Physikalisch-Technische Bundesanstalt

REPORT ON BILATERAL COMPARISON COOMET.AUV.A-K1.1

October 2008

Abstract

A bilateral comparison of primary standards for sound in air, COOMET.AUV.A-K1.1 was conducted in 2004 between the DNDI (Ukraine) and the PTB (Germany) with PTB acting as the linking laboratory to the previous COOMET.AUV.A-K1 comparison. A similar protocol was followed and although measurements were made at twenty-three acoustic frequencies, the results were analysed in terms of degrees of equivalence only at the recommended frequencies of the CCAUV.A-K1 comparison so that the appropriate links could be made. The results were approved by CCAUV in October 2008 are in agreement with all the linked results within the uncertainties.

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CONTENTS

1 Introduction

This report presents results for a bilateral comparison on primary standards for sound in air, COOMET.AUV.A-K1.1.

A Draft B report was produced after the participants commented and agreed on the content of Draft A. It was submitted to and approved by the CCAUV in October 2008.

According to the technical protocol, the DNDI was one of the originally participating NMIs of the COOMET.AUV.A-K1 intercomparison on the pressure reciprocity calibration of LS1P microphones. During the discussion of the results of this main comparison it was agreed that a bilateral comparison between the State Scientific Research Institute DNDI Systema, Ukraine (UA), and the Physikalisch-Technische Bundesanstalt (PTB), Germany (DE), should be performed as a supplement to the COOMET.AUV.A-K1 comparison. The PTB undertook the role of the pilot laboratory.

2 Comparison protocol

The protocol is equivalent to that for the regional key comparison COOMET.AUV.A-K1 with respect to its general regulations. However, only one travelling microphone was used in this bilateral comparison.

The protocol specified the determination of the pressure sensitivity level of an IEC 61094-1 [1] type LS1P microphone at standard environmental conditions in the frequency range from 63 Hz to 10 kHz. Both participants were to calibrate the microphone 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 summary of the methodology for the measurement procedure.

One LS1P microphone, type Brüel & Kjaer 4160, serial number 2302520, was supplied by PTB. This microphone was not circulated during the COOMET.AUV.A-K1 comparison. The microphone was check-calibrated at the PTB after purchase in the year 2002. It was transported to the DNDI for the intercomparison measurement in September 2004. After the transport back to the PTB the microphone was calibrated again in November 2004.

3 Stability of travelling standards

The stability of the microphone was monitored by observing all calibrations throughout this bilateral comparison. Figure 1 shows the results, referred to their mean value and the PTB uncertainty limits. The sensitivity levels vary at all frequencies less than the declared PTB measurement uncertainty, thus confirming that the microphones had an acceptable level of stability during the measurements.

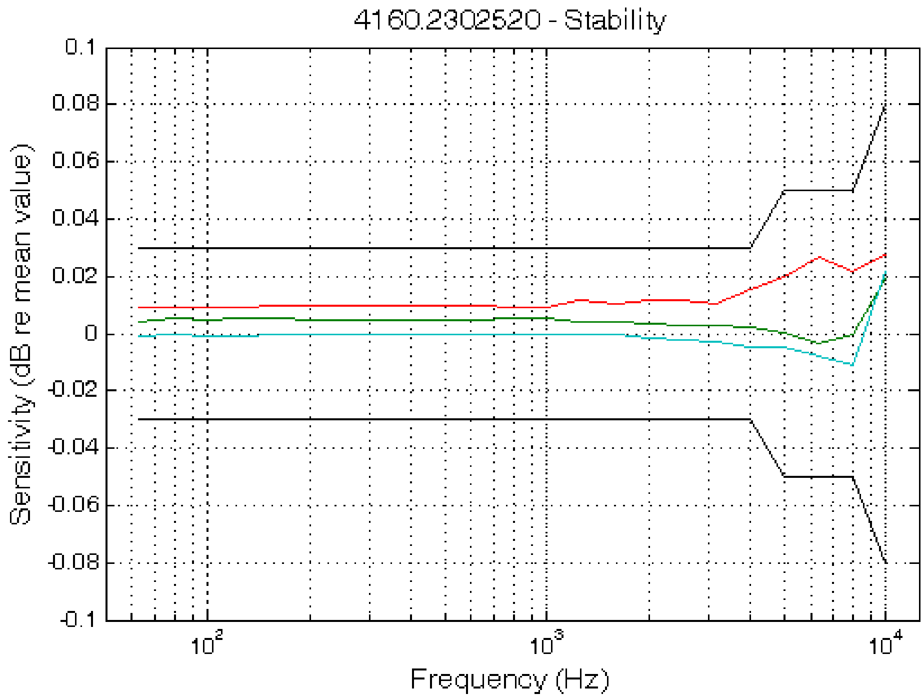

Fig. 1 Stability of the travelling standard microphone 4160.2302520 measurements over frequency, compared to PTB uncertainty (*k* = 2).

The variation of the measured sensitivity levels with time at 250 Hz is plotted in Figure 2.

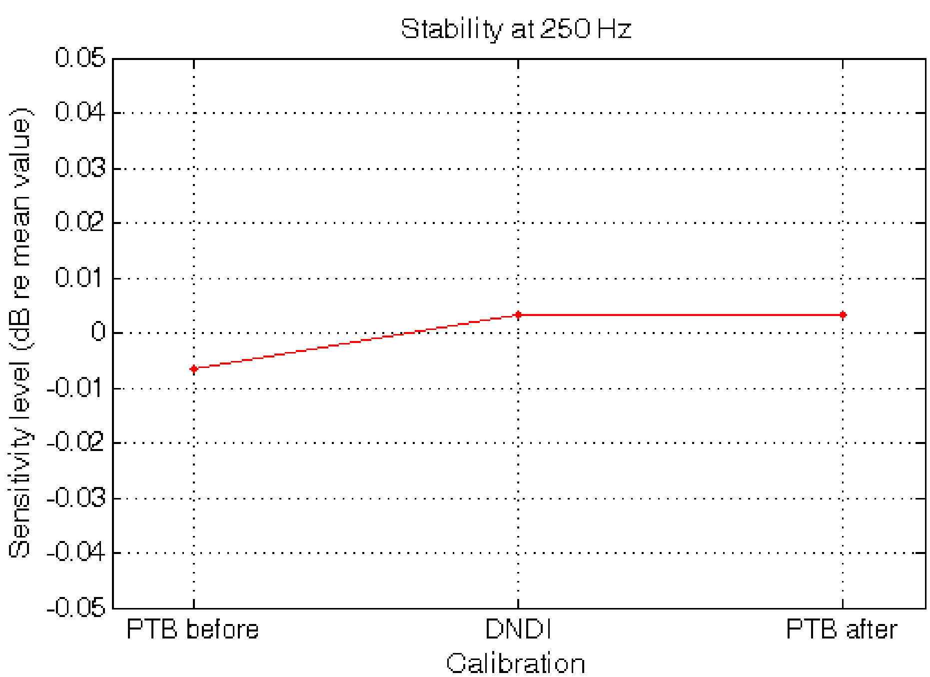

Fig. 2 Typical variation with time at *f* = 250 Hz for the travelling standard

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 to regard the microphone as sufficiently stable.

4 Methodologies

For both participants the calibration method used was based on IEC 61094-2. Short descriptions of the measurement procedures have been supplied by the participants :

DNDI Systema, Ukraine

"The calibration of the microphones was made by means of a semi-automatic pressure reciprocity calibration system type YE-2II and its software. The system type YE-2II consists of the Brüel&Kjaer device type 4143 connected to a measurement apparatus, power supply, ftlter and PC. Only the acoustic part of 4143, its amplifiers and its source of polarization voltage are used. The measurement apparatus consists of a precise two channel digital voltmeter. It measures the electrical transfer impedance of pairs of coupled microphones. Software is inc1uded for sensitivity calibration and for measurement control. Radial ware motion, additional surface owing to the thread, typical values of the static pressure coefficient and the temperature coefficient, a typical resonance frequency and loss factor were taken into account. The frequency dependence of the equivalent volume was calculated via low frequency equivalent volume, resonance frequency and loss factor. The low frequency equivalent volume was determined as a difference between total volume and front volume. The total volume was determined by an acoustical method with the device type 4143. The front volume was determined via the depth of the front cavity. The depth of the front cavity was determined by an optical method."

PTB, Germany

"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."

5 Reported results and uncertainties

The pressure sensitivity levels of the microphone determined by both participants and the associated declared uncertainties are shown in Table 1.

Frequency	PTB	DNDI	PTB	DNDI
	Sensitivity		Uncertainty	
Hz		dB re 1 V/Pa		
63	-26.90	-26.90	0.03	0.05
80	-26.91	-26.91	0.03	0.05
100	-26.92	-26.92	0.03	0.05
125	-26.93	-26.93	0.03	0.05
160	-26.94	-26.94	0.03	0.05
200	-26.94	-26.95	0.03	0.05
250	-26.95	-26.95	0.03	0.05
315	-26.95	-26.95	0.03	0.05
400	-26.95	-26.96	0.03	0.05
500	-26.95	-26.96	0.03	0.04
630	-26.95	-26.96	0.03	0.04
800	-26.95	-26.95	0.03	0.04
1000	-26.93	-26.94	0.03	0.04
1250	-26.91	-26.93	0.03	0.04
1600	-26.88	-26.89	0.03	0.04
2000	-26.83	-26.84	0.03	0.04
2500	-26.76	-26.77	0.03	0.04
3150	-26.65	-26.66	0.03	0.04
4000	-26.52	-26.53	0.03	0.04
5000	-26.42	-26.44	0.05	0.05
6300	-26.57	-26.59	0.05	0.06
8000	-27.54	-27.57	0.05	0.08
10000	-30.09	-30.01	0.08	0.12

Table 1. Pressure sensitivity levels and declared measurement uncertainties at k = 2 in dB re 1 V/Pa as reported for microphone 4160.2302520

6 Analysis of the results and degrees of equivalence

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, and it was used to prove the equivalence of the results of the two participants. Degrees of equivalence in terms of the deviations 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 for all frequencies specified in the Technical Protocol of COOMET.AUV.A-K1.1.

The aim of this bilateral comparison was to link its results to the CCAUV.A-K1 reference value, using PTB as link laboratory. Therefore, the analysis described below was performed for all frequencies used in the CCAUV.A-K1 comparison [4] .

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-K1.1 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 (two COOMET and one CCAUV measurement), 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

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

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**. 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:

DNDI (UA) = 1;
PTB (DE) = 2.

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

$y_1 ... y_3$: measurement results on the microphone 4160.2303520 in COOMET.AUV.A-K1.1,

y_4 : difference of PTB from the CCAUV.A-K1 KCRV,

y_5 : the constraint (difference from CCAUV KCRV is forced to zero).

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

$\hat{\beta}_1 \ldots \hat{\beta}_2$: differences from the estimated KCRV for the laboratories 1 and 2,

$\hat{\beta}_3$: result for the travelling microphone, related to the KCRV,

$\hat{\beta}_4$: remaining difference from the constraint (essentially zero).

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

$$\mathbf{X} = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Columns 1 relates to DNDI, column 2 to PTB, column 3 to the travelling standard, column 4 to the link with the CCAUV KCRV.

Row 1 relates to the DNDI measurement in this comparison, rows 2 and 3 to the two PTB measurements before and after DNDI, row 4 describes the link (deviation of PTB from CCAUV KCRV) and row 5 the constraint.

The number of degrees of freedom of this model is

$$\nu = g - h = 5 - 4 = 1. \tag{5}$$

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]

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

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

Table 2 shows the results of the equivalence test applied to the model described above.

Frequency Hz	χ^2_{obs}	$P\{\chi^2(\nu) > \chi^2_{obs}\}$ **%**
63	0.74	39
125	0.74	39
250	0.74	39
500	2.96	9
1000	2.96	9
1250	2.96	9
1600	2.96	9
2000	2.96	9
2500	0.74	39
3150	0.74	39
4000	0.74	39
5000	0.27	61
6300	0.00	100
8000	0.27	61

Table 2. 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 given by their deviations and associated 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 $\hat{\mathbf{C}}$:

$$U_i = k\sqrt{\hat{\mathbf{C}}_{ii}}\,, \tag{6}$$

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

Table 3 lists the deviations and their uncertainties for all frequencies.

Frequency	UA		DE	
(Hz)	***D*j** **(dB)**	***U*j** **(dB)**	***D*j** **(dB)**	***U*j** **(dB)**
63	0.01	0.06	0.00	0.03
125	0.02	0.06	0.01	0.03
250	0.02	0.06	0.01	0.03
500	0.01	0.06	0.01	0.03
1000	0.01	0.06	0.01	0.03
1250	0.00	0.06	0.01	0.03
1600	0.02	0.06	0.02	0.03
2000	0.01	0.06	0.01	0.03
2500	0.02	0.06	0.02	0.03
3150	0.01	0.06	0.01	0.03
4000	0.01	0.06	0.01	0.03
5000	0.01	0.08	0.02	0.05
6300	0.00	0.09	0.02	0.05
8000	-0.04	0.11	-0.01	0.05

Table 3. Deviations from the KCRV and their expanded uncertainties (*k* = 2).

The average deviations per laboratory are plotted over frequency in Figure 3.

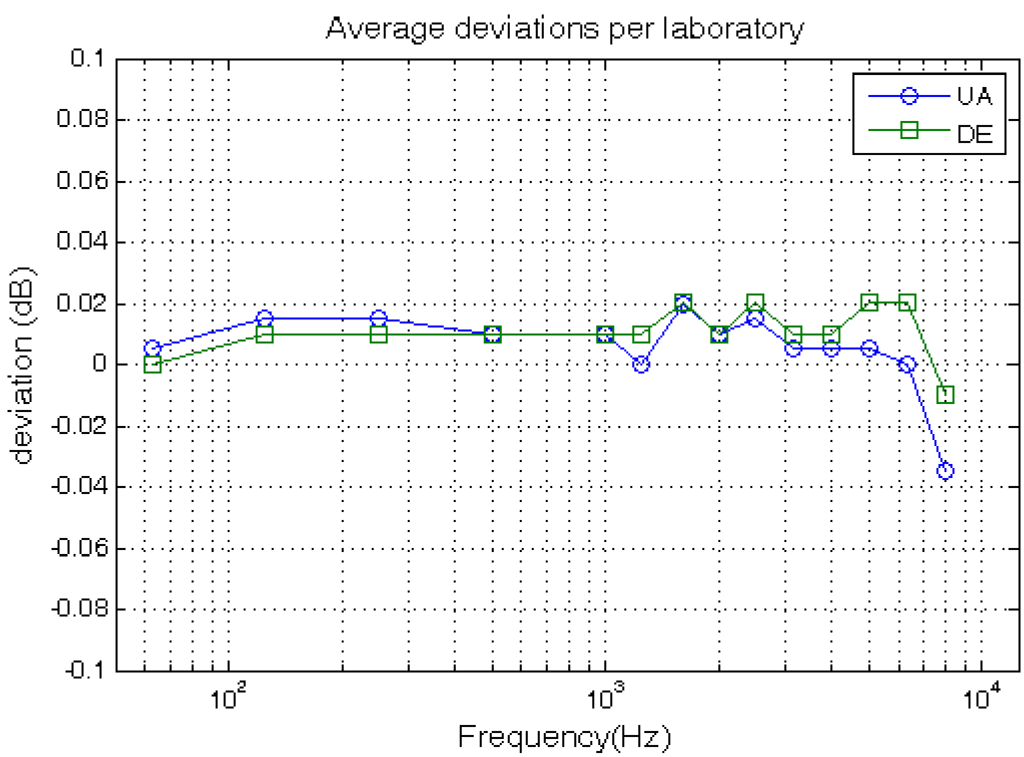

Fig. 3 Average deviations per laboratory

Figures 4 and 5 demonstrate the degrees of equivalence for the frequencies 250 Hz and 1000 Hz for all laboratories.

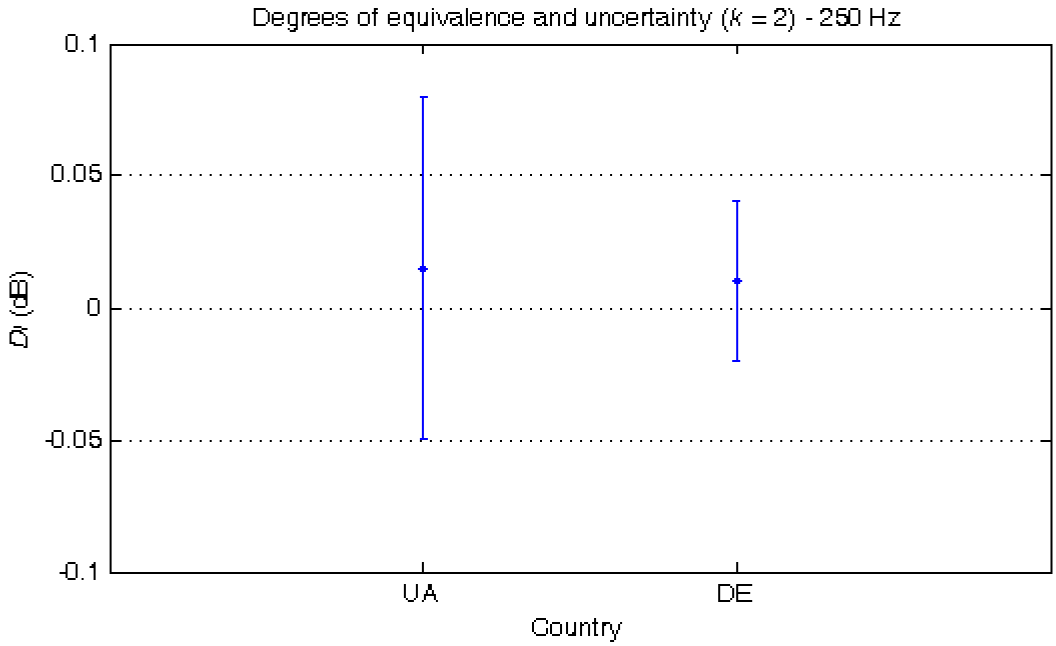

Fig. 4 Degrees of equivalence with the KCRV at 250 Hz

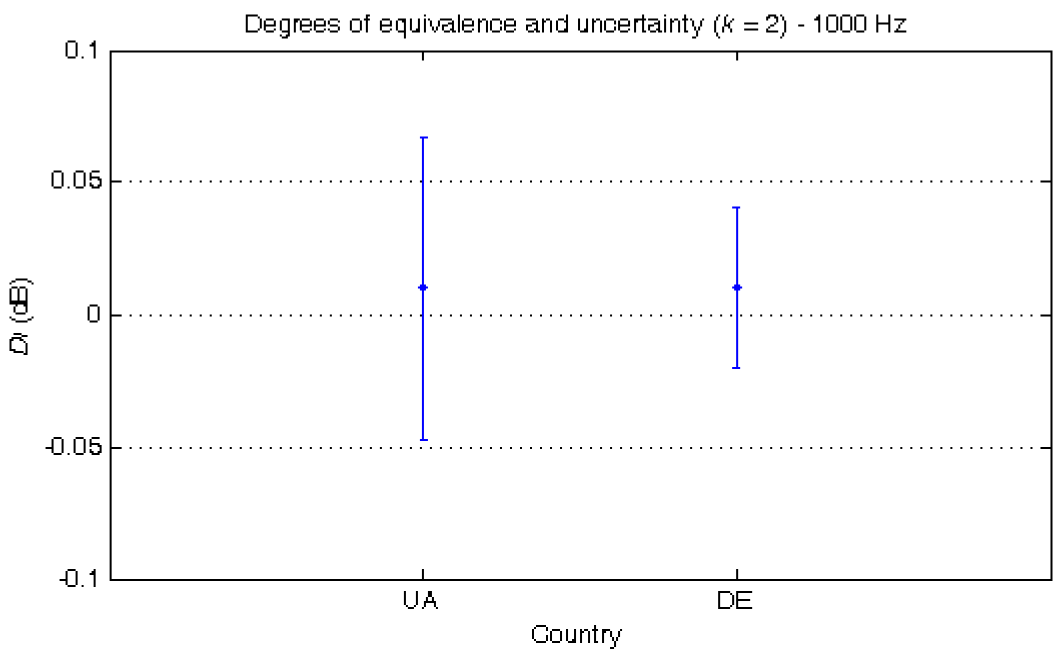

Fig. 5 Degrees of equivalence with the KCRV at 1000 Hz

The mutual degrees of equivalence (deviation $D_{i,j}$ of laboratory i from laboratory j and their expanded uncertainties $U_{i,j,}$) 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 4 to 7 list the mutual degrees of equivalence, being the deviations and their expanded uncertainties for the frequencies 250 Hz and 1000 Hz.

250 Hz	UA	DE
UA	-	0.01
DE	-0.01	-

Table 4. Mutual degrees of equivalence at 250 Hz, deviations in dB

250 Hz	UA	DE
UA	-	0.06
DE	0.06	-

Table 5. Mutual degrees of equivalence at 250 Hz, uncertainties (*k* = 2) in dB

1000 Hz	UA	DE
UA	-	0.00
DE	0.00	-

Table 6. Mutual degrees of equivalence at 1000 Hz, deviations in dB

1000 Hz	UA	DE
UA	-	0.06
DE	0.06	-

Table 7. Mutual degrees of equivalence at 1000 Hz, uncertainties (*k* = 2) in dB

7 Conclusions

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

Consistency tests of the data and the evaluation of the degrees of equivalence, the latter being the deviations and 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 CCAUV.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

The microphone parameters used for the calculation of the sensitivity data are presented in Table A1.

Parameter	**DNDI**	**PTB**
Total volume, mm^3	673	680
Front volume, mm^3	542[1]	562[2]
Equivalent volume, mm^3	131	118
Front cavity depth, mm	1,975	1,974
Resonance frequency, Hz	8200	8250
Loss factor	1,05	1,00
Low frequency static pressure oefficient, dB/kPa	-0,0152	-0,0152
Low frequency temperature coefficient, dB/K	-0,002	-0,002
	[1]calculated from cavity depth	[2]including excess volume

Table A1. Microphone parameters reported by the laboratories

Annex B – Uncertainty Budgets

1) 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 conditioı				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

2) DNDI (UA)

2) DNDI (UA)

Ordinal No	Input quantity	Sign	Standard uncertainty on frequency				
			63 Hz	250 Hz	1000 Hz	4 kHz	10 kHz
	Type A (10^{-4} dB)						
1	Repeatibility of electrical transfer impedance measurement		38	33	35	29	64
	Type B (10^{-4} dB)						
2	Voltage ratio	U_{12}	81	81	61	61	61
3	Voltage ratio	U_{13}	81	81	61	61	61
4	Voltage ratio	U_{23}	81	81	61	61	61
5	Temperature	T	2	2	3	13	18
6	Static pressure	p_s	46	45	46	59	31
7	Relative humidity	H	2	2	2	3	14
8	Condenser capacity	C_s	25	25	25	25	25
9	Frequency	f	0	0	1	33	68
10	Water vapor saturation pressure	p_m	0	0	0	0	2
11	Acoustic compliance	C	83	83	79	22	32
12	Acoustic mass	L	0	0	2	11	88
13	Acoustic resistance	R	0	0	7	71	77
14	Ratio $V_{e(r)}/V_{e(i)}$	α	0	0	3	35	44
15	Front cavity depth	l_F	122	122	121	90	145
16	Coupler length	l_{c1}	1	0	1	15	113
17	Coupler length	l_{c2}	1	0	1	18	136
18	Coupler diameter	d_c	1	0	0	0	0
19	Front cavity diameter	d_{F1}	26	26	26	26	27
20	Coupler volume (passport)	V_{cp}	1	1	1	1	2
21	Polarizing voltage	U_p	13	13	13	13	13
22	Resonance frequency	f_0	0	0	0	8	62
23	Static pressure coefficient	a_{ops}	29	29	29	29	29
24	Temperature coefficient	a_{ot}	24	24	24	24	24
	Type B overall standart uncertainty		216	215	193	185	305
	Overall uncertainty(k=2)		430	430	390	370	610