, d_2) \\ 0 & 0 & u^2(x_{3,1}, x_{3,1}) & 0 & 0 & 0 \\ 0 & 0 & 0 & u^2(x_{4,1}, x_{4,1}) & 0 & 0 \\ u(d_1, x_{1,1}) & u(d_1, x_{2,1}) & 0 & 0 & u^2(d_1, d_1) & u(d_1, d_2) \\ u(d_2, x_{1,1}) & u(d_2, x_{2,1}) & 0 & 0 & u(d_2, d_1) & u^2(d_2, d_2) \end{pmatrix},$$

where  $u^2(q)$  denotes the variance of  $q$  and  $u(q_1, q_2) = u(q_2, q_1)$  denotes the covariance of  $q_1$  and  $q_2$ , involving covariances of types 1 to 3 from the above list. (Note: the case described involves only a single microphone ( $m=1$ ) and so covariances of type 4, which relate to measurements of different microphones in the RMO comparison, do not arise. In both CCAUV.A-K5 and EURAMET.AUV.A-K5, a single microphone was used for the analysis.)

The covariances can be quantified by identifying those effects for each laboratory that are common to the different measurements made by the laboratory. Suppose that the KC reference value used as the basis for the DoEs calculated in the KC is given by the inverse-variance weighted mean of the measured values  $x_{j,0}, j = 1, \dots, N_0$ , where the  $L$  linking laboratories that participated in the RMO comparison are identified by indices  $l = 1, \dots, L$ , and the remaining laboratories did not participate in the RMO comparison. Then, the value components of the DoEs for the linking laboratories are given by

$$d_l = (1 - w_l)x_{l,0} - \sum_{j \neq l} w_j x_{j,0}, \quad w_j = \frac{1/u^2(x_{j,0})}{\sum_n 1/u^2(x_{n,0})}.$$

Furthermore, for  $k = 0$  (data in the KC) and  $k = 1, \dots, m$  (data in the RMO comparison), let

$$\varepsilon_{i,k} = \varepsilon_{i,k}^R + \varepsilon_i^S,$$

where  $\varepsilon_{i,k}^R$  and  $\varepsilon_i^S$  denote, respectively, the random and systematic components of  $\varepsilon_{i,k}$ , i.e., the part of the error that is different for each measurement made by the laboratory and the part that is common to all measurements made by the laboratory. Then, for linking laboratories  $l \neq n$ :

$$u(d_l, d_n) = (w_l - 1)w_l u^2(x_{l,0}) + (w_n - 1)w_n u^2(x_{n,0}) + \sum_{j \neq l,n} w_j^2 u^2(x_{j,0}), \quad (\text{type 1})$$

$$u(d_l, x_{l,k}) = (1 - w_l)u(x_{l,0}, x_{l,k}) = (1 - w_l)u^2(\varepsilon_l^S), \quad (\text{type 2})$$

$$u(d_l, x_{n,k}) = -w_n u(x_{n,0}, x_{n,k}) = -w_n u^2(\varepsilon_n^S), \quad (\text{type 3})$$

and for laboratories  $i = 1, \dots, N$ , in the RMO comparison and microphones  $k \neq j$ :

$$u(x_{i,k}, x_{i,j}) = u^2(\varepsilon_i^S). \quad (\text{type 4})$$

Estimates of the unknown parameters  $y_k$  and  $\Delta_i$  and the associated uncertainties are obtained by solving the ‘‘generalised least-squares’’ problem<sup>6</sup>

$$\min_y \mathbf{e}^T \mathbf{V}^{-1} \mathbf{e},$$

although these contributions are zero in this case as only one microphone has been considered.

A chi-squared statistical test was used to test the consistency of the data  $x$  and covariance matrix  $V$  with the model equations. In all cases the test passed, indicating that the performances of the linking laboratories are consistent between the two key comparisons.

A motivation for the approach is as follows. Consider the (simplest) case of a single microphone ( $m = 1$ ) and a single linking laboratory ( $L = 1$ ) so that the number of model equations is the same as the number of unknown parameters (note that this is the case for this comparison for sensitivity phase at frequencies below 20 Hz). Then, the model equation for the DoE for the linking laboratory and the model equation for its measurement in the RMO comparison define the reference value  $y_1$  for the single microphone (and preserve the DoE for the linking laboratory), i.e.,

$$y_1 = x_{1,1} - d_1, \quad \Delta_1 = d_1.$$

The remaining model equations for the measurements made by the other laboratories in the RMO comparison then define the DoEs for those laboratories as being the differences between their measured values and the reference value, i.e.,

$$\Delta_i = x_{i,1} - y_1, \quad i = 2, \dots, N.$$

Furthermore, the uncertainties associated with the solution estimates are given by

$$u^2(y_1) = u^2(x_{1,1}) + u^2(d_1) - 2u(x_{1,1}, d_1)$$

and

$$u^2(\Delta_1) = u^2(d_1), \quad u^2(\Delta_i) = u^2(x_{i,1}) + u^2(y_1), \quad i = 2, \dots, N.$$

The proposed formulation involving the solution of a GLS problem generalises the approach to treat a general number of microphones and a general number of linking laboratories, although it is not possible in that case to satisfy the model equations exactly.

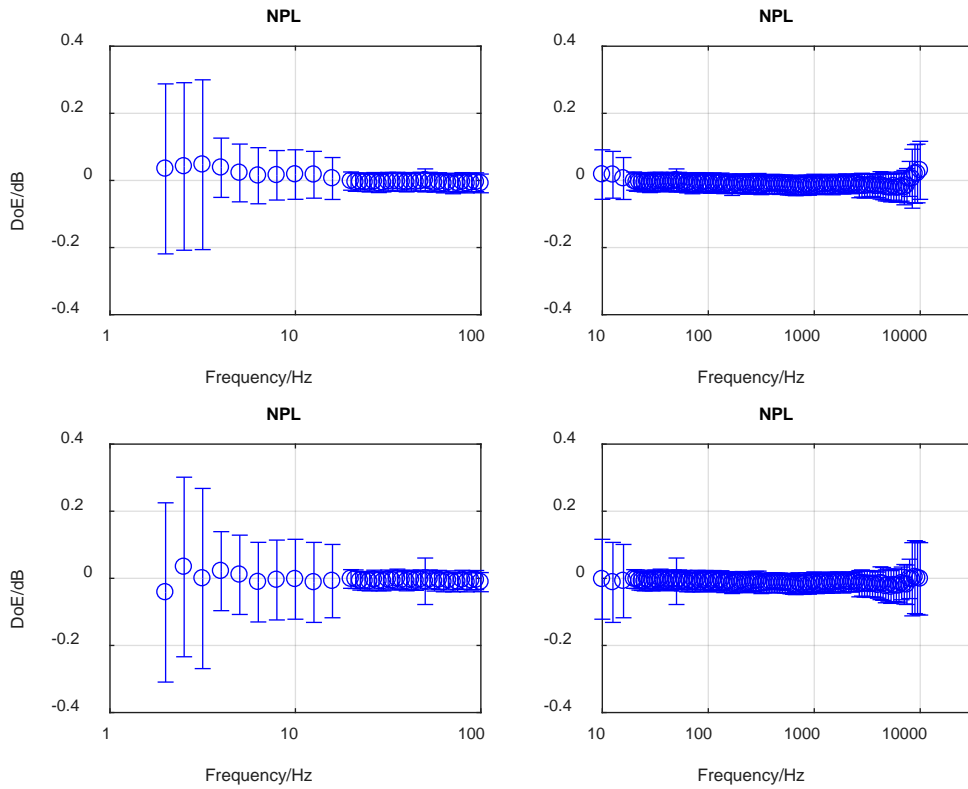
## 6 DEGREES OF EQUIVALENCE AND UNCERTAINTIES

The degrees of equivalence have been calculated using measurements made with microphone 4160 2036126 only, and linked to the KCRV established in CCAUV.A-K5 by the method described above.

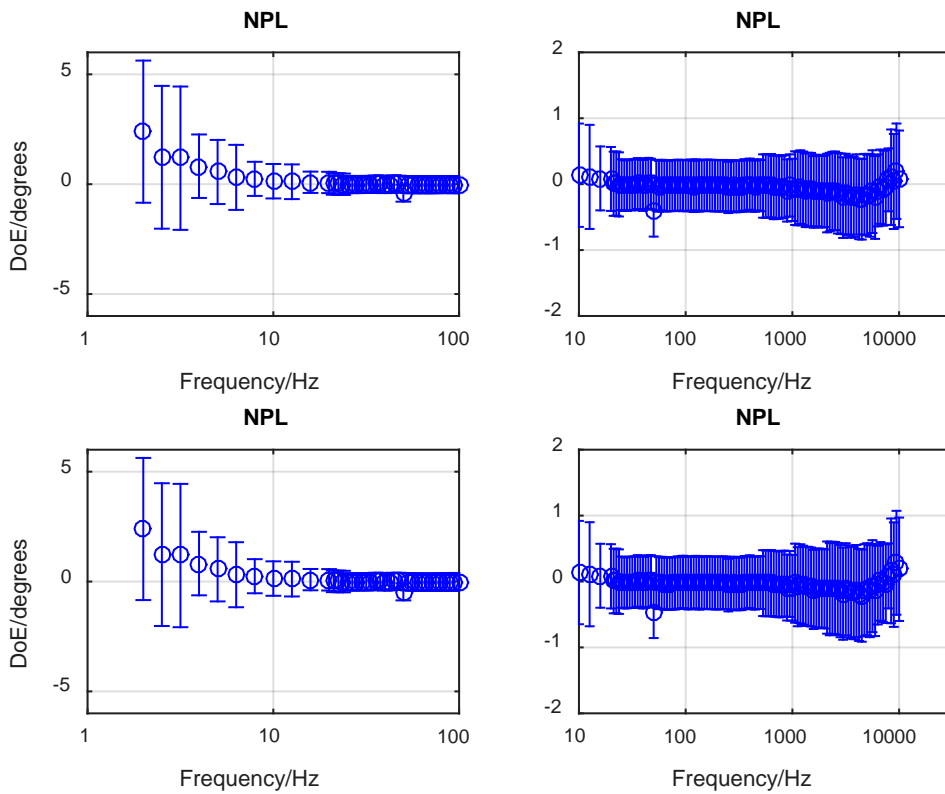
### 6.1 GRAPHS OF DEGREES OF EQUIVALENCE TO THE KCRV FOR EACH PARTICIPANT

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

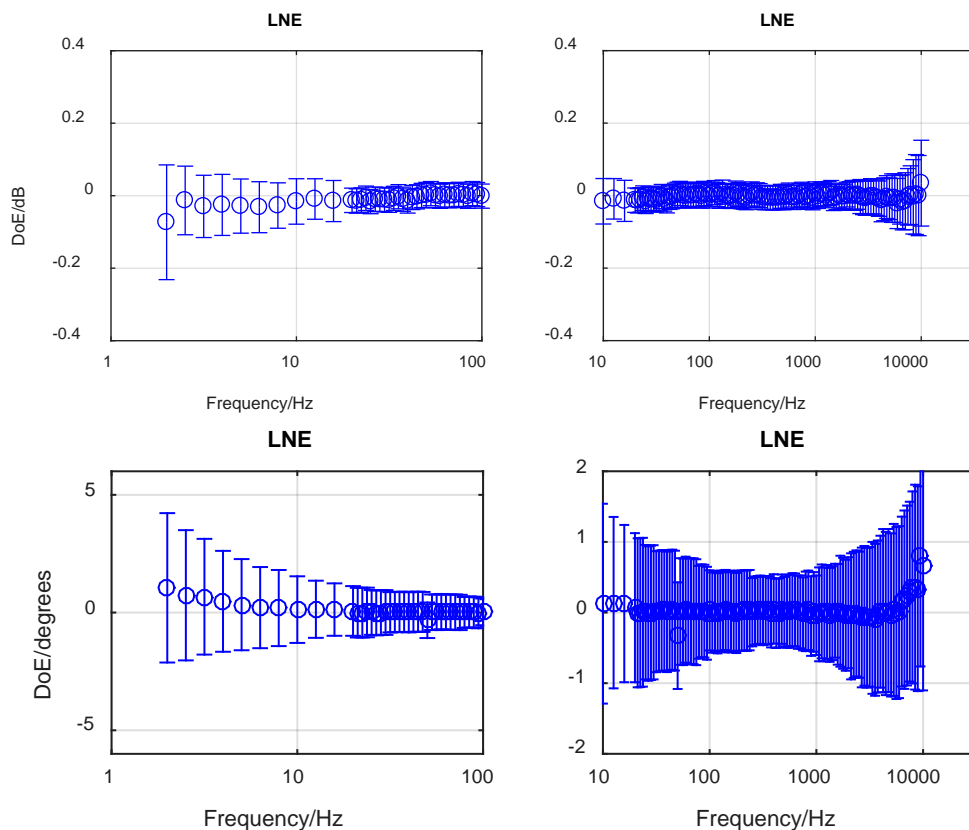
For linking laboratories NPL and INRIM, the DoEs for CCAUV.A-K5 are shown directly below the DoEs for EURAMET.AUV.A-K5 for comparison. The similarity of the DoEs for the two linking laboratories across the two key comparisons illustrates the high degree of correlation for these results and lends extra confidence to the linking process.



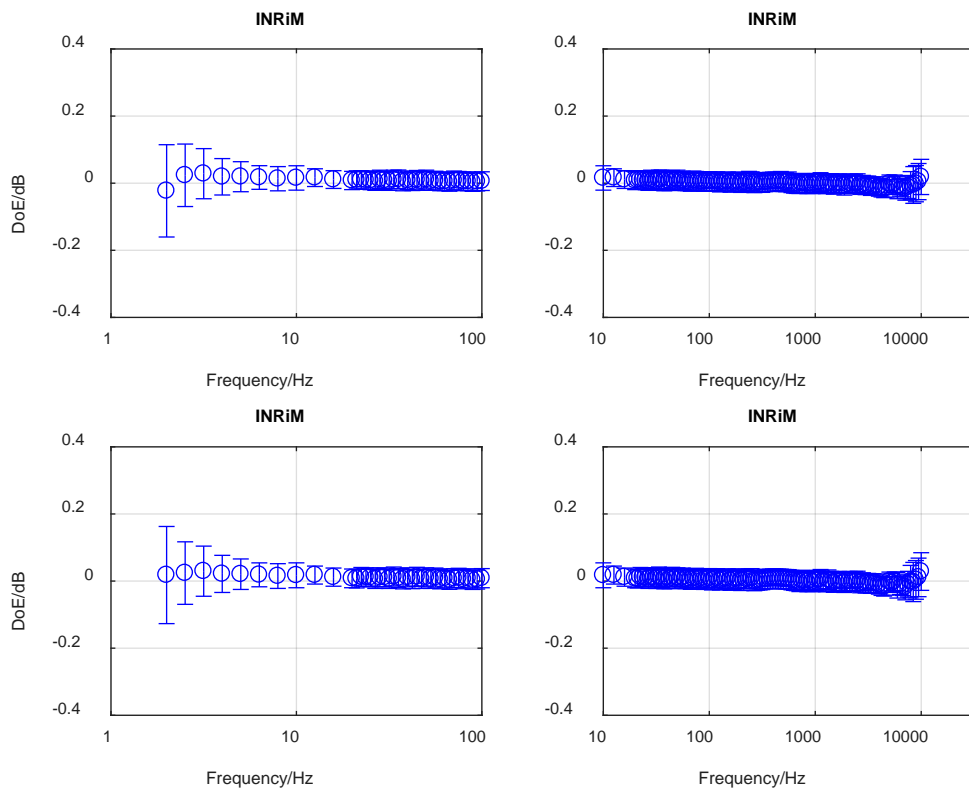
**Figure 5(a). Degrees of Equivalence for NPL sensitivity level measurements with uncertainties for a coverage factor  $k=2$  for EURAMET.AUV.A-K5 (top) and CCAUV.A-K5 (bottom)**



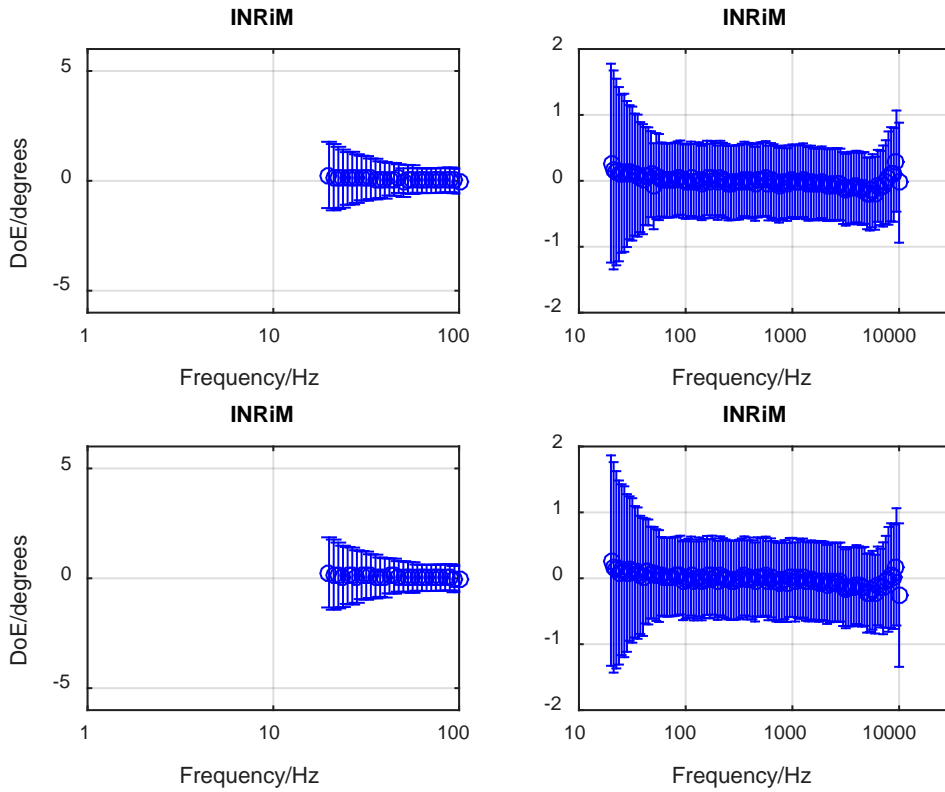
**Figure 5(b). Degrees of Equivalence for NPL sensitivity phase measurements with uncertainties for a coverage factor  $k=2$  for EURAMET.AUV.A-K5 (top) and CCAUV.A-K5 (bottom)**



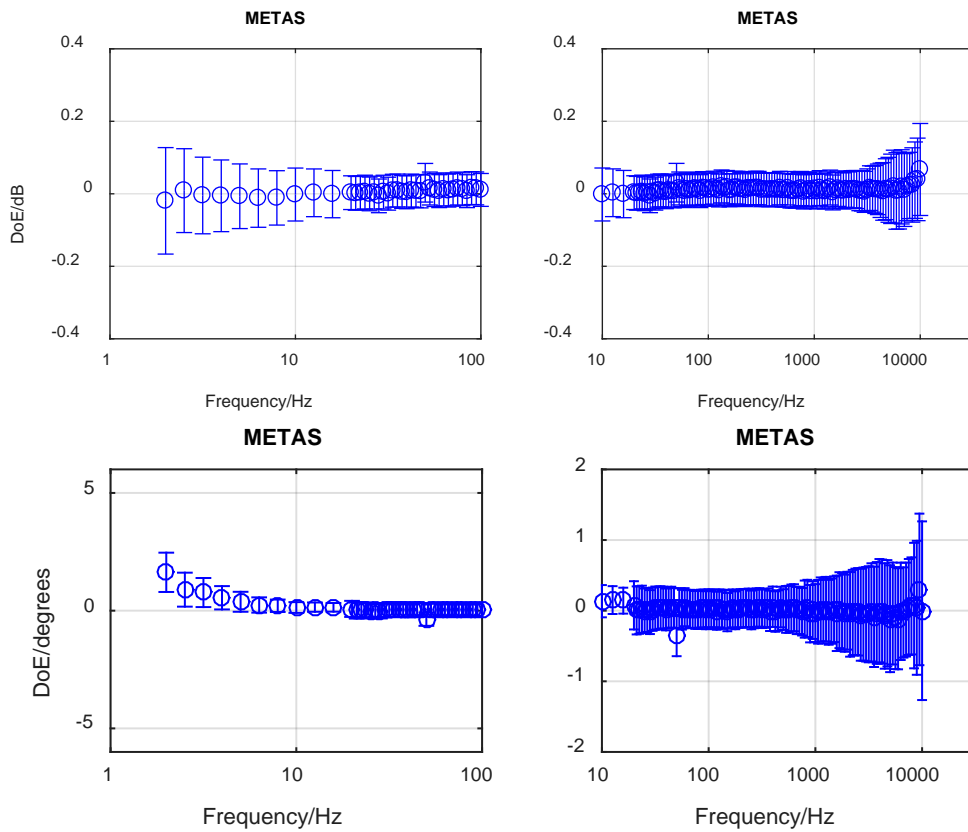
**Figure 5(c). Degrees of Equivalence (DoEs) for LNE sensitivity level and phase measurements with uncertainty bars corresponding to coverage factor  $k=2$**



**Figure 5(d) Degrees of Equivalence for INRiM sensitivity level measurements with uncertainties for a coverage factor  $k=2$  for EURAMET.AUV.A-K5 (top) and CCAUV.A-K5 (bottom)**

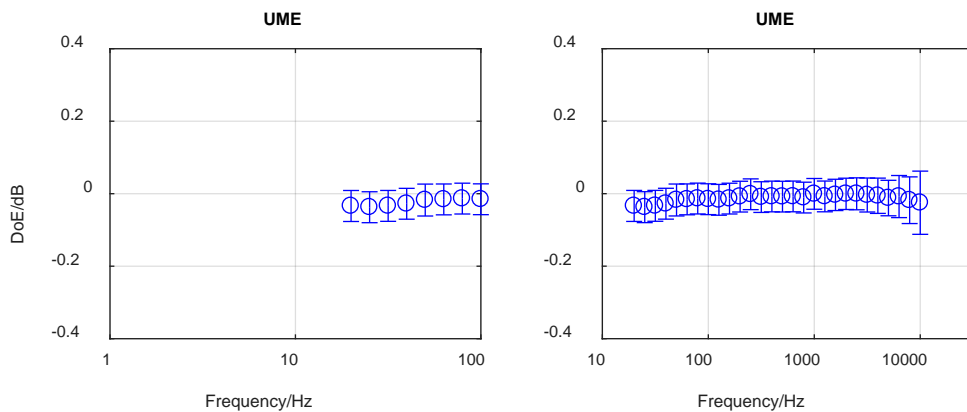


**Figure 5(e). Degrees of Equivalence for INRiM sensitivity phase measurements with uncertainty for coverage factor  $k=2$  for EURAMET.AUV.A-K5 (top) and CCAUV.A-K5 (bottom)**

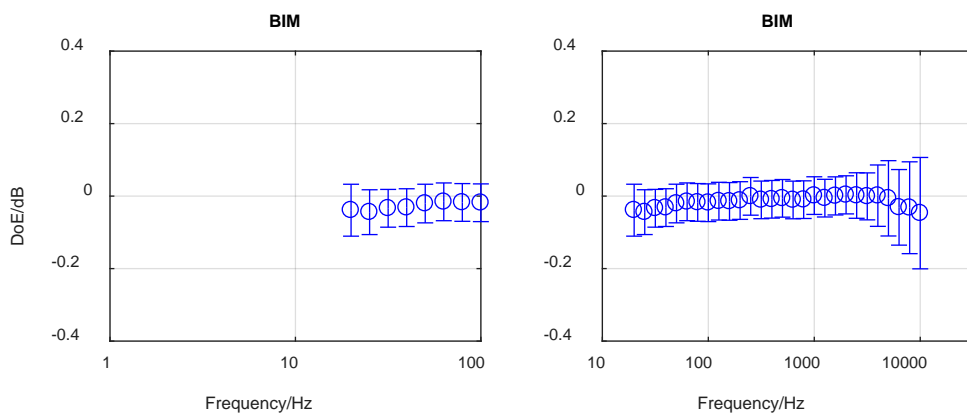


**Figure 5(f). Degrees of Equivalence (DoEs) for METAS sensitivity level and phase measurements with uncertainty bars corresponding to coverage factor  $k=2$**

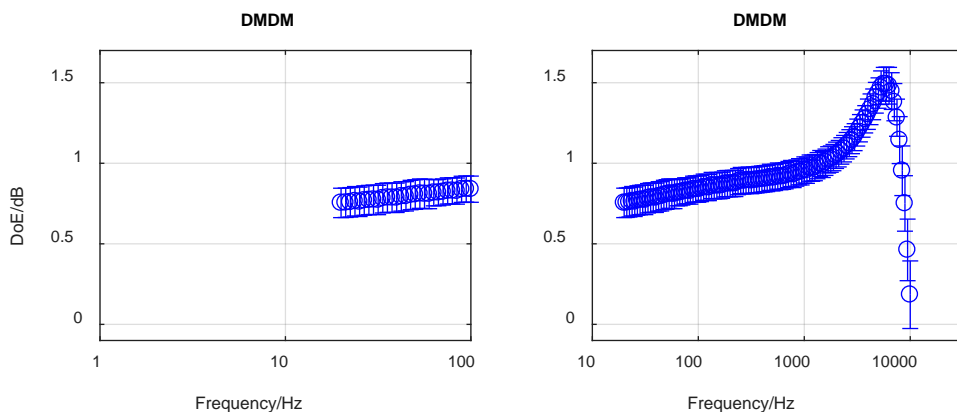




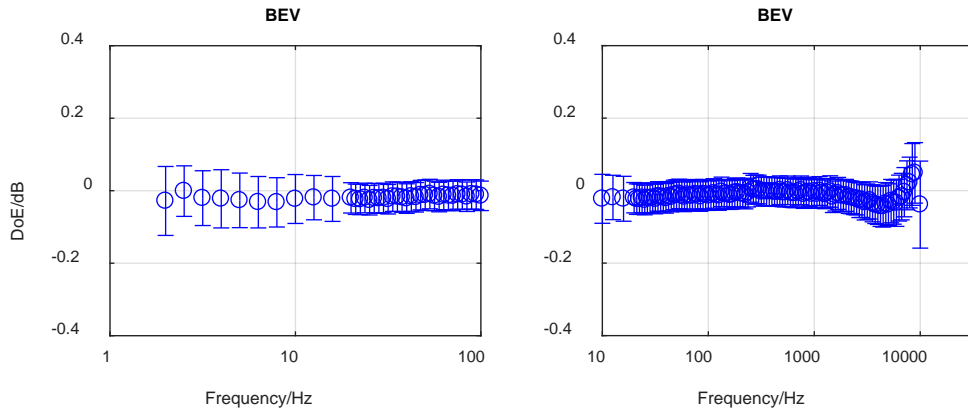
**Figure 5(g). Degrees of Equivalence (DoEs) for UME sensitivity level measurements with uncertainty bars corresponding to coverage factor  $k=2$**



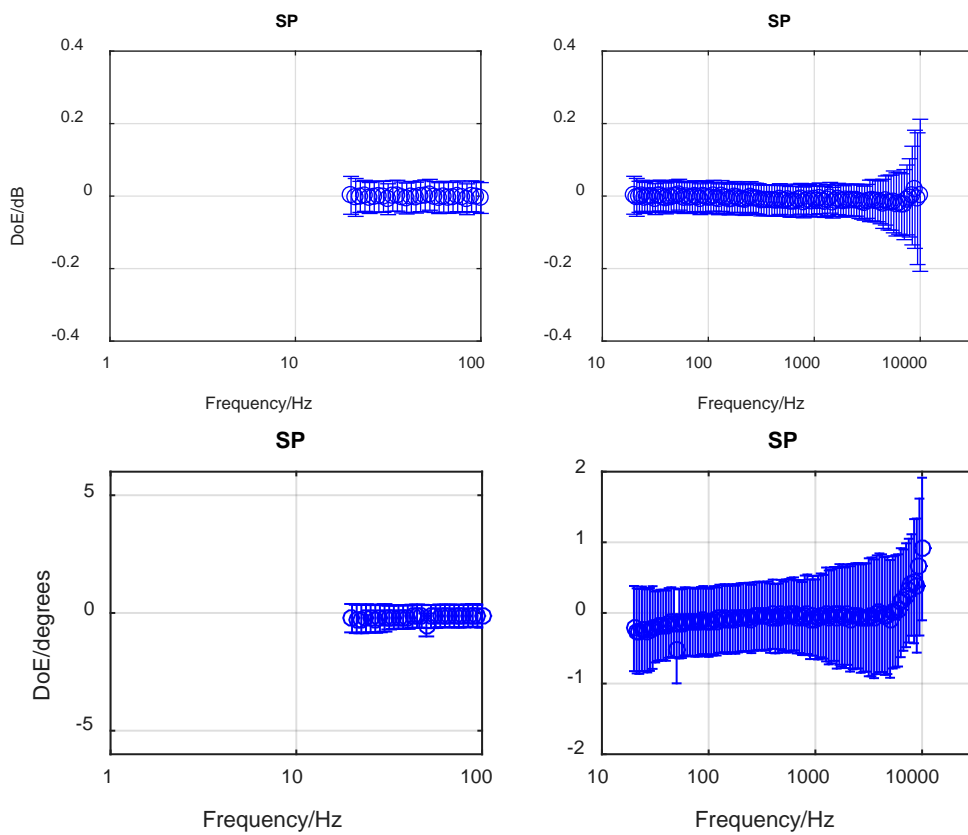
**Figure 5(h). Degrees of Equivalence (DoEs) for BIM sensitivity level measurements with uncertainty bars corresponding to coverage factor  $k=2$**



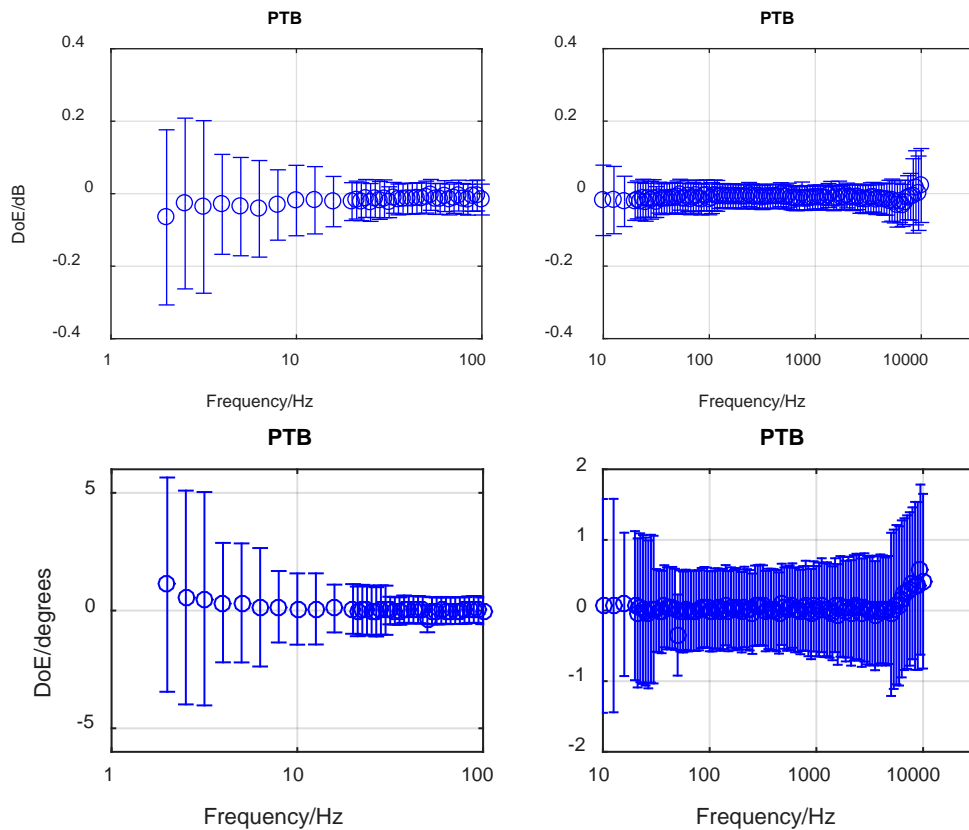
**Figure 5(i). Degrees of Equivalence (DoEs) for DMDM sensitivity level measurements with uncertainty bars corresponding to coverage factor  $k=2$  (note alternative vertical scale)**



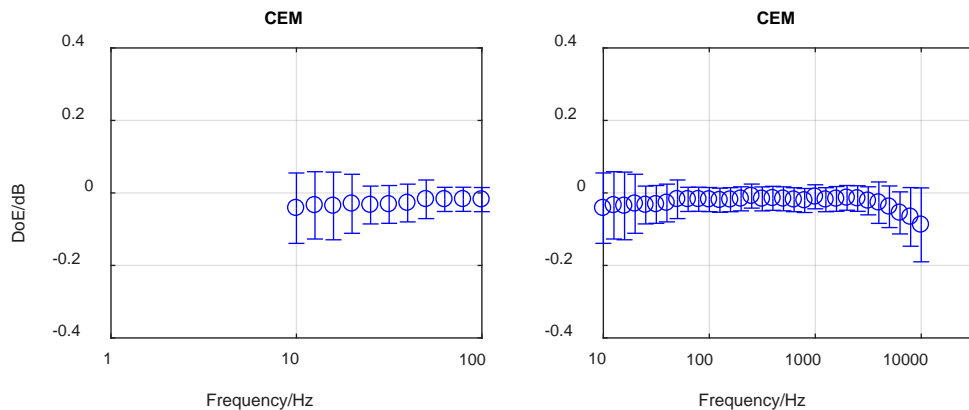
**Figure 5(j). Degrees of Equivalence (DoEs) for BEV for sensitivity level measurements with uncertainty bars corresponding to coverage factor  $k=2$**



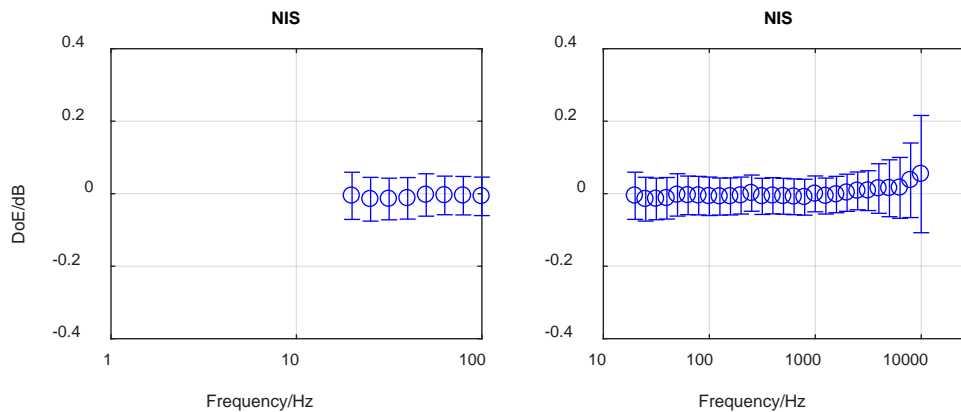
**Figure 5(k). Degrees of Equivalence (DoEs) for SP (RISE) for sensitivity level and phase measurements with uncertainty bars corresponding to coverage factor  $k=2$**



**Figure 5(l). Degrees of Equivalence (DoEs) for PTB sensitivity level and phase measurements with uncertainty bars corresponding to coverage factor  $k=2$**



**Figure 5(m). Degrees of Equivalence (DoEs) for CEM sensitivity level measurements with uncertainty bars corresponding to coverage factor  $k=2$**



**Figure 5(n). Degrees of Equivalence (DoEs) for NIS sensitivity level measurements with uncertainty bars corresponding to coverage factor  $k=2$**

## 7 CONCLUSION

This report describes the results for key comparison EURAMET.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.

Twelve national metrology institutes took part in the key comparison: NPL (United Kingdom), LNE (France), INRIM (Italy), METAS (Switzerland), UME (Turkey), BIM (Bulgaria), DMDM (Republic of Serbia), BEV (Austria), SP (RISE) (Sweden), PTB (Germany), CEM (Spain), and NIS (Egypt). The UK National Physical Laboratory (NPL) 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, the other proving to be unstable.

Values for both sensitivity level and sensitivity phase and have been linked to the CCAUV.A K5 key comparison reference value (KCRV). The link was provided by two NMIs (NPL and INRIM) for the majority of measured frequencies. For frequencies below 20 Hz for sensitivity phase, there was only one linking laboratory (NPL).

With the exception of DMDM, all the participants presented Degrees of Equivalence to the KCRV in compliance with the respective claimed expanded uncertainties.

## 8 ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of Dr Richard Barham for his expert help and advice. The financial support of the National Measurement System, part of the UK Government's Department of Business, Energy and Industrial Strategy, made it possible for NPL to pilot this project.

## 9 REFERENCES

- [1] AVISON, J and BARHAM, R. Report on key comparison CCAUV.A-K5: Pressure calibration of laboratory standard microphones in the frequency range 2 Hz to 10 kHz, *NPL REPORT AC11*, September 2014
- [2] AVISON, J. Technical protocol for key comparison EURAMET.AUV.A-K5, Version 4, March 2014. National Physical Laboratory, United Kingdom 2014

- [3] IEC 61094-2:2009, *Measurement microphones - Part 2: Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique*
- [4] BIPM, Measurement comparisons in the CIPM MRA, *CIPM MRA-D-05*, Version 1.5
- [5] TOMAN, B. and POSSOLO, A., Laboratory effects models for interlaboratory comparisons. *Accredit Qual Assur.*, 2009, **14**, 553-563.
- [6] WHITE, D.R., On the analysis of measurement comparisons, *Metrologia*, 2004, **41**, number 3.

## ANNEX A: DETAILED STABILITY ANALYSIS

The following analysis was carried out to determine if the microphones' sensitivities changed by a statistically significant amount during the key comparison. Stability measurements were carried out at exact mid-band third octave frequencies. Each frequency was analysed separately.

For each frequency, a weighted least squares method was used to calculate a best fit constant function, of the form  $y=C$ , and a best fit straight line function, of the form  $y=mx+C$ , for the sensitivity (level and phase) of each microphone as a function of time  $x$ . The data was weighted according to the pilot laboratory's type A standard uncertainty. This uncertainty represents the expected variation between measurements made at a particular frequency. (It is a conservative estimate, usually applied as a tolerance on the standard deviation of three repeated measurements.) This value was used in preference to the combined standard uncertainty because the type B effects are expected to act systematically and the objective was to establish if the variation in the stability measurements was outside the usual range of random variation between measurements.

### A.1 CONSISTENCY OF FITS

The consistency of each fit was assessed using a chi-squared test. A threshold based on the 95<sup>th</sup> percentile of a chi-squared distribution with degrees of freedom equal to the number of data points minus the number of parameters (i.e. one parameter for a constant fit or two parameters for a straight line fit) was used to determine if the test was passed. If the best fit constant was consistent according to the chi-squared test, the microphone sensitivity was considered to have been stable throughout the key comparison. If the best fit constant was found to be an inconsistent fit and the best fit straight line a consistent fit, then the estimate of the slope parameter of the fit and its associated uncertainty was used to describe the drift of the microphone sensitivity.

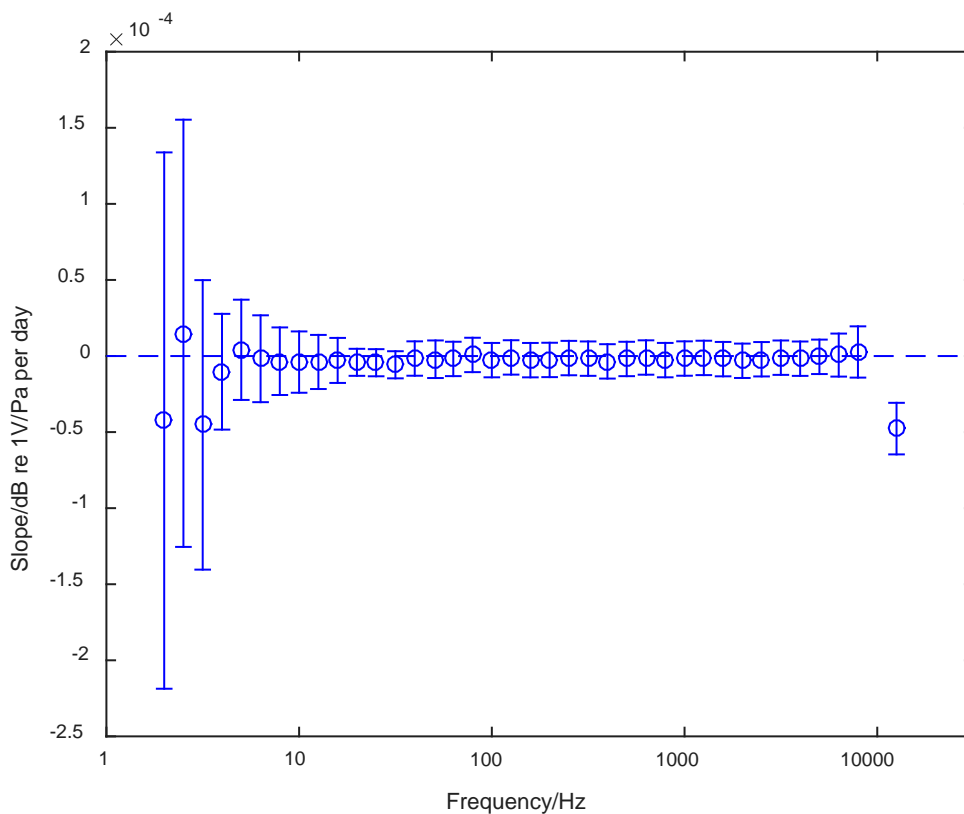
### A.2 DRIFT PARAMETERS FOR BEST-FIT STRAIGHT LINES

The following graphs provide information about the drift (slope) parameters in the best-fit straight-lines. In particular, the third graph in each set shows the estimates and  $k = 2$  uncertainty bars as a function of frequency.

At very low frequencies the uncertainties are large compared with the size of the drift. It is therefore difficult to make decisions about the presence, or absence, of a drift, based on measured data for these frequencies.

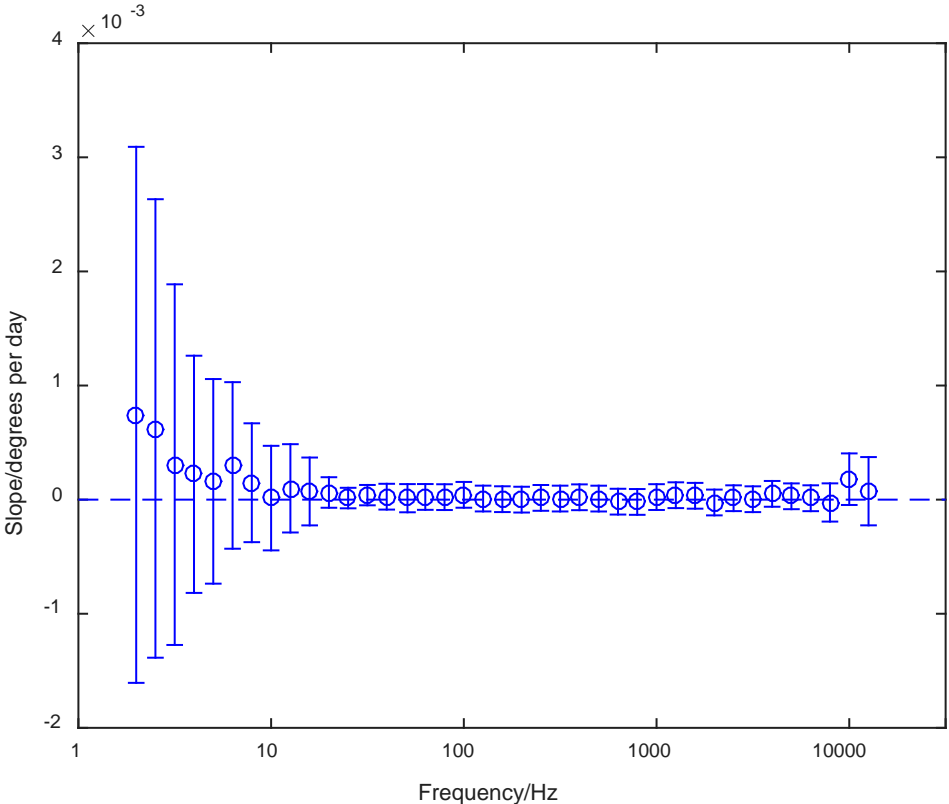
Of the graphs shown below, both sensitivity level and phase graphs for 4160 2036126 show uncertainty bars that include zero for every frequency. This adds extra confidence to the assertion that the microphone was stable throughout the key comparison. The 4160 811014 sensitivity level graph shows uncertainty bars that do not include zero, through all but the lowest and highest frequencies. This indicates that the microphone sensitivity level was subject to a statistically significant drift during the key comparison. The sensitivity phase graph for 4160 811014 shows uncertainty bars that include zero for all frequencies.

A.2.1 4160 2036126 Sensitivity level



**Figure 6(a). Drift of 4160 2036126: slope (m) of the best fit straight line ( $y=mx+C$ ) that describes the drift in sensitivity level of the microphone, during the key comparison, at each frequency, with  $k=2$  uncertainty bars**

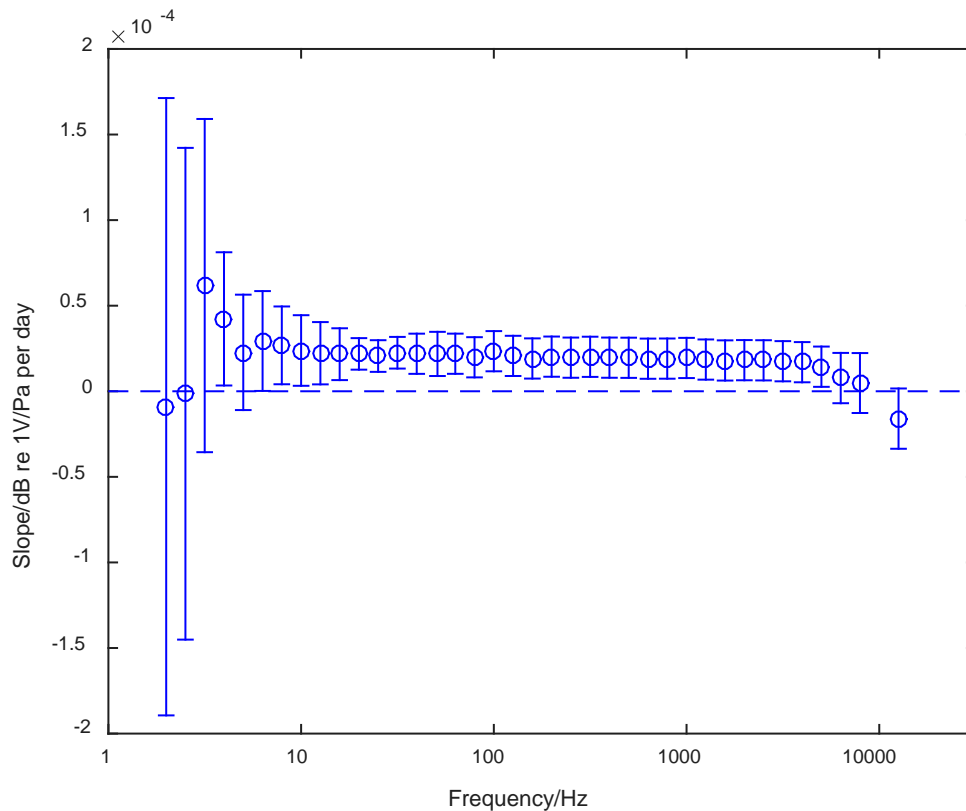
A.2.2 4160 2036126 Sensitivity phase



**Figure 6(b). Drift of 4160 2036126: slope (m) of the best fit straight line ( $y=mx+C$ ) that describes the drift in sensitivity phase of the microphone, during the key comparison, at each frequency, with  $k=2$  uncertainty bars**

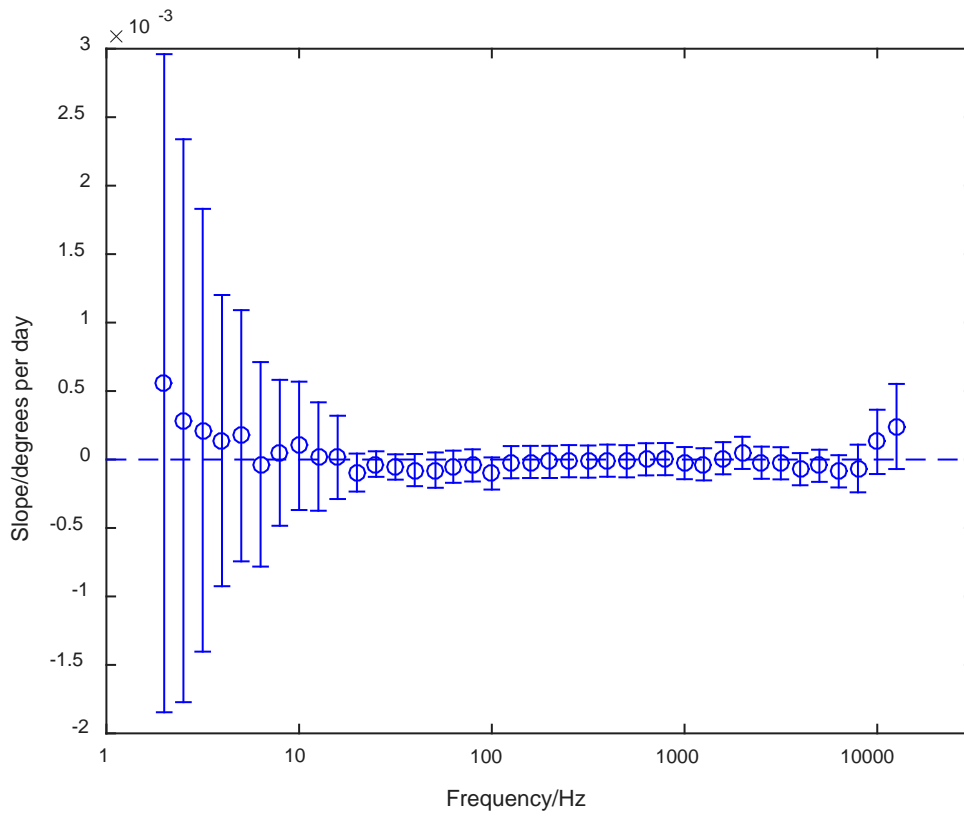


A.2.3 4160 811014 Sensitivity level



**Figure 6(c). Drift of 4160 811014: slope (m) of the best fit straight line ( $y=mx+C$ ) that describes the drift in sensitivity level of the microphone, during the key comparison, at each frequency, with  $k=2$  uncertainty bars**

A.2.4 4160 811014 Sensitivity phase



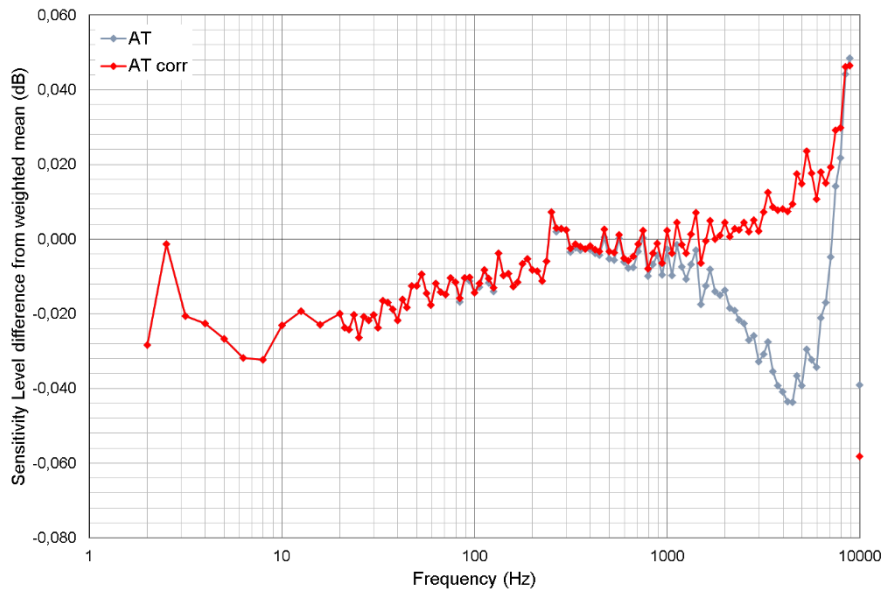
**Figure 6(d). Drift of 4160 811014: slope (m) of the best fit straight line ( $y=mx+C$ ) that describes the drift in sensitivity phase of the microphone, during the key comparison, at each frequency, with  $k=2$  uncertainty bars**

**ANNEX B: BEV CALCULATION REVISION**

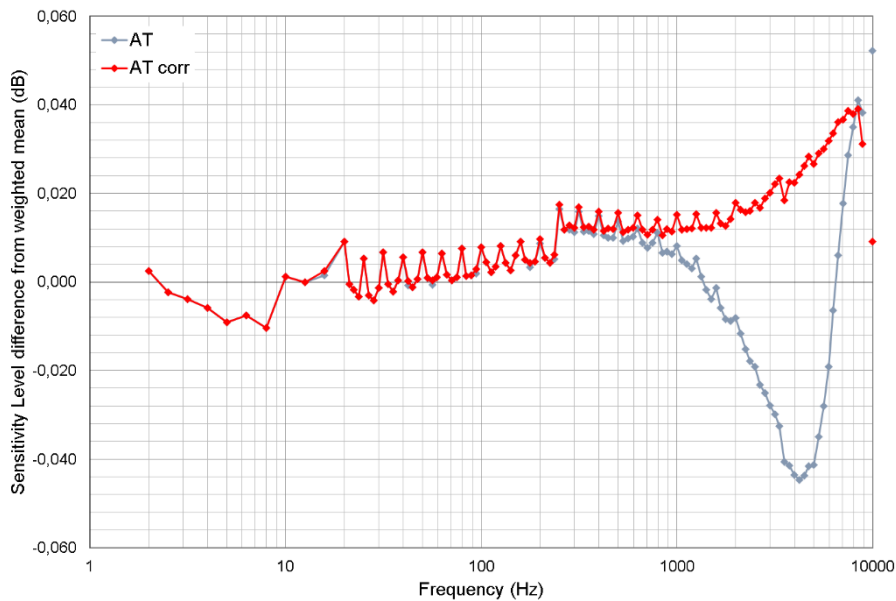
The BEV software for the calculation of level sensitivity was flawed at the time of the K5 comparison. The lumped parameter correction term was wrongly multiplied with the equivalent volume. The correct calculation is:

$$V_{eq} \Rightarrow \frac{V_{eq}}{1 - \frac{f^2}{f_0^2} + jd \frac{f}{f_0}}$$

This would lead to certain corrections of Austria’s K5 results. The following charts show the differences to the estimated sensitivity levels of Austria’s K5 results and the corrected values for both microphones.



**Austria’s sensitivity level results for 4160 2036126, shown as difference from the estimated sensitivity level K5 (blue) and K5 corrected (red)**



**Austria’s sensitivity level results for 4160 0811014, shown as difference from the estimated sensitivity level K5 (blue) and K5 corrected (red)**