Physikalisch-Technische Bundesanstalt

REPORT ON KEY COMPARISON COOMET.AUV.A-K1

Final Report

October 2008

Abstract

A regional key comparison on primary standards for sound in air, COOMET.AUV.A-K1, based on pressure reciprocity calibration of laboratory standard microphones, was held in 2002. The results were submitted to and approved by the CCAUV in October 2008. Six National Metrology Institutes took part and the results of five of the laboratories have been linked to the corresponding CCAUV.A-K1 comparison. A generalized least squares approach was used to determine the degrees of equivalence for fourteen acoustic frequencies and the results demonstrate agreement within the stated uncertainties.

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CONTENTS

1 Introduction

This report presents results for the regional key comparison on primary standards for sound in air, COOMET.AUV.A-K1. The Draft B report was produced after all participants commented and agreed on the content of Draft A. It was submitted to the CCAUV for approval in October 2008.

2 Protocol

The basis of this comparison was the pressure reciprocity calibration of laboratory standard microphones (LS1P microphones as specified in IEC 61094-1 [1]). According to the Technical Protocol six National Metrology Institutes took part and the Physikalisch-Technische Bundesanstalt, Germany, piloted the project. The participants are listed in Table 1.

Participant (in the order of participation)	Acronym	Country	Country code
Physikalisch-Technische Bundesanstalt	PTB	Germany	DE
Glowny Urzad Miar (Central Office of Measures)	GUM	Poland	PL
Ulusal Metroloji Enstitüsü	UME	Turkey	TR
Slovensky Metrologicky Ustav	SMU	Slovak Republic	SK
State Scientific Research Institute DNDI Systema	DNDI	Ukraine	UA
All-Russian Research and Scientific Institute for Physical, Technical and Radio Measurements	VNIIFTRI	Russia	RU

Table 1. List of participating institutes.

The protocol specified the determination of the pressure sensitivity of two IEC 61094-1 type LS1P microphones in the frequency range from 63 Hz to 10000 Hz at standard environmental conditions. The microphones were circulated as travelling standards and returned to PTB for re-calibration between the measurements of each participant, so that their stability could be monitored. Participants were asked to calibrate both microphones and report the results in their usual 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 [2] and a breakdown of the declared uncertainty showing the component considered.

Two new Brüel and Kjær type 4160 microphones were purchased specifically for this project and calibrated at PTB prior to circulation.

The first participant received the microphones in May 2002 and the measurement phase for all participants was completed in December 2002, except for the final check calibration in the pilot laboratory which was finished in March 2003.

The preliminary analysis of the results for the two travelling microphones revealed that data reported by DNDI (UA) turned out to be anomalous. During the discussion of Draft A among the participants and within the COOMET TC AUV it was agreed not to use these data for the calculation of the internal reference values and their uncertainties.

A further bilateral comparison between DNDI (UA) and PTB (DE) (COOMET.AUV.A-K1.1) was organized in order to check the equivalence with the reference value. The result of this comparison will be reported separately.

Hence, in this report only the results of the remaining five laboratories are reported.

3 Stability of travelling standards

The stability of the microphones was monitored by regular check calibration at the pilot laboratory, just before circulation and again on return of the microphones. Figures 1 and 2 show the results of these calibrations, referred to their mean values and the PTB uncertainty limits. The sensitivity levels vary at all frequencies less than the declared PTB measurement uncertainty, thus confirming that both microphones had an acceptable level of stability during these measurements.

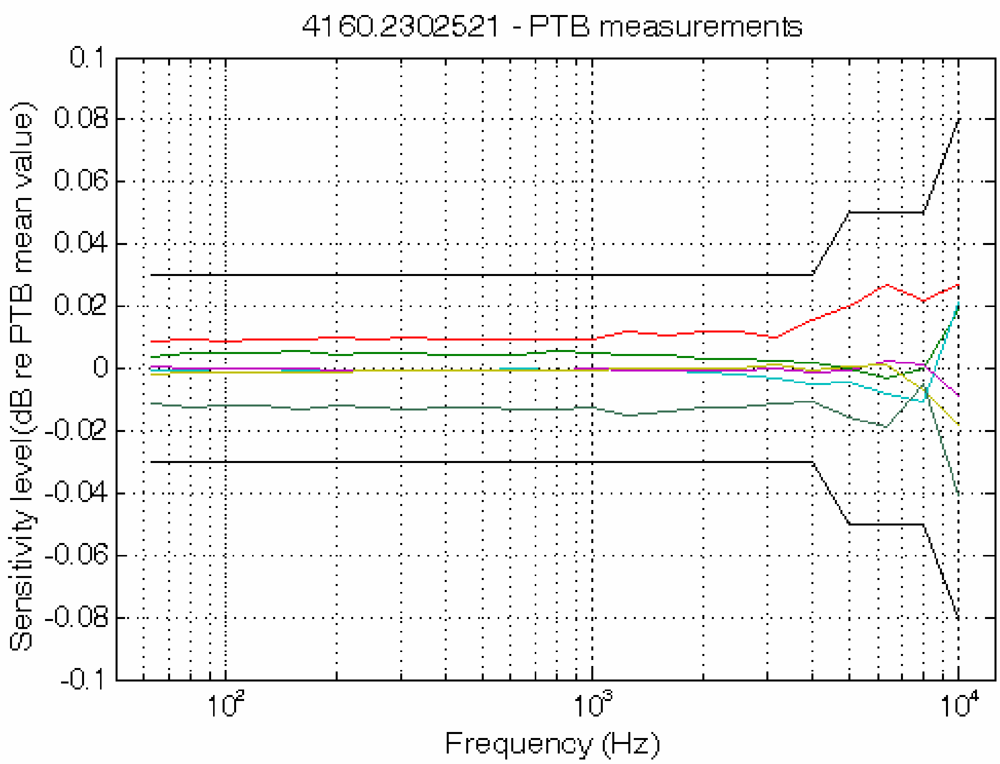

Fig. 1 Stability of the travelling standard microphone 4160.2302521 as PTB measurements over frequency, compared to PTB uncertainty (*k* = 2).

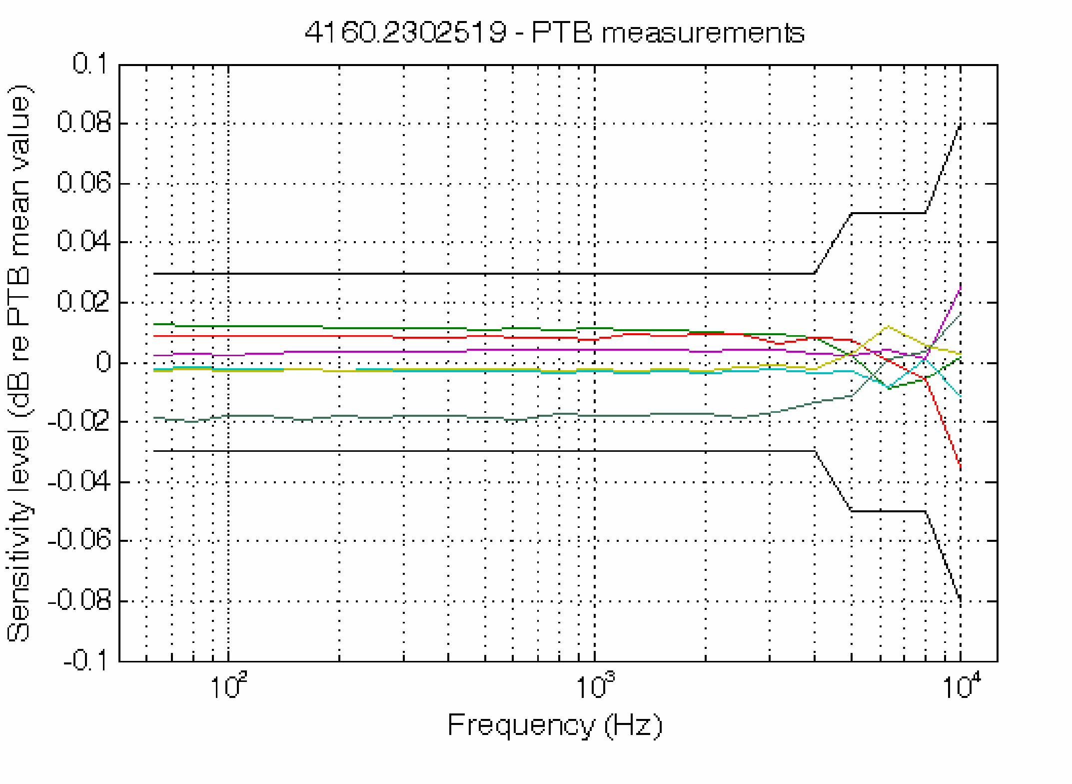

Fig. 2 Stability of the travelling standard microphone 4160.2302519 as PTB measurements over frequency, compared to PTB uncertainty (*k* = 2).

The variation of the measured sensitivity levels with time at 250 Hz is plotted in Figure 3. For both microphones, there seems to be a systematic tendency of a slightly decreasing sensitivity level with time. At the other frequencies the behaviour is similar. The variation with time does not exceed the typical uncertainties stated by the participants. During the discussion of the results in the Draft A phase of the comparison it was agreed not to apply a specific correction for this drift tendency and to regard the microphones as sufficiently stable.

The result of the first calibration for the microphones is the reported PTB value for this comparison. This follows the practice which had been used in previous CCAUV and regional comparisons.

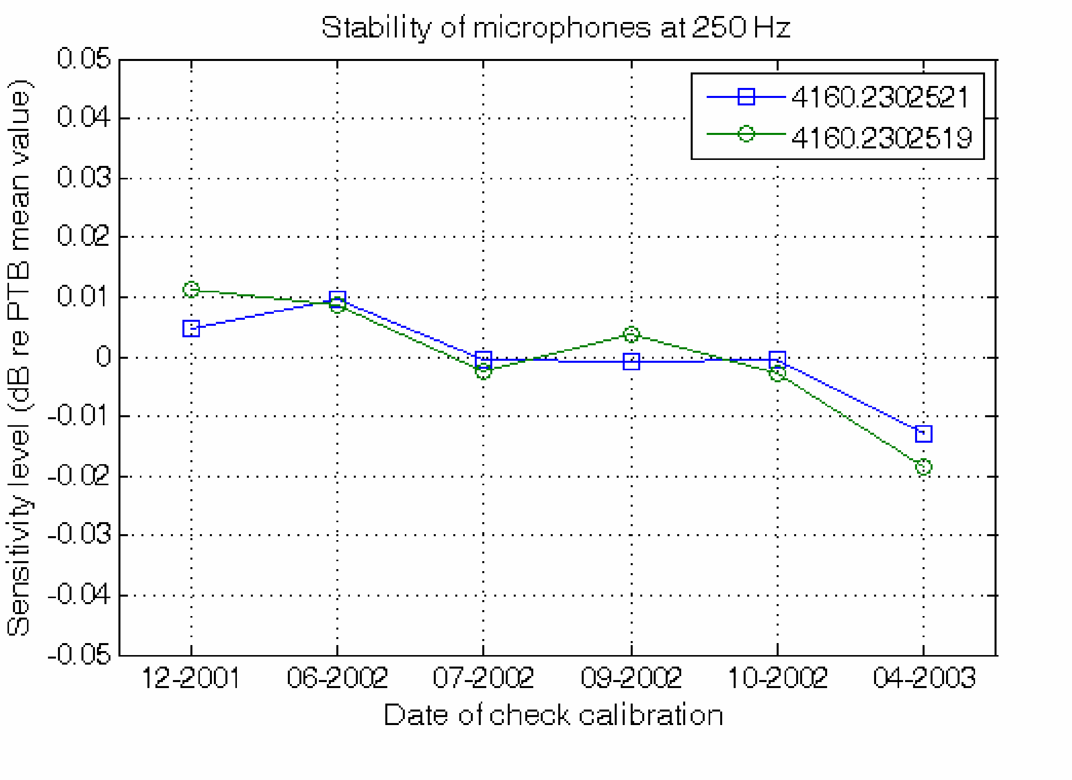

Fig. 3 Typical variation with time at *f* = 250 Hz for both travelling standards

4 Methodologies

According to the protocol the calibration method used had to be based on the International Standard IEC 61092-2. This standard specifies the principle of the procedure, but it does not determine the actual instrumentation and the experimental setup to be used. Therefore, the following short descriptions of the specific facilities used by each participant have been included.

GUM, PL

"In the GUM facility the three-microphone method of measurement is applied. Each microphone is assumed to be reciprocal and can be used as both transmitting and receiving microphone. The actually measured pair of microphones is coupled with a 3 cm^3 plane wave coupler B&K type DB 1392, filled with air at all frequencies. Software developed by NPL is used for calculation of the acoustical transfer impedance according to models presented in IEC 61094-2. The electrical transfer impedance of the actually measured microphone pair is determined by comparison with a properly chosen calibrated resistor connected in series with the transmitting microphone, using the “approximate balance” method developed in NPL. The calibration method complies with the requirements of IEC 61094 2:1992 with an exception concerning the method for determination of the physical properties of air (speed of sound, its temperature dependence, specific heat ratio), where the methodology agreed recently within EUROMET is used.

All measurements are performed in air-conditioned room with temperature maintained at 23,0 °C ± 1 °C and relative humidity maintained at 50 % ±15%. Measurements are conducted only if the static pressure is between 99 kPa and 103,5 kPa. The environmental parameters are measured continuously during the experiment and the results of measurements are automatically taken into account in calculations. The measuring signal source is the function generator Philips PM5136. For all AC voltage measurements two lock-in amplifiers EG&G 5209 are used. The microphone power supplies are special units designed and constructed according to NPL requirements. A special unit containing a set of calibrated resistors with an associated selector and two-way switch has been developed by NPL. The transmitting microphone is connected to the purpose-designed unit providing proper terminal and ground shield arrangements, developed by NPL. The receiving microphone is connected to the preamplifier G.R.A.S. 26AG. All measurements necessary for electrical transfer impedance determination are made automatically at specified frequencies. Polarization voltages are verified to be 200 V ± 0,01 V just before the start of experiments by measurement made directly at the transmitting unit and preamplifier terminals with a Keithley 6517A electrometer. The total volume of microphone (front cavity volume plus diaphragm equivalent volume) is determined acoustically with a computer-aided procedure by comparison with a set of known volumes. A depth-focusing microscope is used for the measurement of the depth of microphone front cavity. For the necessary calculations the nominal values of microphone acoustical parameters (mass, compliance and resistance) supplied by NPL are used."

PTB, DE

"The calibration was performed according to IEC 61094-2, using three microphones coupled in pairs by air filled plane wave couplers of different lengths. The electrical transfer impedance was measured using the main unit of a Brüel&Kjaer reciprocity calibration system 5998, a signal generator HP 33120A, a band pass filter Brüel&Kjaer 1617, and a digital voltmeter HP 3458A. The polarization voltage was checked by a differential voltmeter type Fluke 893A. The resulting sensitivity was calculated using the "Calcmp" software developed at the PTB. Radial wave motion correction was applied according to "K. Rasmussen, Radial wave motion in cylindrical plane-wave couplers. Acta Acustica. No 1. 1993" using the Bessel function model for the diaphragm velocity distribution. The static pressure was measured by a calibrated barometer, Druck DPI 141 and the temperature and humidity by a laboratory meter type Dostmann P 570. All measurements were performed at (23 ± 3) °C. The humidity was within the range 25% to 70% RH. The static pressure limits were (96...104) kPa. The microphone front cavity depth was measured using a depth focussing microscope with a digimatic indicator ID 110. The remaining microphone parameters were determined by data fitting of the results obtained using the above mentioned couplers."

SMU, SK

"The microphone sensitivity was determined by pressure calibration using the reciprocity technique on primary standard equipment of sound pressure in Slovak Institute of Metrology according IEC 61094-2 and following the operating procedure No. 19/250/02. The calibration procedure is computer controlled. The front cavity volume plus the equivalent volume of the microphone was determined by comparison with reference cavities. The equivalent volume was determined by means of the measurement of the electrical impedance of the microphone which was acoustically terminated by the quarter-wavelength tube. The standard equipment is based on the reciprocity technique using two microphones and one auxiliary sound source (active coupler). The measured microphones were fitted on home made preamplifiers which enable electrical alternation from receiver to transmitter and back without mechanical change of microphone position. The construction of the preamplifier enables a very high loading impedance (practically the microphone is unloaded) with very low input-output attenuation of approximately 0,001 dB. The ground-shield configuration is according to IEC 61094-1. Each measuring channel consists of the microphone, preamplifier, infrasound low pass filter and digital multimeter. The active coupler is created by piezoelectrical ring. The total coupler volume is approx. 4 cm^3."

UME, TR

"The open-circuit pressure sensitivity of the microphone with the grid removed was determined by the reciprocity technique described in IEC 61094-2. The sensitivity of each microphone was determined ten times and the reported sensitivity is the arithmetic mean of ten results.

The microphones were coupled in pairs using air filled plane-wave couplers with nominal length of 7,5 mm. The actual dimensions of the coupler were determined by using a coordinate measuring machine at UME Dimension Laboratory. The polarizing voltage applied to the microphone was (200,00 ± 0,05) V. The variation of the polarization voltage during the measurements was monitored by means of a HP 3458A digital multimeter. The polarizing voltage was measured at the port on the reciprocity calibration apparatus, instead of at the terminals of the microphone. The measurements of the electrical transfer impedance were performed by using a main unit of the Brüel & Kjaer Type 4143 Reciprocity Apparatus and a HP 3458A Digital Multimeter. The microphone front cavity depth was measured using a depth focusing microscope with a digimatic indicator. The total and front volume of microphone were measured by an acoustical method using Type 4143 Reciprocity Apparatus. Nominal values for microphone’s acoustic mass, compliance and resistance as declared by the manufacturer were used for the sensitivity calculation. The final sensitivity values were corrected to the reference environmental conditions. The environmental conditions were measured and monitored by a Rotronic HygroPalm instrument and a Brüel & Kjaer UZ 0004 barometer."

VNIIFTRI, RU

In VNIIFTRI the calibration of laboratory standard microphones LS1P is realized in accordance with the IEC Recommendation IEC 61094-2 for the three-microphones method. The measurements are made in three plane wave couplers, having the lengths of 3.7 mm, 7.5 mm and. 8.8 mm. The average value of the microphone sensitivity obtained in three couplers is taken a final result. The frequency range of calibration is 63 Hz to 10 kHz.

The electrical transfer impedance of a pair of acoustically coupled microphones is measured in three stages by means of a reciprocity calibration apparatus B&K type 4143, a microphone preamplifier B&K type 2645, a measuring amplifier B&K type 2636, a filter B&K type 1617, a signal generator Philips type PM 5190 and a multimeter Datron type 1081:

a) a ratio of gains in Channel A and Channel B of the 4143 apparatus is measured, the switch being set in the position 'Balance Comparator Adjustment';

b) the ratio of the voltage at the output of the preamplifier type 2645 and at the reference capacitor is measured when the switch is set to 'Sensitivity Product'. At each frequency the voltage at the preamplifier is measured 5 times with the time interval between the measurements equal to 5 s. The average value is taken as a final result provided the standard deviation does not exceed 0.005 dB. Otherwise the measurements at a given frequency are repeated. The drop of voltage on the reference capacitor on a given frequency is measured only once;
c) the attenuation introduced by the preamplifier type 2645 and by the capacitive load of the receiving microphone is measured with the switch set to 'Insert gain'. The measurements of the voltage at the preamplifier are made as described above for stage b).

The acoustical transfer impedance of a pair of acoustically coupled microphones is calculated according to IEC 611094-2 with the following typical parameters for the microphone:

Cavity depth: 1,95 mm;
Front volume: 535 mm^3;
Acoustic resistance: 2,13 .10^7 Ns/m^5 ;
Acoustic mass: 393,1 kg/m^4
Acoustic compliance: 9,58 10^{-13} m^5/N^4

The physical parameters of air are calculated according to "K. Rasmussen, Calculation methods for the physical properties of air used in the calibration of microphones. DPLA report PL-11b. 1997".

The reference configuration as specified in IEC 61094-1 is used both for the transmitter and the receiver microphones.

The polarizing voltage is being monitored during the whole process of measurements using a voltmeter B&K type WB0781 connected to the output 'Polarizing Voltage' of type 4143.

The environmental conditions (atmospheric pressure, temperature and humidity) are being monitored during the whole process of measurements. The atmospheric pressure is measured by a mercury barometer having the resolution of 0.11nmHg. The measurements are made twice, prior to and after, the measurements of the electrical transfer impedance of a pair of microphones. The average of the two values is taken as the result for a given pair of microphones. The temperature is measured by a thermocouple placed in the special recess of the coupler and filled with oil. The resolution of these measurements is 0.1 °c. The temperature of the air inside the coupler is assumed to be that of the coupler with the microphones installed, after the stabilization time of 5 min has elapsed. The humidity is determined using a hygrometer having the resolution of 2%. The reference environmental conditions are: temperature 23°C, atmospheric pressure 760 mmHg, relative humidity 50%.
Corrections for thermal conductivity and the influence of capillary tubes are applied according to IEC 61094-2.

The microphone sensitivity is corrected to reference environmental conditions using the correction coefficients given in "K. Rasmussen, The influence of environmental conditions on the pressure sensitivity of measurement microphones. Brüel & Kjaer Technical Review. No.1,. 2001". A correction coefficient for the radial wave motion is applied to the acoustical transfer impedance, calculated according to "K. Rasmussen, Radial wave motion in cylindrical plane-wave couplers. Acta Acustica. 1. 1993", assuming that the microphone membrane velocity distribution is described by a Bessel function.

5 Reported results and uncertainties

The pressure sensitivity levels of the two microphones as reported by each participant in calibration certificates are shown in Tables 2 and 3 and the associated declared uncertainties in Table 4. No laboratory declared different uncertainties for the two travelling microphones.

Frequency (Hz)	DE	PL	TR	SK	RU
63	-26.88	-26.90	-26.89	-26.88	-26.93
80	-26.89	-26.91	-26.89	-26.90	-26.94
100	-26.91	-26.93	-26.91	-26.93	-26.95
125	-26.91	-26.93	-26.91	-26.93	-26.96
160	-26.92	-26.94	-26.92	-26.94	-26.97
200	-26.93	-26.95	-26.94	-26.95	-26.98
250	-26.93	-26.95	-26.94	-26.95	-26.98
315	-26.94	-26.95	-26.94	-26.96	-26.98
400	-26.94	-26.97	-26.94	-26.96	-26.99
500	-26.94	-26.97	-26.94	-26.96	-26.99
630	-26.94	-26.96	-26.93	-26.96	-26.98
800	-26.93	-26.95	-26.92	-26.95	-26.98
1000	-26.92	-26.95	-26.93	-26.93	-26.96
1250	-26.90	-26.93	-26.92	-26.91	-26.94
1600	-26.86	-26.89	-26.88	-26.88	-26.90
2000	-26.80	-26.83	-26.83	-26.82	-26.84
2500	-26.72	-26.75	-26.75	-26.74	-26.75
3150	-26.59	-26.62	-26.60		-26.61
4000	-26.43	-26.44	-26.45		-26.43
5000	-26.30	-26.31	-26.31		-26.28
6300	-26.42	-26.41	-26.42		-26.37
8000	-27.43	-27.39	-27.37		-27.34
10000	-30.01	-29.91	-29.94		-29.82

Table 2. Pressure sensitivity levels in dB re 1V/Pa as reported for microphone 4160.2302519

Frequency (Hz)	DE	PL	TR	SK	RU
63	-26.88	-26.89	-26.90	-26.87	-26.90
80	-26.89	-26.90	-26.90	-26.89	-26.92
100	-26.90	-26.91	-26.90	-26.9	-26.93
125	-26.91	-26.92	-26.91	-26.91	-26.94
160	-26.91	-26.93	-26.92	-26.92	-26.95
200	-26.92	-26.94	-26.92	-26.93	-26.95
250	-26.92	-26.94	-26.93	-26.94	-26.96
315	-26.93	-26.94	-26.94	-26.94	-26.96
400	-26.93	-26.95	-26.93	-26.94	-26.96
500	-26.93	-26.95	-26.93	-26.94	-26.96
630	-26.92	-26.95	-26.91	-26.94	-26.96
800	-26.91	-26.94	-26.91	-26.93	-26.94
1000	-26.90	-26.93	-26.90	-26.91	-26.93
1250	-26.87	-26.90	-26.89	-26.88	-26.90
1600	-26.82	-26.85	-26.84	-26.83	-26.85
2000	-26.75	-26.77	-26.74	-26.76	-26.77
2500	-26.64	-26.67	-26.66	-26.65	-26.66
3150	-26.48	-26.50	-26.48		-26.49
4000	-26.26	-26.26	-26.27		-26.26
5000	-26.05	-26.05	-26.05		-26.04
6300	-26.07	-26.07	-26.09		-26.06
8000	-27.15	-27.11	-27.11		-27.10
10000	-30.01	-29.94	-29.94		-29.93

Table 3. Pressure sensitivity levels in dB re 1V/Pa as reported for microphone 4160.2302521

Frequency (Hz)	DE	PL	TR	SK	RU
63	0.03	0.03	0.06	0.04	0.06
80	0.03	0.03	0.06	0.04	0.05
100	0.03	0.03	0.06	0.04	0.04
125	0.03	0.03	0.06	0.04	0.04
160	0.03	0.03	0.06	0.04	0.04
200	0.03	0.03	0.06	0.04	0.04
250	0.03	0.03	0.06	0.04	0.04
315	0.03	0.03	0.06	0.04	0.04
400	0.03	0.03	0.06	0.04	0.04
500	0.03	0.03	0.06	0.04	0.04
630	0.03	0.03	0.06	0.04	0.04
800	0.03	0.03	0.06	0.04	0.04
1000	0.03	0.03	0.06	0.04	0.04
1250	0.03	0.03	0.06	0.04	0.04
1600	0.03	0.03	0.06	0.04	0.04
2000	0.03	0.03	0.06	0.04	0.04
2500	0.03	0.04	0.06	0.05	0.04
3150	0.03	0.04	0.07		0.04
4000	0.03	0.04	0.07		0.04
5000	0.05	0.05	0.07		0.05
6300	0.05	0.05	0.08		0.06
8000	0.05	0.05	0.09		0.08
10000	0.08	0.09	0.12		0.13

Table 4. Declared measurement uncertainties at k = 2 in dB

6 Analysis of the results and linking COOMET.AUV.A-K1 to CCAUV.A-K1

6.1 General

According to the CCAUV guidelines [3] a regional key comparison reference value should be calculated for internal purposes, only. In the Draft A report such a reference value was proposed on the basis of the unweighted mean as an estimator. Degrees of equivalence and their uncertainties were calculated, and they confirmed the consistency of the data by means of the normalized deviations from the internal reference values. This procedure was performed individually for the two travelling standards and for all frequencies specified in the Technical Protocol of COOMET.AUV.A-K1.

Usually, a CCAUV key comparison results in a single key comparison reference value (KCRV) and single degrees of equivalence per participant and frequency. In the present comparison two travelling standards were used and measured by all participants. Three of them (GUM, PTB, VNIIFTRI) also took part in the CCAUV.A-K1 key comparison [4] and, thus, they can provide the link of this regional comparison to the CCAUV comparison KCRV at those frequencies used in both comparisons.

6.2 Description of the model

In order to obtain these aimed-at results, a generalized least squares (GLS) approach was used in this report for the determination of the degrees of equivalence of the participating laboratories. This also enables linking of the COOMET.AUV.A-K1 results to the CCAUV.A-K1 KCRV.

The method was proposed in [5] and uses the model

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{e} \qquad (1)$$

where

$\mathbf{y} = (y_1 \ldots y_g)^T$	is a column vector containing the measurement results,
$\mathbf{X}$	is the $g \times h$ design matrix,
$\boldsymbol{\beta} = (\beta_1 \ldots \beta_h)^T$	is a column vector containing the unknowns, and
$\mathbf{e} = (e_1 \ldots e_g)$	a vector of random errors of disturbances.

Each row of **X,** apart from the last, represents one of the comparison measurements (10 COOMET and three CCAUV measurements), and the associated result is in the corresponding row of vector **y**. The last row of **X** and the last element of **y** are related to the constraint (the difference from the CCAUV KCRV is forced to zero).

In [5] it is shown that the approximation $\hat{\boldsymbol{\beta}}$ of the best linear unbiased estimate $\tilde{\boldsymbol{\beta}}$ can be expressed as

$$\hat{\boldsymbol{\beta}} = \hat{\mathbf{C}}\mathbf{X}^{\mathrm{T}}\hat{\boldsymbol{\Phi}}^{-1}\mathbf{y} \qquad (2)$$

where $\hat{\mathbf{C}}$ is the uncertainty matrix calculated by

$$\hat{\mathbf{C}} = (\mathbf{X}^{\mathrm{T}}\hat{\boldsymbol{\Phi}}^{-1}\mathbf{X})^{-1} \qquad (3)$$

and $\hat{\boldsymbol{\Phi}}$ is the symmetric $g \times g$ input covariance matrix whose diagonal elements are the variances (squared standard uncertainty) associated with each result represented in vector **y**. For the COOMET results the variances reported by the participants (see Table 4), and for the CCAUV data the values reported in [4]. Off diagonal elements allow for correlations between measurements. In this report, following the procedure successfully used in the analysis of previous CCAUV and EUROMET TC.AUV comparisons, a correlation coefficient of 0,7 was applied for measurements made by the same laboratory. Results of different laboratories were considered essentially uncorrelated.

In the following description the laboratories are numbered as:

PTB (DE) = 1;
GUM (PL) = 2;
UME (TR) = 3;
SMU (SK) = 4;
VNIIFTRI (RU) = 5.

The elements of the result vector **y** are:

$y_1 \ldots y_5$: measurement results on the microphone 4160.2303521 in COOMET.AUV.A-K1,

$y_6 \ldots y_{10}$: measurement results on the microphone 4160.2303519 in COOMET.AUV.A-K1,

$y_{11} \ldots y_{13}$: differences of the laboratories PTB, GUM and VNIIFTRI from the CCAUV.A-K1 KCRV,

y_{14} : the constraint (difference from CCAUV KCRV is forced to zero).

The vector $\hat{\boldsymbol{\beta}}$ contains:

$\hat{\beta}_1 \ldots \hat{\beta}_5$: differences from the estimated KCRV for the laboratories 1 …5,

$\hat{\beta}_6 \ldots \hat{\beta}_7$: results for the two travelling microphones, related to the KCRV,

$\hat{\beta}_8$: remaining difference from the constraint (essentially zero).

The design matrix **X** for the model in (1) is

$$\mathbf{X} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

Columns 1 to 5 relate to the five laboratories which took part in the COOMET comparison, columns 7 and 8 to the two travelling standards, column 8 to the link with the CCAUV KCRV.

Rows 1 to 5 relate to the 5 measurements on microphone 4160.2303521, rows 6 to 10 to the 5 measurements on microphone 4160.2303519, rows 11 to 13 describe the link (deviation of the linking laboratories from CCAUV KCRV) and row 14 the constraint.

The number of degrees of freedom of this model is

$$\nu = g - h = 14 - 8 = 6. \quad (5)$$

This model describes the comparison for all frequencies which were used in both comparisons (COOMET and CCAUV). Because SMU only provided measurement results up to 2500 Hz, a modified model had to be used for the higher frequencies. This means that at frequencies over 2500 Hz the sizes of the matrices and vectors were reduced respectively, e.g. **X** has 12 rows and 7 columns, etc. Hence, the number of degrees of freedom is reduced to 5.

6.3 Consistency test of the model

In order to test the goodness-of fit of the model (1) to the measurement results a measure based on the chi-squared distribution was used as given by [6]

$$\chi^2 = (\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}})^T \hat{\boldsymbol{\Phi}}^{-1} (\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}}) \quad (6)$$

Consistency between the model and the measurement is assessed by comparing the observed value of χ^2 with the expected value $E(\chi_\nu^2) = \nu$ in the context of the standard deviation $\sigma(\chi_\nu^2) = \sqrt{2\nu}$. The hypothesis was tested with a significance of 5%, i.e. the probability $P\{\chi^2(\nu) > \chi_{obs}^2\}$ had to be larger than 5%.

Table 5 shows the results of the equivalence test applied to the model(s) described above (different degrees of freedom in dependence on the frequency, see 6.2).

Frequency Hz	χ_{obs}^2	$P\{\chi^2(\nu) > \chi_{obs}^2\}$ %
63	2.80	83
125	2.46	87
250	1.23	98
500	2.25	90
1000	1.13	98
1250	0.85	99
1600	1.06	98
2000	3.56	74
2500	1.36	97
3150	1.60	90
4000	1.94	86
5000	2.10	83
6300	2.68	75
8000	1.73	89

Table 5. Consistency test of the model

For all frequencies the probability is higher than 5%, and, thus, the equivalence hypothesis can not be rejected.

6.4 Degrees of equivalence

The degrees of equivalence for the laboratories and their uncertainties, can be calculated from $\hat{\boldsymbol{\beta}}$ and $\hat{\mathbf{C}}$. The deviations of the i-th laboratory D_i from the KCRV are the elements $\hat{\beta}_1 \ldots \hat{\beta}_5$ and their uncertainties U_i are obtained from the uncertainty matrix $\hat{\mathbf{C}}$:

$$U_i = k\sqrt{\hat{\mathbf{C}}_{ii}}\,, \qquad (6)$$

where k is the coverage factor, k = 2.

Table 6 lists the degrees of equivalence and their uncertainties for all frequencies.

Frequency	DE		PL		TR		SK		RU	
(Hz)	D_j (dB)	U_j (dB)	D_j (dB)	U_j (dB)	D_j (dB)	U_j (dB)	D_j (dB)	U_j (dB)	D_j (dB)	U_j (dB)
63	0.01	0.03	0.00	0.03	0.00	0.06	0.02	0.05	-0.02	0.05
125	0.02	0.03	0.01	0.03	0.02	0.06	0.01	0.05	-0.01	0.03
250	0.02	0.03	0.01	0.03	0.02	0.06	0.01	0.05	-0.01	0.03
500	0.02	0.03	0.00	0.03	0.03	0.06	0.01	0.05	-0.01	0.03
1000	0.02	0.03	0.00	0.03	0.02	0.06	0.01	0.05	-0.01	0.03
1250	0.02	0.03	0.00	0.03	0.00	0.06	0.01	0.05	-0.01	0.03
1600	0.02	0.03	0.00	0.03	0.01	0.06	0.01	0.05	-0.01	0.03
2000	0.02	0.03	0.00	0.03	0.01	0.06	0.01	0.05	-0.01	0.03
2500	0.02	0.03	0.00	0.03	0.00	0.06	0.01	0.05	-0.01	0.04
3150	0.01	0.03	0.00	0.03	0.01	0.07			-0.01	0.04
4000	0.01	0.03	0.01	0.03	-0.01	0.07			0.00	0.04
5000	0.01	0.04	0.00	0.04	0.00	0.08			0.01	0.05
6300	0.01	0.04	0.02	0.04	0.00	0.09			0.04	0.07
8000	-0.01	0.04	0.04	0.04	0.04	0.10			0.06	0.08

Table 6. Degrees of equivalence to the KCRV and their expanded uncertainties (k = 2).

The average deviations per laboratory are plotted over frequency in Figure 4.

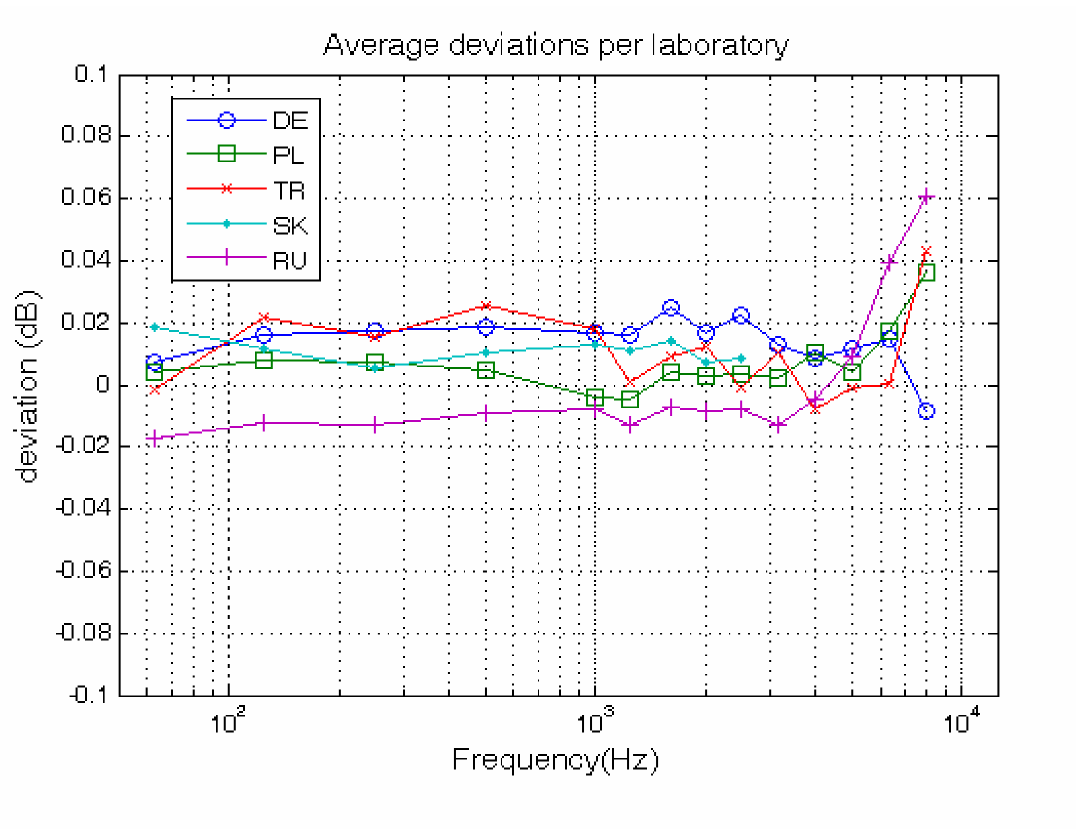

Fig. 4 Average deviations per laboratory

Figures 5 and 6 demonstrate the degrees of equivalence for the frequencies 250 Hz and 1000 Hz for all laboratories.

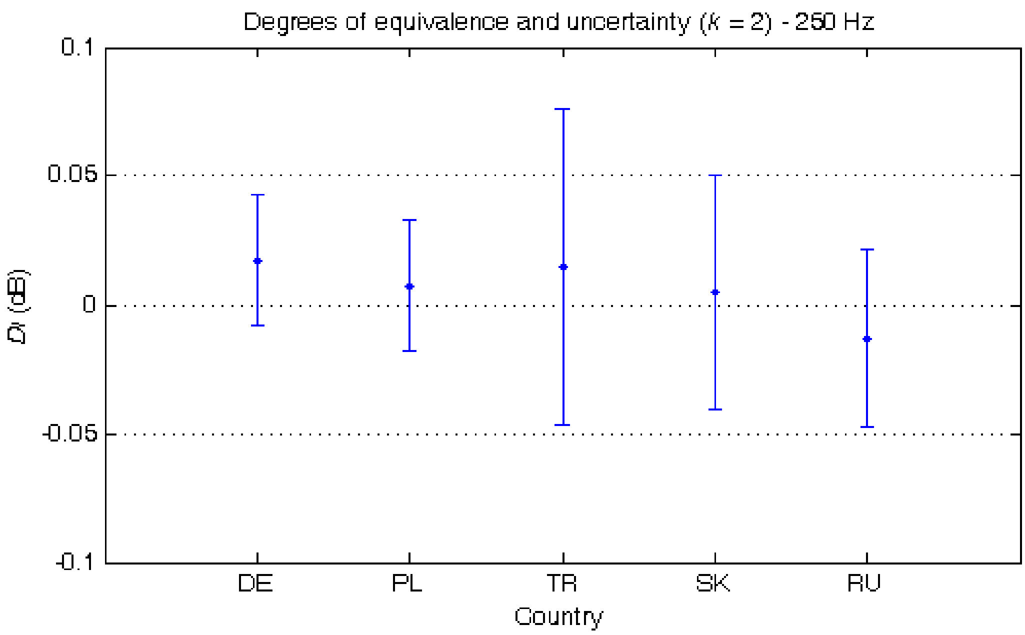

Fig. 5 Degrees of equivalence with the KCRV at 250 Hz

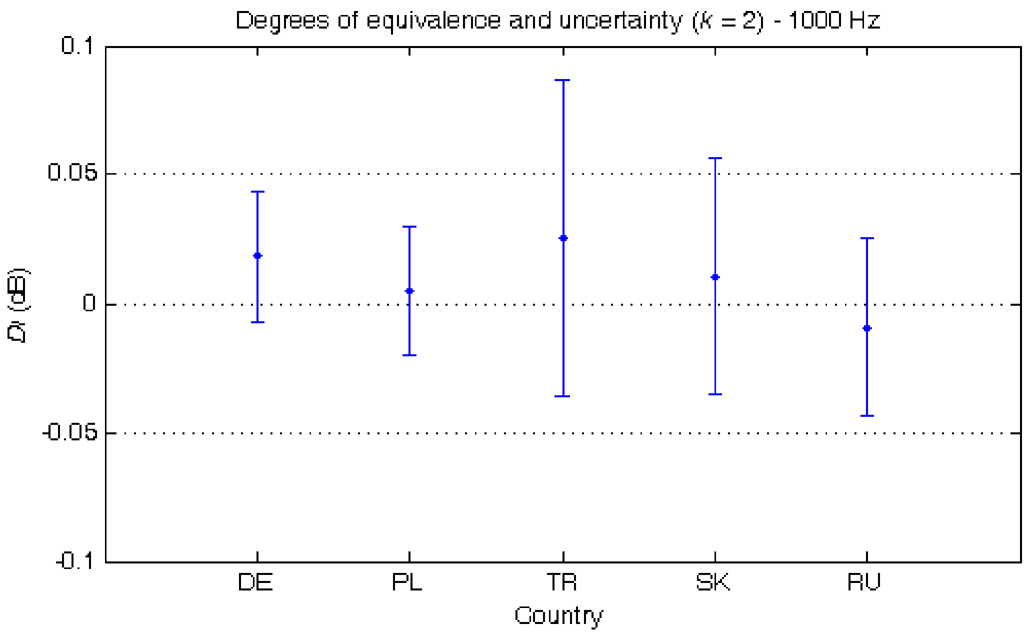

Fig. 6 Degrees of equivalence with the KCRV at 1000 Hz

The mutual degrees of equivalence (deviation $D_{i,j}$ of laboratory i from laboratory j) can be obtained from and $\hat{\boldsymbol{\beta}}$ and $\hat{\mathbf{C}}$ as:

$$D_{i,j} = \hat{\beta}_i - \hat{\beta}_j \tag{7}$$

and their uncertainties

$$U_{i,j} = k\sqrt{\hat{C}_{ii} + \hat{C}_{jj} + \hat{C}_{ij}} \tag{8}$$

where k is the coverage factor, $k = 2$.

Tables 7 to 10 list the mutual degrees of equivalence and their expanded uncertainties for the frequencies 250 Hz and 1000 Hz..

250 Hz	DE	PL	TR	SK	RU
DE	-	0.01	0.00	0.01	0.03
PL	-0.01	-	-0.01	0.00	0.02
TR	0.00	0.01	-	0.01	0.03
SK	-0.01	0.00	-0.01	-	0.02
RU	-0.03	-0.02	-0.03	-0.02	-

Table 7. Mutual degrees of equivalence at 250 Hz, deviations in dB

250 Hz	DE	PL	TR	SK	RU
DE	-	0.03	0.06	0.04	0.04
PL	0.03	-	0.06	0.04	0.04
TR	0.06	0.06	-	0.07	0.06
SK	0.04	0.04	0.07	-	0.05
RU	0.04	0.04	0.06	0.05	-

Table 8. Mutual degrees of equivalence at 250 Hz, uncertainties (*k* = 2) in dB

1000 Hz	DE	PL	TR	SK	RU
DE	-	0.01	-0.01	0.01	0.03
PL	-0.01	-	-0.02	-0.01	0.01
TR	0.01	0.02	-	0.02	0.03
SK	-0.01	0.01	-0.02	-	0.02
RU	-0.03	-0.01	-0.03	-0.02	-

Table 9. Mutual degrees of equivalence at 1000 Hz, deviations in dB

1000 Hz	DE	PL	TR	SK	RU
DE	-	0.03	0.06	0.04	0.04
PL	0.03	-	0.06	0.04	0.04
TR	0.06	0.06	-	0.07	0.06
SK	0.04	0.04	0.07	-	0.05
RU	0.04	0.04	0.06	0.05	-

Table 10. Mutual degrees of equivalence at 1000 Hz, uncertainties (*k* = 2) in dB

7 Conclusions

The results of the intercomparison proved the equivalence of all participating laboratories for all frequencies to the associated KCRV of the CCAUV.A-K1 within the estimated uncertainties.

Single degrees of equivalence were determined per laboratory and between pairs of laboratories. Consistency tests of the data and the evaluation of the degrees of equivalence with their associated uncertainties show that in all cases the results are in good agreement.

8 References

[1] IEC 61094-1, Measurement Microphones - Part 1: Specifications for Laboratory Standard Microphones, second edition, Geneva, International Electrotechnical Commission, 2004

[2] IEC 61094-2, Measurement Microphones Part 2: Primary Method for Pressure Calibration of Laboratory Standard Microphones by the Reciprocity Technique-First Edition, Geneva, International Electrotechnical Commission, 1992

[3] Brief guidelines for linking RMO key comparisons to the CIPM KCRV. CCAUV/04-27, BIPM 26 May 2004.

[4] Barham, R., Report on key comparison CCUAV.A-K1, Metrologia, 2003, 40, Tech. Suppl., 09002

[5] Sutton, C.M., Analysis and linking of international measurement comparisons. Metrologia **41**(2004), 272-277.

[6] Nielsen, L., Evaluation of measurement intercomparisons by the method of least squares. Danish Institute of Fundamental Metrology, DFM-99-R39, 1999.

Annex A – Microphone parameters

Tables A1 and A2 show the values for the microphone parameters used by the participants for the determination of the sensitivity levels.

	DE	PL	TR	SK	RU
total volume (mm^3)	682,0	666,0	677,8	-	-
front volume (mm^3)	-	-	535,5	543,0	535,0
cavity depth (mm)	1.974	1,983	1,971	-	1,95
equivalent volume (mm^3)	127	133	147	125	136
res. freq. (Hz)	8450	8160	8400	8230	8200
loss factor	1.04	1.05	1.18	1.09	1.05
acoustic mass (kg m^{-4})	396,0	406,0	345,0	427	393,1
acoustic compliance (10^{-13} $kg^{-1} m^4 s^{2}$)	8,959	9,36	10,4	8,7	9.58
acoustic resistance (10^7 kg $m^{-4}s^{-1}$)	2,207	2,2	2,15	2,41	2,13
low freq temp. coeff. (dB/K)	-0,002	-	-	-0,003	-0,002
low freq press. coeff. (dB/kPa)	-0,0152	-	-	-0,00184	-0.015

Table A1 - Stated parameters for microphone 4160.2302519

NOTE: If laboratories provided the acoustic impedance of the microphones as acoustic mass, compliance and resistance, the equivalent set of parameters (equivalent volume, resonance frequency and loss factor) was calculated from them in order to provide a more convenient overview.

	DE	PL	TR	SK	RU
total volume (mm^3)	685,0	667,0	678,1	-	-
front volume (mm^3)	-	-	532,8	542,0	535,0
cavity depth (mm)	1,968	1,977	1,961	-	1,95
equivalent volume (mm^3)	130	133	147	127	136
res. freq. (Hz)	8110	8160	8400	8100	8200
loss factor	1.1	1.06	1.18	1.05	1.05
acoustic mass (10^7 kg m^{-4})	420,0	406,0	345,0	433,0	393,1
acoustic compliance (10^{-13} $kg^{-1}m^4s^2$)	9,171	9,36	10,4	8,9	9.58
acoustic resistance (10^7 kg $m^{-4}s^{-1}$)	2,354	2,2	2,15	2,31	2,13
low freq temp. coeff. (dB/K)	-0,002	-	-	-0,003	-0,002
low freq press. coeff. (dB/kPa)	-0,0152	-	-	-0,00184	-0.015

Table A2 - Stated parameters for microphone 4160.2302521

NOTE: If laboratories provided the acoustic impedance of the microphones as acoustic mass, compliance and resistance, the equivalent set of parameters (equivalent volume, resonance frequency and loss factor) was calculated from them in order to provide a more convenient overview.

Annex B – Review of anomalies and changes to the declared results

According to the CIPM guidelines the pilot laboratory has the task to decide whether the results of any participant are anomalous before declaring the complete set of data to all participants. During the first review of the reported data, the results of DNDI (UA) and SMU (SK) seemed to be anomalous, and both laboratories were therefore given the chance to review their data. No indication of the kind or magnitude of the possible discrepancy was given.

SMU (SK)

The results of the pilot laboratory and those of the other participants had not been known by SMU prior to sending revised results.

The SMU detected a transmission error of the microphone loss factor value to the database of the basic measuring programme so that the sensitivity was calculated with wrong values.

These changes were accepted before SMU was informed about the results of the other participants and about those of the pilot laboratory. Only the *revised* data are used in the main part of this report.

Frequency	**4160.2302519**		**4160.2302521**	
Hz	**original**	**revised**	**original**	**revised**
63	-26.85	-26.88	-26.84	-26.87
80	-26.88	-26.90	-26.86	-26.89
100	-26.89	-26.93	-26.88	-26.9
125	-26.91	-26.93	-26.89	-26.91
160	-26.92	-26.94	-26.91	-26.92
200	-26.94	-26.95	-26.92	-26.93
250	-26.94	-26.95	-26.93	-26.94
315	-26.95	-26.96	-26.93	-26.94
400	-26.96	-26.96	-26.94	-26.94
500	-26.97	-26.96	-26.95	-26.94
630	-26.98	-26.96	-26.94	-26.94
800	-26.98	-26.95	-26.96	-26.93
1000	-26.98	-26.93	-26.95	-26.91
1250	-26.98	-26.91	-26.94	-26.88
1600	-26.96	-26.88	-26.91	-26.83
2000	-26.90	-26.82	-26.84	-26.76
2500	-26.82	-26.74	-26.74	-26.65

Table B1. Original an the revised data reported by SMU

DNDI (UA)

The results of the pilot laboratory and those of the other participants had not been known by DNDI prior to sending the first revised results (revised (1)). The first revision was accepted before the declaration of the complete set of data.

After that DNDI discovered that a misinterpretation of the microphone parameters lead to an error in the determination of the total effective volume of the microphones and re-calculated the results (revised (2)) in the table. This re-calculation provided sensitivity levels which agree very well with the mean value. Because of the knowledge of the other data at the time of the re-calculation these data were not accepted to be included in the calculation of the reference value during the discussion of Draft A.

A further bilateral comparison between DNDI (UA) and PTB (DE), COOMET.AUV.A-K1.1, was organized in order to check the equivalence with the reference value. The result of this comparison will be reported separately.

Frequency	**4160.2302519**			**4160.2302521**		
Hz	**original**	**revised (1)**	**revised (2)**	**original**	**revised (1)**	**revised (2)**
63	-26.98	-26.98	-26.89	-26.96	-26.96	-26.88
80	-26.98	-26.98	-26.90	-26.97	-26.97	-26.89
100	-27.00	-27.00	-26.92	-26.98	-26.98	-26.91
125	-27.00	-27.00	-26.93	-26.99	-26.99	-26.91
160	-27.01	-27.01	-26.94	-27.00	-27.00	-26.93
200	-27.02	-27.02	-26.95	-27.01	-27.01	-26.94
250	-27.03	-27.03	-26.96	-27.01	-27.01	-26.95
315	-27.03	-27.03	-26.96	-27.02	-27.02	-26.95
400	-27.03	-27.03	-26.97	-27.02	-27.02	-26.95
500	-27.04	-27.04	-26.97	-27.01	-27.01	-26.95
600	-27.03	-27.03	-26.97	-27.01	-27.01	-26.95
800	-27.02	-27.02	-26.96	-27.00	-27.00	-26.94
1000	-27.00	-27.00	-26.95	-26.98	-26.98	-26.92
1250	-26.98	-26.98	-26.92	-26.94	-26.94	-26.89
1600	-26.94	-26.94	-26.88	-26.89	-26.89	-26.84
2000	-26.87	-26.87	-26.82	-26.82	-26.82	-26.77
2500	-26.77	-26.77	-26.73	-26.70	-26.70	-26.65
3150	-26.64	-26.64	-26.60	-26.52	-26.52	-26.48
4000	-26.45	-26.45	-26.44	-26.28	-26.28	-26.27
5000	-26.28	-26.28	-26.29	-26.03	-26.03	-26.05
6300	-26.37	-26.37	-26.41	-26.06	-26.06	-26.10
8000	-27.48	-27.48	-27.43	-27.23	-27.23	-27.18
10000	-30.54	-30.54	-30.09	-30.55	-30.55	-30.10

Table B2. Original an the revised data reported by DNDI

Annex C – Uncertainty budgets

In the following the uncertainty budgets as reported by the participants are reproduced for reference.

PTB (DE)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	**LS1P microphones**								**Frequency in Hz**								
2																	
3									**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**10k**
4																	
5	**Type A uncertainty, as standard deviation (10^{-4} dB)**																
6																	
7	**Source of uncertainty**																
8	**Normal distribution**																
9					Repeatibility of electrical				50	50	50	50	50	50	75	100	160
10					transfer impedance measurement												
11																	
12	*Estimate of a type A uncertainty (S.D.), k=1*								50	50	50	50	50	50	75	100	160
13																	
14																	
15																	
16																	
17	**Type B uncertainty, as semi-ranges (10^{-4} dB)**																
18																	
19	**Source of uncertainty**																
20	**Rectangular distribution**																
21																	
22	Measurement				Resistance box				10	10	10	10	10	10	10	10	10
23					Stray capacitance				30	30	30	30	30	30	30	30	30
24					Polarization Voltage				22	22	22	22	22	22	22	22	22
25																	
26	Microphone parameters				Acoustic impedance (fit)				200	200	200	200	200	200	200	400	600
27					Cavity depth				1	1	1	1	1	1	1	2	2
28																	
29	Couplers				Diameter				10	10	10	10	10	10	10	10	10
30					Length				20	20	20	20	20	15	15	15	20
31																	
32	Correction of results to normal environmental conditioi				Static pressure				30	30	30	30	30	30	30	30	30
33					Temperature				20	20	20	20	20	20	20	20	20
34																	
35	Environmental conditions				Static pressure				30	30	30	30	30	30	30	30	30
36					Temperature				5	5	5	5	5	5	5	5	10
37					Humidity				5	5	5	5	5	5	5	10	15
38																	
39	Rounding error								50	50	50	50	50	50	50	50	50
40																	
41																	
42																	
43	*Estimate of type B uncertainty (S.D.), k=1*								125	125	125	125	125	125	125	236	350
44																	
45																	
46																	
47																	
48	**Overall uncertainty (10^{-4} dB)**																
49																	
50			Type A, k=2						100	100	100	100	100	100	150	200	320
51			Type B, k=2						250	250	250	250	250	249	249	471	700
52																	
53			*Overall uncertainty, k=2*						269	269	269	269	269	268	291	512	769
54																	
55									63	125	250	500	1k	2k	4k	8k	10k

GUM (PL)
Summary of the uncertainty evaluation

1. Type B uncertainty components (rectangular probability distribution assumed, number of degrees of freedom $\nu_i \rightarrow \infty$)

No	Uncertainty source	Components of Type B uncertainty expressed as distribution halfwidths (mB) at frequency											
		63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	2,5 kHz	3,15 kHz	4 kHz	5 kHz	6,3 kHz	8 kHz
1	Resistance box accuracy	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
2	Res. box stray capacitance	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
3	Res. box nonlinearity	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
4	Speed of sound (dry air)	0	0	0	0	0	0	0,01	0,01	0,02	0,03	0,04	0,07
5	Change of sound speed with humidity	0	0	0	0	0	0,01	0,01	0,02	0,04	0,06	0,09	0,15
6	Specific heats ratio	0,27	0,27	0,28	0,28	0,28	0,28	0,28	0,29	0,29	0,29	0,30	0,31
7	Coupler radius	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09
8	Coupler length	0,20	0,21	0,20	0,20	0,21	0,20	0,18	0,17	0,15	0,11	0,06	0,04
9	Cavity depth	0	0	0	0	0	0	0	0	0	0,02	0,02	0,02
10	Front cavity volume	0,26	0,26	0,26	0,26	0,26	0,24	0,24	0,22	0,20	0,16	0,08	0,04
11	Theory of adding volume	0	0	0	0,01	0,02	0,06	0,09	0,14	0,22	0,35	0,58	1,01
12	Acoustic compliance	0	0	0,01	0,03	0,08	0,36	0,60	1,01	1,70	2,43	2,11	1,10
13	Acoustic mass	0	0	0,01	0,03	0,13	0,51	0,78	1,17	1,62	1,80	1,11	0,43
14	Acoustic resistance	0	0	0	0,01	0,03	0,12	0,16	0,20	0,20	0,02	0,25	0,31
15	Heat conduction theory	0,01	0,01	0	0	0,03	0,11	0,16	0,24	0,36	0,51	0,72	1,08
16	Thermal diffusivity	0,22	0,16	0,11	0,08	0,05	0,04	0,04	0,03	0,03	0,03	0,02	0,02
17	Capillary radius	0,43	0,48	0,38	0,17	0,03	0,02	0,03	0,01	0,01	0	0	0
18	Air viscosity	0,08	0,08	0,06	0,03	0,01	0	0	0	0	0	0	0
19	Static pressure determination	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,13	0,13
20	Humidity determination	0,01	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,03	0,03	0,05	0,07
21	Temperature determination	0	0	0	0	0,01	0,03	0,05	0,07	0,13	0,20	0,31	0,50
22	Polarizing voltage	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
23	Pressure radial non-uniformity	0	0	0	0	0	0,01	0,05	0,08	0,11	0,18	0,26	0,38
24	Temperature dependence of microphone parameters	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23
25	Static pressure dependence of microphone parameters	0,34	0,34	0,34	0,34	0,34	0,34	0,34	0,34	0,34	0,34	0,34	0,34
26	Transmitter ground shield	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
27	Receiver ground shield	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07
28	Rounding error	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
Resultant Type B uncertainty expressed as distribution halfwidth		1,251	1,2616	1,221	1,17	1,168	1,32	1,533	1,956	2,656	3,297	2,833	2,313
Resultant Type B uncertainty expressed as standard deviation		0,722	0,728	0,705	0,675	0,674	0,762	0,885	1,129	1,534	1,904	1,636	1.336

2. Type A uncertainty components (normal probability distribution assumed, large number of repetitions)

No	Uncertainty source	Components of Type A uncertainty expressed as standard deviations (mB) at frequency											
		63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	2,5 kHz	3,15 kHz	4 kHz	5 kHz	6,3 kHz	8 kHz
1	Allowed repeatability	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,25	1,50	1,75
2	Front cavity volume	0,78	0,78	0,78	0,78	0,78	0,72	0,72	0,66	0,60	0,48	0,24	0,12
Resultant Type A uncertainty expressed as standard deviation		1,27	1,27	1,27	1,27	1,27	1,23	1,23	1,20	1,17	1,34	1,52	1,75

3. Overall uncertainty

Type of uncertainty	Uncertainty (mB) at frequency											
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	2,5 kHz	3,15 kHz	4 kHz	5 kHz	6,3 kHz	8 kHz
Resultant Type B uncertainty expressed as standard deviation	0,722	0,728	0,705	0,675	0,674	0,762	0,885	1,129	1,534	1,904	1,636	1,336
Resultant Type A uncertainty expressed as standard deviation	1,27	1,27	1,27	1,27	1,27	1,23	1,23	1,20	1,17	1,34	1,52	1,75
Expanded Type B uncertainty at k=2	1,444	1,456	1,41	1,35	1,348	1,524	1,77	2,258	3,068	3,808	3,272	2,672
Expanded Type A uncertainty at k=2	2,54	2,54	2,54	2,54	2,54	2,46	2,46	2,40	2,34	2,68	3,04	3,50
Overall uncertainty at k=2	2,92	2,93	2,90	2,87	2,87	2,90	3,03	3,29	3,85	4,66	4,46	4,40
Overall uncertainty rounded, dB	0,03	0,03	0,03	0,03	0,03	0,03	0,04	0,04	0,04	0,05	0,05	0,05

UME (TR)

UNCERTAINTY BUDGET FOR COOMET.AUV.A-K1 COMPARISON

SOURCE OF UNCERTAINTY	Probability distribution	Standard Uncertainty (x 10^{-4} dB) Frequency (Hz)												
		63	125	250	500	1000	2000	2500	3150	4000	5000	6300	8000	10000
Microphone Parameters														
Cavity Depth	rectangular	0	0	0	0	0	0	3	3	3	5	5	3	0
Front cavity volume	rectangular	134	134	134	134	134	122	122	111	101	79	54	41	218
Acoustic compliance	rectangular	0	0	0	6	17	35	58	92	110	127	138	121	115
Acoustic mass	rectangular	0	0	0	6	6	17	23	29	29	6	35	46	150
Acoustic resistance	rectangular	0	0	6	9	12	32	43	75	101	118	72	32	144
Mic. pressure correction	rectangular	52	52	52	52	52	46	35	35	17	12	17	52	138
Mic. temperature correction	rectangular	22	22	22	22	22	22	22	22	22	22	22	22	22
Electrical Measurements														
Voltage ratio measurements	normal	65	65	65	65	65	65	65	65	82	82	82	82	82
Stray capacitance	rectangular	58	58	58	58	58	87	87	115	115	115	115	115	115
Transmitter ground shield	rectangular	3	3	3	3	3	3	3	3	3	3	3	3	3
Receiver ground shield	rectangular	4	4	4	4	4	4	4	4	4	4	4	4	4
Polarization voltage	rectangular	13	13	13	13	13	13	13	13	13	13	13	13	13
Coupler														
Radius of coupler	rectangular	29	29	29	29	29	29	29	29	29	29	29	29	29
Length of coupler	rectangular	17	17	17	17	17	17	17	17	14	14	6	6	21
Theory														
Speed of sound	rectangular	6	6	6	6	6	6	8	8	8	8	8	13	16
Heat conduction theory	rectangular	27	25	24	24	24	26	28	33	43	56	76	110	183
Theory of adding volume	rectangular	0	0	0	1	1	3	5	8	13	20	33	58	108
Air viscosity	rectangular	12	12	9	5	2	0	0	0	0	0	0	0	0
Capillary radius	rectangular	33	37	29	13	2	2	2	1	1	0	0	0	0
Pressure radial non-uniformity	rectangular	0	0	0	0	0	1	3	5	6	10	15	22	31
Environmental Conditions														
Static pressure	rectangular	17	17	17	17	17	17	17	17	17	17	17	17	17
Temperature	rectangular	1	1	1	1	1	1	1	2	2	4	6	10	17
Humidity	rectangular	6	6	6	6	6	6	6	6	6	6	6	6	6
Other														
Allowed repeatability	normal	250	250	250	250	250	250	250	250	250	275	300	400	400
Rounding error	rectangular	29	29	29	29	29	29	29	29	29	29	29	29	29
Combined Uncertainty	normal	309	310	309	308	308	312	316	336	348	372	385	470	594
Expanded Uncertainty	normal	619	619	617	615	616	625	632	671	696	745	771	940	1188
Reported Uncertainty (dB)	normal	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,07	0,07	0,07	0,08	0,09	0,12

SMU (SK) **Slovenský metrologický ústav**

Summary of the uncertainty budget for COOMET.AUV.A-K1

Microphones type LS 1P

Type B standard uncertainty of the microphone sensitivity

Uncertainty source	**Distribution**	**Contribution to the standard uncertainty in (mV/Pa)**						
		Frequency (Hz)						
		63	**125**	**250**	**500**	**1000**	**2000**	**2500**
Voltage $u_{M,u}$	rectangular	0,0057	0,0054	0,0052	0,0052	0,0051	0,0050	0,0048
Capacity of the measured cond. $u_{M,Cmer}$	normal	-0,0026	-0,0026	-0,0026	-0,0026	-0,0026	-0,0026	-0,0026
Air density $u_{M,\rho}$	rectangular	-0,0324	-0,0324	-0,0324	-0,0324	-0,0324	-0,0324	-0,0324
Sound velocity $u_{M,C0}$	rectangular	-0,0212	-0,0177	-0,0203	-0,0204	-0,0199	-0,0202	-0,0203
Cross area the cavity $u_{M,S}$	rectangular	0,0147	0,0147	0,0147	0,0147	0,0147	0,0147	0,0147
Equiv.length of the cavity $u_{M,le}$	rectangular	-0,0841	-0,0895	-0,0809	-0,0805	-0,0820	-0,0812	-0,0817
Measuring frequency $u_{M,f}$	normal	-2,6E-06	-2,7E-06	-2,5E-06	-2,6E-06	-2,5E-06	-2,6E-06	-2,5E-06
Pressure correction $u_{M,kp}$	normal	-0,0184	-0,0184	-0,0184	-0,0184	-0,0184	-0,0184	-0,0184
Temperature correction $u_{M,kt}$	normal	-0,0035	-0,0035	-0,0035	-0,0035	-0,0035	-0,0035	-0,0035
Polarization voltage $u_{M,up}$	rectangular	0,00035	0,00035	0,00035	0,00035	0,00035	0,00035	0,00035
Heat conductivity in the closed cavity $u_{M,KHCG}$	rectangular	0,00017	0,00012	0,00008	0,00006	0,00004	0,00003	0,00003
Type B overall uncertainty in (mV/Pa)		0,096	0,100	0,093	0,093	0,094	0,093	0,094
Type B overall round up uncertainty in (mV/Pa)		0,100	0,100	0,100	0,100	0,100	0,100	0,100
Type B overall uncertainty in (dB)		0,018	0,018	0,018	0,018	0,018	0,018	0,018

Remark: The uncertainties of the microphone acoustic impedance parameter components by means of equivalent volumes are implemented in equivalent lenght of cavity.

Correlation dependency between some parameters e.g.head conductivity and sound velocity due to small value (6.4E-5 mmV/Pa) are omitted.

The partial uncertainty from measuring frequency setting accuracy is possible too neglect.

Type A standard uncertainty of the microphone sensitivity

Uncertainty source in (dB)	**Frequency (Hz)**						
	63	**125**	**250**	**500**	**1000**	**2000**	**2500**
Repeatibility during narrow time gap	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009
Repeatibility with another microphone or position changing	0,003	0,002	0,003	0,006	0,005	0,004	0,003
Type A overall uncertainty in (dB)	0,003	0,002	0,003	0,006	0,005	0,004	0,003

Combined uncertainty

Uncertainty source in (dB)	**Frequency (Hz)**						
	63	**125**	**250**	**500**	**1000**	**2000**	**2500**
Type A overall uncertainty in (dB)	0,003	0,002	0,003	0,006	0,005	0,004	0,003
Type B overall uncertainty in (dB)	0,018	0,018	0,018	0,018	0,018	0,018	0,018
Rounding error (dB)	0,001	0,001	0,001	0,001	0,001	0,001	0,001
Physical constants (dB)	0,005	0,005	0,005	0,005	0,005	0,005	0,005
Combined uncertainty	0,0190	0,0188	0,0190	0,0197	0,0194	0,0192	0,0190
Expanded uncertainty (k = 2)	0,038	0,038	0,038	0,039	0,039	0,038	0,038
Reported uncertainty (dB)	0,04	0,04	0,04	0,04	0,04	0,04	0,05

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SOURSE OF UNCERTAINTY	Components of uncertainty (×10^3 dB)												
	Frequency, Hz												
	63	125	250	500	1000	2000	2500	3150	4000	5000	6300	8000	10000
Electr. transfer impedance	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Distance between micr.	0.0	0.0	0.0	0.0	0.2	0.6	1.0	1.6	2.6	4.2	6.8	10.7	18.6
Volume of coupltr	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.4	1.4	1.4
Acoustic compliance	17.1	17.1	17.3	17.3	16.8	15.1	13.5	11.0	6.8	1.0	2.7	2.6	6.6
Acoustic resistance	0.0	0.0	0.1	0.3	1.1	4.3	6.7	10.1	14.3	16.7	11.1	3.7	21.6
Acoustic mass	0.0	0.0	0.0	0.1	0.5	1.8	2.5	3.3	3.2	0.8	3.3	4.9	19.6
Temperature	0.9	0.7	0.6	0.6	0.7	1.5	2.1	3.2	4.8	7.5	11.7	18.3	31.5
Pressure	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Huvidity	1.1	1.1	1.1	1.1	1.2	1.4	1.6	1.8	2.3	2.9	4.0	5.7	8.8
Type A uncertainty U_A×10^3, dB	27.0	13.0	12.0	12.0	12.0	13.0	13.0	13.0	13.0	17.0	25.0	35.0	55.0
Overall type B uncertainty U_B, dB	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.015	0.016	0.019	0.033
Overall expanded uncertainty (k=2) U, dB	0.06	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.06	0.08	0.13