FINAL REPORT ON THE KEY COMPARISON CCAUV.A-K3

CENTRO NACIONAL DE METROLOGÍA
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-

May 2006

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Abstract

This is the final report for key comparison CCAUV.A-K3 on the sensitivity calibration of laboratory standard microphones in the frequency range from 31.5 Hz to 31.5 kHz. Fifteen national measurement laboratories took part in this key comparison and the Centro Nacional de Metrología (CENAM), Mexico, piloted the project with the assistance of the Danish Primary Laboratory for Acoustics (DPLA), Denmark. Four travelling standard microphones were circulated to the participants in two loops linked through the measurements of the CENAM and the DPLA. The participants' results in the form of sensitivity measurements (dB re 1 V/Pa) and full uncertainty budgets were collected throughout the project. Reference values for all four standard microphones have been calculated using a linear least squares minimization method. The differences between measurements and references have been averaged to obtain the degrees of equivalence per laboratory and inter-laboratory. The deviations are all below 0.1 dB, except at 31.5 kHz. A frequency of 1000 Hz has been chosen to illustrate the degrees of equivalence. In all cases, the deviation is smaller than the associated uncertainty.

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INTRODUCTION

The CCAUV.A-K3 comparison is the third key comparison in acoustics organized by the CCAUV, aiming to support the primary standards for sound in air. The standards are LS2P laboratory standard microphones (½ inch). The calibration is performed by reciprocity technique, using plane wave couplers. The CENAM is the pilot laboratory, with the technical assistance of the DPLA.

This Final Report contains the results of the CCAUV.A-K3. Previously, a Draft A was circulated and presented to the participant National Metrology Institutes (NMIs) attending the third CCAUV meeting in September 2004. The Draft A report was approved. As stated in the CIPM guidelines for key comparisons, a Draft B of the report was prepared afterwards and distributed to the CCAUV members in March 2006. The Draft B has been accepted and therefore it has become the Final Report of the CCAUV.A-K3 comparison. The Final Report is public, while the drafts are only meant for discussion among participants.

The participants who submitted measurement results to the Danish Primary Laboratory for Acoustics (DPLA) have received previously the results of the measurements performed by the DPLA during the key comparison.

The report includes the measurement results from the participants, information about their measurement methods, and calculations leading to degrees of equivalence per laboratory and between pairs of laboratories.

1. THE COMPARISON PROTOCOL

In December 2002, a protocol was issued containing the practical procedures to circulate the standards and a general framework for the measurements. The actual participants are listed in table 1.

The comparison consisted of two circulations (A and B) with two standards per circulation: a total of four LS2P microphones were circulated. There were some changes to the original circulation plan:

- GUM and CENAM swapped positions. This decision was taken before the last version of the protocol was issued.
- CSIR was not able to participate, and INMETRO took its place in circulation B.
- INMETRO was moved from circulation A to circulation B, with the same dates. CENAM replaced INMETRO in circulation A.
- NPLI could not participate in the conditions stated in the protocol.

1.1. Improvements to the protocol

Some minor corrections to the protocol are proposed, since this protocol could be used as a model for future comparisons in the CCAUV or within RMOs. These practical topics came forward on examination of the measurement data, and are:

- The set of frequencies to be used by the laboratories in their measurements should be specified unambiguously in the protocol. The LNE, NIM and the INMETRO expressed the sensitivities at exact frequencies rather than the nominal frequencies mentioned in the protocol. This is probably due to the request for a “standard certificate” by the protocol, which can be contradictory with the specification of nominal frequencies. The exact frequency results were corrected for this comparison, as will be discussed later.

Participant	Acronym	Country	Country code	Regional Metrology Organization	Circulation
Danish Primary Laboratory for Acoustics	DPLA	Denmark	DK	EUROMET	A and B
National Physical Laboratory	NPL	United Kingdom	UK	EUROMET	A
Physikalisch-Technische Bundesanstalt	PTB	Germany	DE	COOMET (EUROMET)	A
National Metrology Institute of Japan	NMIJ	Japan	JP	APMP	A
Laboratoire National d'Essais	LNE	France	FR	EUROMET	A
Korea Research Institute of Standards and Science	KRISS	Korea	KR	APMP	A
Central Office of Measures	GUM	Poland	PL	EUROMET	A
Centro Nacional de Metrología	CENAM	Mexico	MX	SIM	A and B
National Institute of Standards and Technology	NIST	United States	US	SIM	A
National Institute of Metrology	NIM	China	CN	APMP	B
National Measurement Laboratory	CSIRO	Australia	AU	APMP	B
National Research Council	NRC	Canada	CA	SIM	B
Ulusal Metrolojì Enstitüsü	UME	Turkey	TR	EUROMET	B
Instituto Nacional de Metrologia, Normalizacão e Qualidade Industrial	INMETRO	Brazil	BR	SIM	B
All-Russian Scientific and Research Institute for Physical-Technical and Radiotechnical Measurements	VNIIFTRI	Russian Federation	RU	COOMET	B

Table 1.Participants in the CCAUV.A-K3 key comparison.

- It may be advisable to ask for three decimals for the sensitivity figures. As will be shown, the results are rather grouped. The third decimal can bring useful information, at least in a primary key comparison with this level of agreement. A majority of the laboratories reported results with three decimals, while the rest reported only two. The results are presented in the way they were reported.

- Microphone parameters were requested in the protocol. However, a description of the methods for obtaining them is desirable and could be requested.

- In the future, it could be possible to avoid transportation by hand of the microphones. To do this, the specifications of a special container should be included in the protocol. The container should maintain the microphones under acceptable ambient conditions. This method has been successfully employed within the EUROMET and for the bilateral comparison between the DPLA and the NPLI.

- If more than one microphone is circulated, the correlation between measurements made by the same laboratory might be requested in order to facilitate the calculations.

2. TRAVELLING MICROPHONES

Four Brüel & Kjær 4180 microphones were circulated in this comparison, all of them supplied by the DPLA. They were grouped in two pairs, in this way:

- Circulation A: 4180.1395456 and 4180.1627783
- Circulation B: 4180.1124046 and 4180.1395455

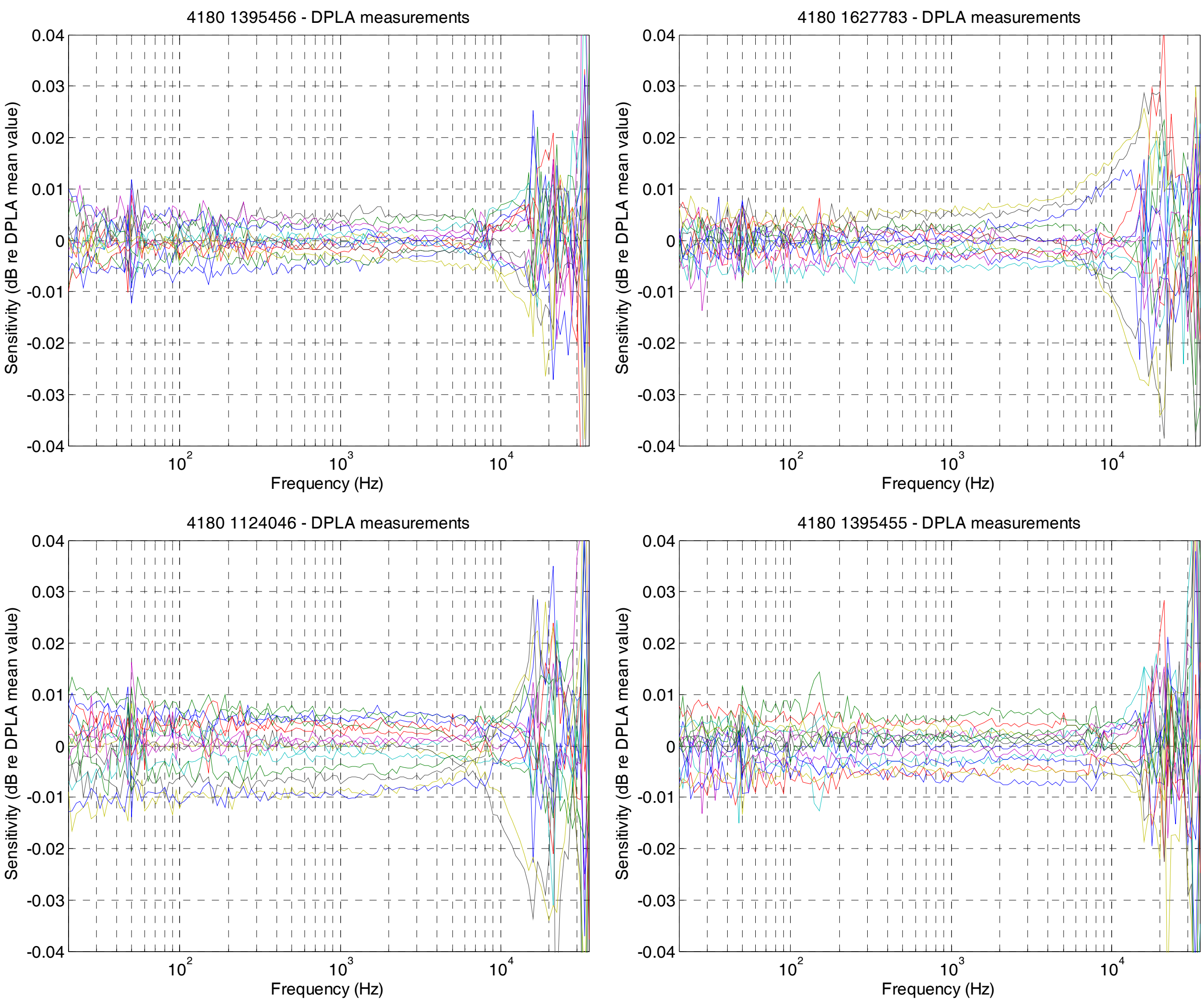

Figure 1. DPLA measurements over frequency during the CCAUV.A-K3 comparison.

The stability of the standards has been controlled by measurements at the DPLA before and after its circulation to every participant. Figure 1 shows, for every microphone, the sensitivities over frequency obtained at the DPLA referred to their mean.

The results in figure 1 vary much less than the DPLA declared uncertainty. This is apparent in figure 2, where the same information is plotted over the DPLA's uncertainty bounds in a wider sensitivity scale.

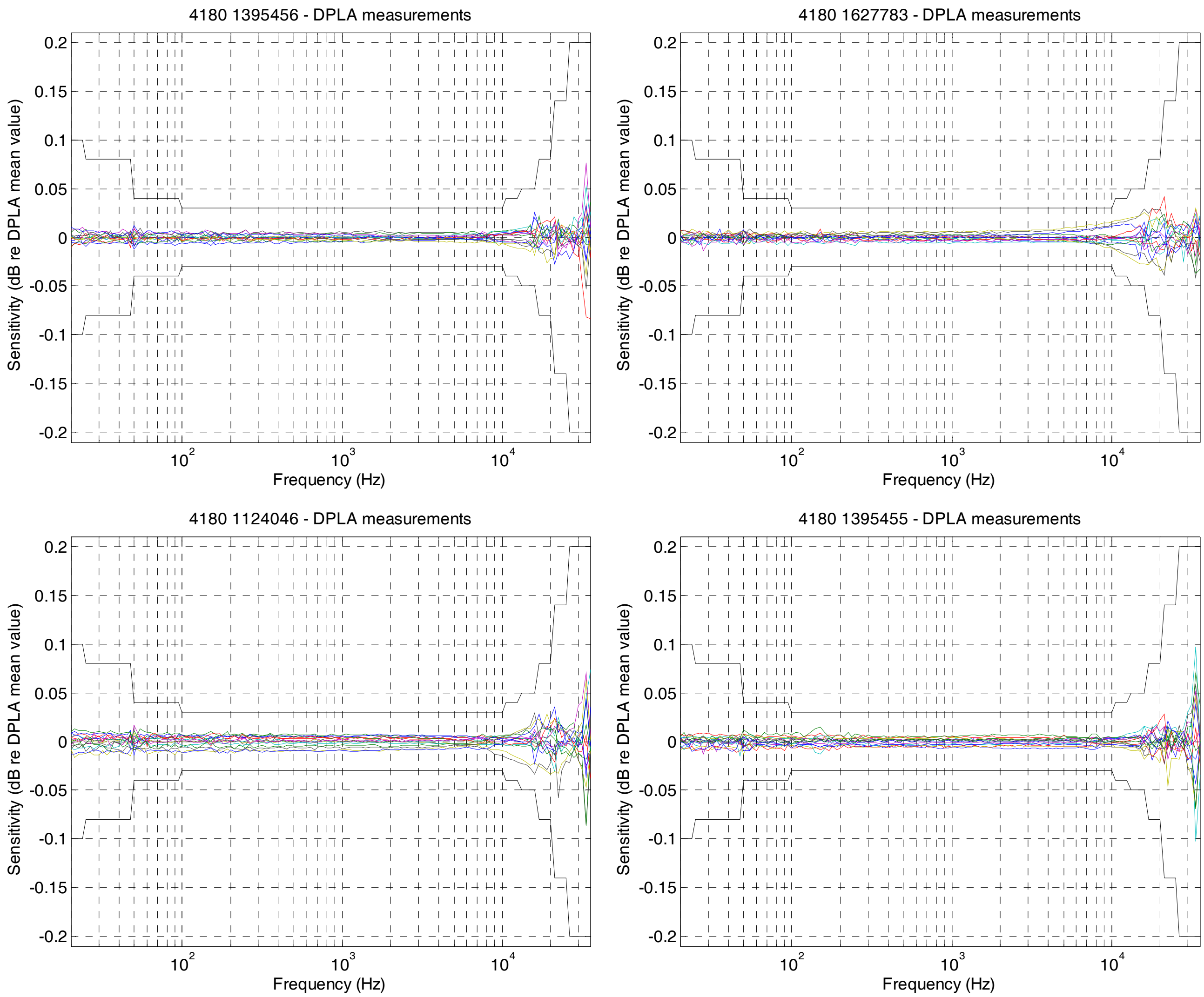

Figure 2. DPLA measurements over frequency, with the DPLA uncertainty bounds.

The temporal evolution of the sensitivities at 1 kHz is presented in Figure 3. All sensitivity values, included the DPLA's, are referred to the mean of all laboratories for every microphone.

The very first measurement from the DPLA for each microphone is used as the reported DPLA result for the comparison. This practice has been established in previous CCAUV comparisons.

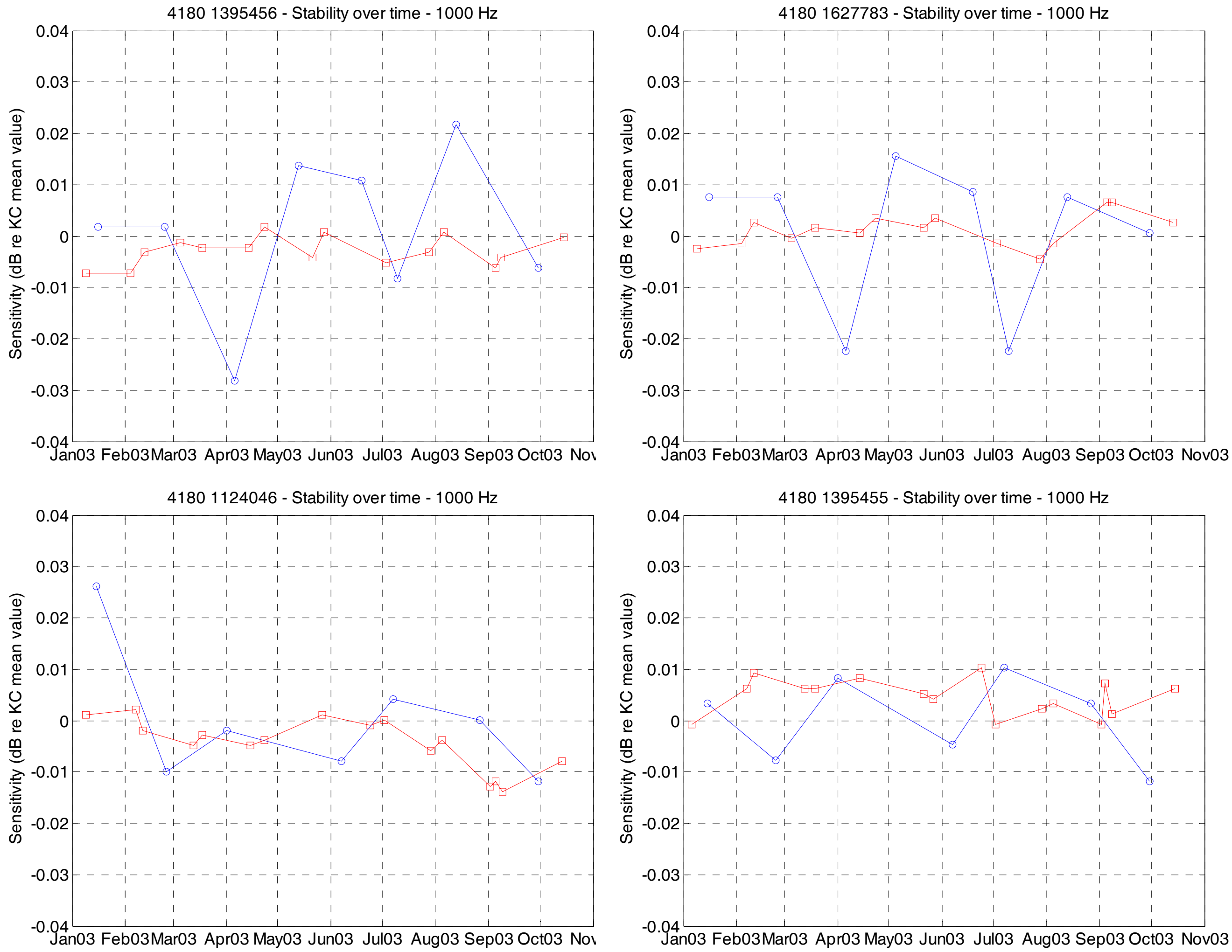

Figure 3. Temporal evolution of the measurements for all microphones at 1 kHz. In red squares, the DPLA measurements relative to overall mean for the microphone. In blue circles, measurements from the participant laboratories relative to overall mean for the microphone.

3. RESULTS

3.1. Microphone parameters

	Front cavity depth (mm)	Equivalent volume (mm3)	Front volume (mm3)	Resonance frequency (kHz)	Loss factor	Temperature coefficient at 250 Hz (dB/K)	Pressure coefficient at 250 Hz (dB/kPa)
4180.1395456							
CENAM	0,508	9,67	34,98	21,08	1,05	-0,002	-0,00589
DPLA	0,514	9,30	34,60	21,20	0,98	0,0004	-0,00594
GUM	0,503	6,68	36,82	22,33	1,05	0	-0,0055
KRISS	0,496	11,80	34,37	22,00	1,05	-0,0012	-0,0055
LNE	0,490	11,10	33,29	21,20	1,02	-0,002	-0,005547
NIST	0,509	9,20	34,98	22,00	1,05	-	-
NMIJ	0,500	10,50	34,00	22,00	1,05	-0,002	-0,006
NPL	0,514	8,30	35,73	20,06	1,12	0	-0,0055
PTB	0,506	9,21	35,39	21,10	1,05	-	-
4180.1627783							
CENAM	0,468	8,87	31,43	22,50	1,12	-0,002	-0,00537
DPLA	0,469	8,50	31,70	22,70	1,05	-0,0031	-0,00537
GUM	0,457	6,09	33,31	23,05	1,07	0	-0,0055
KRISS	0,460	10,20	31,88	22,00	1,05	-0,0012	-0,0055
LNE	0,490	7,60	33,29	22,50	1,02	-0,002	-0,005382
NIST	0,461	9,20	31,66	22,00	1,05	-	-
NMIJ	0,470	8,90	31,90	22,00	1,05	-0,002	-0,006
NPL	0,453	8,30	32,22	20,06	1,12	0	-0,0055
PTB	0,459	9,21	31,19	23,20	1,10	-	-
4180.1124046							
CENAM	0,491	9,37	33,11	22,85	1,08	-0,002	-0,0059
CSIRO	0,484	9,20	33,50	23,50	1,03	-0,002	-0,0061
DPLA	0,481	9,20	32,60	23,50	1,10	-0,0031	-0,00577
INMETRO	0,485	9,40	32,95	22,00	1,07	-	-0,0052
NIM	0,491	9,10	33,40	22,00	1,05	-0,002	-0,0055
NRC	0,482	9,30	32,74	23,00	1,03	-	-
UME	0,500	9,00	33,40	22,00	1,05	-	-
VNIIFTRI	0,481	9,20	32,74	22,00	1,05	-0,0012	-0,0055
4180.1395455							
CENAM	0,502	8,68	34,13	21,50	1,01	-0,002	-0,0052
CSIRO	0,490	9,50	33,90	21,80	1,02	-0,002	-0,0061
DPLA	0,488	9,60	33,00	21,80	1,03	-0,0015	-0,00570
INMETRO	0,492	9,43	33,44	22,00	1,07	-	-0,0052
NIM	0,492	9,20	33,40	22,00	1,05	-0,002	-0,0055
NRC	0,493	9,30	33,49	23,00	1,03	-	-
UME	0,500	9,20	34,00	22,00	1,05	-	-
VNIIFTRI	0,485	9,20	33,01	22,00	1,05	-0,0012	-0,0055

Table 2 (a). Microphone parameters reported by the laboratories

The parameters front cavity depth, equivalent volume, front volume, resonance frequency, loss factor, temperature coefficient and pressure coefficient, reported for the four microphones circulated, are presented in table 2 (a). In the cases of the GUM, NPL and the PTB, the parameters reported were acoustic mass (m_a), acoustic compliance (c_a) and acoustic resistance (r_a), shown in table 2 (b). To provide consistent values in table 2 (a), equivalent volume (v_{eq}), resonance frequency (f_o) and loss factor (d) were derived in the three cases from the reported parameters using the expressions:

$$v_{eq} = \gamma \cdot p_s \cdot c_a$$
$$f_0 = \frac{1}{2 \cdot \pi} \frac{1}{\sqrt{m_a \cdot c_a}} \quad (1)$$
$$d = 2 \cdot \pi \cdot f_0 \cdot c_a \cdot r_a$$

where γ is the specific heat ratio in air at reference conditions (1,400 757 3) and p_s is the standard pressure (101,325 kPa).

	Acoustic mass (kg/m^4)	Acoustic compliance (m^5/N)	Acoustic resistance (N·s/m^5)
4180.1395456			
GUM	1079,0	$4{,}710 \cdot 10^{-14}$	$1{,}595 \cdot 10^{8}$
NPL	1076,0	$5{,}850 \cdot 10^{-14}$	$1{,}520 \cdot 10^{8}$
PTB	876,6	$6{,}490 \cdot 10^{-14}$	$1{,}220 \cdot 10^{8}$
4180.1627783			
GUM	1110,0	$4{,}294 \cdot 10^{-14}$	$1{,}718 \cdot 10^{8}$
NPL	1076,0	$5{,}850 \cdot 10^{-14}$	$1{,}520 \cdot 10^{8}$
PTB	725,1	$6{,}490 \cdot 10^{-14}$	$1{,}163 \cdot 10^{8}$

Table 2 (b). Microphone parameters originally reported by three laboratories.

The methods for obtaining microphone parameters differ among laboratories. Information on these methods was requested and has been included in section 4.3.

3.2. Conversion of results at exact frequencies to nominal frequencies

Three laboratories (LNE, NIM and INMETRO) reported their measurements in exact frequencies. In order to produce consistent results, a correction has been applied to the reported results of these laboratories. The reported frequencies and the corrections applied are listed in table 3.

The method employed to estimate this correction makes use, as a reference, of the average of all the DPLA measurements performed during the comparison. The DPLA results are given at 1/12 octave nominal frequencies from 20 Hz to 35 500 Hz. The correction to be added to the reported sensitivity corresponding to a nominal frequency f_0 is:

***correction,* dB** = [(nominal frequency f_0, Hz) – (*exact frequency reported*, Hz)] · *slope* where:

$$slope = [(DPLA\ sensitivity \text{ at } (f_0 + 1/12\ octave), \text{dB}) - (DPLA\ sensitivity \text{ at } (f_0 - 1/12\ octave), \text{dB})] / [(f_0 + 1/12\ octave, \text{Hz}) - (f_0 - 1/12\ octave, \text{Hz})]$$

This correction, in principle, should contribute to the uncertainty of the result. However, only high frequency results, which have larger uncertainties, need noticeable corrections. It is assumed that the overall uncertainty is not affected by this correction.

Nominal frequency (Hz)	LNE			NIM			INMETRO		
	Reported frequency (Hz)	Correction to reported sensitivity (x0,01 dB)		Reported frequency (Hz)	Correction to reported sensitivity (x0,01 dB)		Reported frequency (Hz)	Correction to reported sensitivity (x0,01 dB)	
		4180 1395456	4180 1627783		4180 1124046	4180 1395455		4180 1124046	4180 1395455
31,5	31,62	0,0160	0,0085	31,62	0,0131	0,0141	31,62	0,0131	0,0141
63	63,09	0,0056	0,0042	63,10	0,0021	0,0046	63,10	0,0021	0,0046
125	125,88	0,0256	0,0159	125,89	0,0107	0,0163	125,89	0,0107	0,0163
250	251,17	0,0148	0,0046	251,19	0,0046	0,0108	251,19	0,0046	0,0108
500	501,14	0,0054	0,0025	501,19	0,0015	0,0024	501,19	0,0015	0,0024
1000	999,90	0,0000	0,0001	1000,00	0,0000	0,0000	1000,00	0,0000	0,0000
2000	1995,10	0,0180	0,0148	1995,26	0,0128	0,0183	1995,26	0,0128	0,0183
4000	3980,70	0,1701	0,1348	3981,07	0,1065	0,1510	3981,07	0,1065	0,1510
6300	6309,00	-0,1183	-0,0881	6309,57	-0,0733	-0,1089	6309,57	-0,0733	-0,1089
8000	7942,50	0,8138	0,5727	7943,28	0,4240	0,6626	7943,28	0,4240	0,6626
10000	9999,00	0,0131	0,0085	10000,00	0,0000	0,0000	10000,00	0,0000	0,0000
12500	12588,00	-0,3964	-0,1131	12589,25	0,1215	-0,1231	12589,25	0,1215	-0,1231
16000	15847,00	-3,2431	-2,7219	15848,93	-2,8080	-3,2952	15848,92	-2,8082	-3,2954
20000	19951,00	-2,4328	-1,9514	19952,62	-1,7938	-2,1873	19952,63	-1,7935	-2,1868
25000	25116,00	6,1720	5,4203	25118,87	5,4168	5,9466	25118,87	5,4168	5,9466
31500	31620,00	4,3678	4,4080	-	-	-	-	-	-

Table 3. Correction of sensitivity results from exact to nominal frequencies.

3.3. Calibration methods and reporting of results

In this section the descriptions of the measurement systems provided by the laboratories are included in italics. After circulation of Draft A, the laboratories were asked to provide descriptions of the methods employed to estimate microphone parameters. This information is also included.

CENAM: *"The open circuit sensitivity is determined by means of the reciprocity technique. The microphone under test is subsequently acoustically coupled in pairs with two microphones in a closed coupler (plane wave coupler). The sensitivity of the microphone is obtained from the measurements of the electrical transfer impedance function between the pairs of microphones and the acoustical transfer impedance between the microphones. This is realized in compliance with the International Standard IEC 61094-1992. Four different plane wave couplers are* *used in each measurement. Also, the coupled microphones are placed inside a pressure chamber that can be pressurized from the ambient static pressure at the Laboratory to the reference static pressure (101,3 kPa).*

<u>Summary of the procedure employed at CENAM for acoustic parameters determination for each calibrated microphone:</u>

- *The front cavity depth of the microphone was measured using a Leitz microscope with 300x magnification, and a TESA optical parallel. The depth of the cavity was determined measuring 20 positions distributed over the diaphragm, by placing an optical parallel on the microphone front.*
- *The equivalent volume, front volume, resonance frequency and loss factor of each microphone were determined using the following steps:*
    - *Firstly, the sensitivities of the microphones were determined using the acoustic parameters values calculated with empirical equations;*
    - *Next, the acoustic parameters values were adjusted until equal sensitivities were obtained for the four couplers involved in the calibration procedure. All plane wave couplers have different lengths and therefore, different volumes.*
- *The static pressure coefficient of each microphone was determined by means of linear regression analysis, between the sensitivities obtained at five different static pressures from 85 kPa to 104 kPa and the respective static pressures of measurement.*
- *The temperature coefficient used in the sensitivity calculation corresponds with the typical value reported by the microphone's manufacturer."*

CSIRO: *"(1) The sensitivity was determined in whole octave intervals from 31,5 Hz to 6.3 kHz and in 1/3 octave intervals from 8 kHz to 25 kHz as well as 31.5 kHz using the method described in IEC Standard 61094-2 Measurement Microphones - Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique.*
(2) The polarising voltage applied to the microphone was 200.00 ± 0.01 V.
(3) The measurement data was analyzed using the computer software MP.EXE Microphone Pressure Sensitivity calibration program, Version 3.0 September 1999 E. Sandermann Olsen, K. Rasmussen from Technical University of Denmark. The software flag for the correction for radial wave motion was set to "cal" so that the corrections were applied.
(4) The temperature and pressure correction coefficients used to adjust the sensitivities to standard conditions were -0.002 dB/°C and -0.0061 dB/Pa respectively."

<u>Microphone parameter estimation:</u>

Front Cavity Depth

Front cavity depth was determined from 4 measurements taken around the microphone annulus and 5 points across the diaphragm and including a point near the approximate centre of the microphone diaphragm. A Société Genevoise

d'Instruments de Physique Tri Optic was used with a non-contacting depth measuring microscope. The device uses two targets which are visible through the eyepiece of a microscope. The height is determined by recording the elevation of the measuring head after adjusting the height of the measuring head until the targets are superimposed upon one another.
The front cavity depth was calculated as the difference between the means of the readings on the annulus and the readings on the diaphragm.

Front Cavity Volume

The front cavity volume was determined from the measured front cavity depth and the nominal area calculated from the nominal diameter of the diaphragm, 9.3 mm for a LS2 microphone according to IEC 61094-1. The volumes were later corrected using data fitting in connection with determination of the equivalent volume.

Equivalent Volume

Equivalent volume was estimated by data fitting. With the front cavity volume fixed, the equivalent volume was adjusted so that the total volume gave minimal deviations from the mean between the results of the couplers at low to medium frequencies. When these differences were minimized further adjustments were made to reduce the differences at high frequencies.

Resonance Frequency

Resonance frequency was determined by measurement of the phase relationship between the stimulation from an electrostatic actuator and the output signal. The resonance frequency was determined as the point on the graph where the difference in phase between the drive signal and the output signal passed through 90 º.

Damping Factor

Damping factor was determined from the ratio of the sensitivity in the flat region of the sensitivity response graph below about 1 kHz, to the maximum sensitivity at the resonance peak. "

DPLA: *"DPLA measured the standards at least before and after being sent to every other laboratory. A total of 15 measurement rounds for circulation A and 16 measurement rounds for circulation B were reported by DPLA. This information has been circulated. Later on, a minor correction to DPLA measurements affecting some of the results at 25 and 31.5 kHz has also been circulated before the release of this report.*

The very first measurement round for every microphone reported by DPLA has been used as the officially reported DPLA result.

<u>Measurement principle</u>

The calibration is performed as a full reciprocity calibration according to IEC 61094 2, using three microphones pair wise coupled through air filled Plane Wave couplers of different lengths (nominal lengths 3-4-5-6 mm). The resulting sensitivity is calculated using the MP.EXE software. Radial wave motion correction is applied.

Measuring equipment

The main component of the equipment used is a calibration apparatus developed and built in 1984 at DTU. The receiver microphone is connected to a preamplifier B&K 2673 with insert voltage facilities (driven ground shield) and the current through the transmitter microphone is determined by the voltage across an impedance in series with the microphone. This measurement impedance (nominal 10nF || 0.7MOhm) is calibrated in the frequency range 60 Hz to 40 kHz and the results extrapolated down to 20 Hz.
An external polarization voltage was applied by a Fluke DC Voltage Calibrator type 343A.
The static pressure is measured by a calibrated barometer, Druck DPI 140 and the temperature by a Pt 100 resistance located close to the coupler.
All measurements are conducted in a temperature controlled room at 23.0 ºC ± 1.5 ºC. Humidity is kept within the range 40% to 60% RH.

The transfer function is measured using a two channel B&K Pulse analyzer in connection with SSR software (Steady State Response software). The measurements were conducted in 1/12 octave steps from 20 Hz to 31.5 kHz. Each transfer function is determined as the average of 5 sweeps with a detector band of 0.01 dB.
The microphone front cavity depth is measured using a depth focussing microscope. The remaining microphone parameters are determined by datafitting of the results obtained using the above mentioned 4 couplers. Once determined the microphone parameters remain unchanged during all calibrations. Due to longitudinal resonances in the couplers the high frequency limits for the couplers are 35, 32, 24 and 21 kHz resp. Thus, at the highest frequencies the results is the average of a calibration in only two couplers.

In the results originally released by DPLA some of the calibrations by mistake included results taken beyond the frequency limits. This was corrected later."

GUM: *"Deviations from the recommendations given in IEC 61094-2:*
- *The speed of sound value equal to 345,874 004 55 m/s (according to EUROMET recommendation) was used in the calculations.*
- *The method proposed by Cramer for the determination of temperature dependence of sound speed (see Cramer, O., JASA v. 93, pp. 2510-2516) was used in the calculations.*
- *The method proposed by Cramer for specific heat ratio determination (see publication specified above) was used in the calculations.*

Methodology used for microphone parameters determination

The acoustical impedance of a microphone is derived from measurements of its electrical impedance with zero acoustical impedance at the microphone diaphragm. An impedance bridge Wayne Kerr 6425 is used for this measurement. The proper acoustical conditions are established by making the microphone transmit into a quarter-wavelength closed tube. The length of this tube can be adjusted for use at different frequencies. A stepper motor attached to the tube enables different lengths to be set automatically. Special circuit is provided to isolate the impedance bridge input from 200 V microphone polarization voltage. Measurements are performed at frequencies from 500 Hz to 40 kHz. For the calculation it is also necessary to know the low-frequency value of the microphone sensitivity and the blocked capacitance of the microphone (obtained from measurement at 100 kHz). From the results of electrical impedance measurements, the microphone complex equivalent volume values at all frequencies are calculated.

Next the special approximation procedure is used to obtain the components of microphone acoustical impedance. Microphone is here modelled as simple mass-spring-damper system with a single degree of freedom. The measured data are read and the point plots of real and imaginary equivalent volume experimental values as functions of frequency are produced on the computer screen. Then the initial values of acoustical mass, acoustical compliance and acoustical resistance of the microphone are calculated and displayed and the best-fit curves based on these values are plotted within the same co-ordinate system. The operator then has the option to change any of these parameters to optimize the fitting of the theoretical curves to experimental data points.

The total volume of the microphone (the sum of diaphragm equivalent volume and the physical volume of front recess) is determined acoustically. A quantity called „Front Volume", defined as the total volume minus the modulus of the equivalent volume of the diaphragm, is used in the calculation of the microphone sensitivity.

Total volume is determined by comparing the sound pressure generated in a test chamber formed partly by the microphone with that generated when the microphone is replaced with other known volumes. The sound pressure in the chamber is inversely proportional to the chamber volume and is measured with a monitor microphone. One of two known volumes used is smaller and the other is larger than total volume of the microphone. Linear interpolation is used to derive total volume of the microphone from the results obtained with the microphone and the known volumes. As the sound pressure generated in a small chamber depends significantly on the temperature and static pressure in the chamber, one of the known volumes is also used for testing the measurement conditions stability throughout the procedure. Measurements are made at five preset frequencies in the range (100 to 500) Hz.

The depth of microphone front cavity is measured using a depth-focussing microscope equipped with a dial gauge to monitor the vertical displacement of the lens (focal length of 0,5 mm). The cavity depth is calculated as the difference between dial gauge readings at the surface of front ring and at the surface of diaphragm.

It is also possible to use the nominal values of microphone parameters (provided by NPL) in calculation of microphone sensitivity. These values for 4180 microphones are shown below:

acoustical mass of the diaphragm:	$1{,}076 \cdot 10^{3}$ $kg \cdot m^{-4}$,
acoustical compliance of the diaphragm:	$5{,}850 \cdot 10^{-14}$ $m^{5} \cdot N^{-1}$;
acoustical resistance of the diaphragm:	$1{,}520 \cdot 10^{8}$ $N \cdot s \cdot m^{-5}$,
front volume of the microphone:	$34{,}5$ mm^{3},
depth of front cavity:	*0,49 mm."*

INMETRO: *"The open-circuit pressure sensitivity of the microphone was determined by the Reciprocity Technique at the 1/3rd-octave frequencies from 31.5 Hz to 25 kHz. Two air-filled plane wave couplers were used to cover the entire frequency range. One 0.7* cm^3 *plane wave coupler was used for calibrations from 31.5 Hz to 2 kHz and one 0.4* cm^3 *plane wave coupler was used for calibrations from 31.5 Hz to 25 kHz.*
A total of six complete calibration runs were carried out (one per day). Each single calibration run comprehended three cycles of measurements. The first cycle was carried out with the 0.7 cm^3 *coupler and two other cycles were carried out with the 0.4* cm^3 *coupler. These two cycles using the same coupler differed from each other by the switch of microphone positions as transmitter or receiver in the measuring chain. The result of a single calibration run was computed as the arithmetic mean of the results obtained for these three cycles.*
All measurements were conducted in accordance with the recommendations of the standard IEC 61094-2 - Measurement microphones – Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique.

Microphone parameters

Front Cavity Length: The front cavity length was measured by an optical method using a depth-focussing microscope. Four points were measured on the top of the microphone rim and five points were measured on the microphone diaphragm, as shown in figure 1. At first the mean depth of the central point (Cp) was determined (1-9, 3-9, 5-9, 7-9). In sequence, the front cavity length (L_{Fi}) *was determined from the mean of five distances (1-2, 3-4, 5-6, 7-8, Cp).*

Five measurement runs were carried out (L_{F1}; L_{F2}; L_{F3}; L_{F4}; L_{F5}) *and the final mean value* (L_{Fm}) *of the front cavity length was determined.*

Front Volume: The microphone front volume was determined in accordance with equation: $V_F = (\pi \cdot d^2/4) \cdot L_{Fm}$
where:
V_F *is the microphone front volume* (mm^3);
d is the microphone inner diameter (9.3 mm);
L_{Fm} *is the microphone front cavity length (mm)."*

KRISS: *"The open-circuit pressure sensitivity of the microphone was determined by the reciprocity technique described in IEC 61094-2. Two air-filled plane wave couplers with nominal lengths of 4.7 mm and 9.4 mm were used to cover the entire frequency range. The front cavity depth of the microphone was measured using an optical method. The equivalent volume was determined by minimizing the sensitivity level differences obtained in the low frequency range.*
A capillary tube was blocked by a needle and no capillary corrections were applied. Measurements were repeated five times at the local environmental conditions and final sensitivity levels were corrected to the reference environmental conditions."

LNE: *"The front cavity depth of the microphone is measured using an optical method. Four measurements were made at the diaphragm circumference and one on the diaphragm centre. Determinations of the other microphone parameters were carried out by running a calibration in two different couplers (nominal length 9.3 mm and 4.7 mm). The global microphone volume is first determined by minimizing the sensitivity level differences obtained in the low frequency range. For this operation, equivalent volume, loss factor and resonance frequency are set to the typical values of the microphone model. Ratio of front volume and equivalent volume is determined next. The loss factor is determined by successive changes with the resonance frequency which is calculated as a 90 degree phase shift obtained by interpolation in the sensitivity curve. Data fitting procedure is carried out until obtaining the best sensitivity agreement in the largest frequency range.*

Measurements were made in accordance of IEC 61094-2 except for physical properties of air witch were calculated using method given in the document [K. Rasmussen. Calculation methods for the physical properties of air used in the calibration of microphones. Report PL-11b, 1997. Dept of Acoustic Technology, Technical University of Denmark]. The radial wave motion correction was applied according to the document [K. Rasmussen. Radial wave motion in cylindrical plane-wave couplers. Acta Acustica. No 1. 1993] when using the Bessel function motion.

The used coupler was a B&K UA 1430. Coupler cavity mean diameter and coupler cavity mean length were measured using a 3D measuring machine. No capillarity tube and no grease were used and measurements were made at the local environmental conditions. Measurements were carried out at all the 1/3 octave frequency from 31,5 Hz until 25 kHz and repeated five times."

NIM: *"The measurement of the microphone sensitivity was made by the reciprocity calibration system in accordance with the IEC 61094-2 at the exact octave frequencies from 31.5 Hz to 6.3 kHz and exact 1/3rd octave frequencies from 8kHz to 25kHz. Six complete measurements were carried out and two different plane-wave couplers (Bruel and Kjaer UA 1430 and UA 1414) were used. The temperature of the room during the measurement was controlled. No grease and no capillarity tubes were used.*

The resulting sensitivity was calculated by the software MP.EXE.

The front cavity depth of the microphone was measured using an optical method first, and the value then used to calculate the front volume.

The value of the equivalent volume was determined such that the sensitivity difference obtained between the sensitivity curves using the two couplers were minimized.

Nominal values were used for the other parameters of the microphone, such as loss factor, resonance frequency, pressure coefficient and temperature coefficient.

The coupler parameters such as length and diameter were measured but when calculating the sensitivity the nominal coupler dimensions, supplied by B&K (the same diameters 9.3 mm but different lengths 4.7 mm and 9.4 mm) were used."

NIST: *"To obtain the reported results, measurements were performed on the two microphones circulated in the comparison and a third such microphone owned by NIST (to complete the necessary triad) according to IEC 1094-2: 1992, in two air-filled plane-wave couplers (Bruel and Kjaer UA 1430 and UA 1414) with cavities of the same nominal diameters (9.3 mm) but different lengths (nominally 4.7 mm and 9.4 mm, not including the front cavity depths of the microphones). Coupler cavity diameters were measured with a bore micrometer (Brown & Sharpe type 00880102). Coupler cavity lengths were measured using a stylus probe comparator system (Heidenhain MT 101K and VRZ 181 bidirectional counter) with optically encoded scale and digital readout indicator.*

For each coupler, measurements were performed with a bung (unique to that coupler) essentially blocking the capillary tube acoustically at the frequencies of measurement. Therefore, no capillary corrections were applied. Results from the measurements in the longer coupler are reported at frequencies from 31.5 Hz to 4 kHz. At frequencies greater than 4 kHz, results from the measurements in the shorter coupler are reported.

Other critical components of the measurement system included a signal generator (Hewlett-Packard 8904A), a digital voltmeter (Agilent 3458A), and the following Bruel and Kjaer instruments: 1617 band pass filter, 5998 apparatus with transmitter and receiver units (respectively, ZE 0796 and 2673, both with modification WH 3405 grounded guard), and UA 1412 fixture and accessories.

Microphone front cavity depths were measured using a measuring microscope system (Nikon MM-11 with trinocular head, bright field/dark field objectives, and Digimicro MU-501C with SC-111 readout z-axis photoelectric digital measuring system) capable of direct visual observation and video display modes. To avoid the uncertainties in depth-of-focus in direct visual observation due to adaptation of the eyes, video display was used. The depth of the cavity was determined for multiple positions by placing a gage block of calibrated thickness on the microphone front, focusing on the upper surface of the block, and (through a circular hole in the block) focusing on the microphone diaphragm. For each microphone, bright field *and dark field measurements were performed and the average of all these measurements was taken.*

For each microphone, a nominal front cavity volume of 34 mm^3 was adjusted initially by assuming a nominal diameter of 9.3 mm for the front cavity and using this value and the difference between the measured and nominal (0.5 mm) front cavity depths to adjust the nominal front cavity volume. Further adjustments were made to this volume for each microphone, and the calculation of its sensitivity level was repeated for each coupler, until the agreement in these calculated levels over the approximate frequency range 250 Hz to 2000 Hz in the two couplers was acceptably close (typically about 0.005 dB or better). For each microphone, the value of front cavity volume that resulted in this agreement was used to obtain the reported sensitivity levels.

For each microphone, the following nominal values of parameters were used in the calculations (determination of microphone impedance, etc.):
Resonance frequency: 22.00 kHz
Equivalent volume: 9.2 mm^3
Loss factor: 1.05

Microphone polarizing voltage (measured at the low-impedance test jacks on the power supply with the digital voltmeter and at the transmitter unit and receiver preamplifier microphone connection terminals with a high-impedance, nulling, differential voltmeter [Fluke 893A]) was 200.00 V."

NMIJ: *"The pressure sensitivity was determined in compliance with IEC 61094-2, using a reciprocity calibration system developed by NMIJ. Two air-filled plane-wave couplers with the cavity volume of 0.7 cm^3 and 0.4 cm^3 were used. Reported sensitivity was based on the measurement using the long coupler from 31.5 Hz to 500 Hz and the short coupler from 1 kHz to 31.5 kHz. No grease was applied to the contacting surfaces between the microphones and the coupler. Capillary tube correction was considered to be unnecessary because a capillary tube was blocked by a needle bung. Correction for radial wave-motion was not applied either.*

All the measurements were conducted within a temperature controlled room (23 ± 0.5 ºC). The sensitivity was corrected to the reference environmental conditions by using K. Rasmussen's method: " The static pressure and temperature coefficients of laboratory standard microphones," Metrologia ***36*** *(1999). At 31.5 kHz, only pressure dependency has been corrected because of no reliable temperature coefficient.*

Microphone parameters were determined as follows. The resonance frequency and loss factor were taken from Brüel & Kjær's nominal values. Front depth was measured using a microscope calibrated by a block gauge. Equivalent volume was estimated so that the deviation between the sensitivities for both couplers was minimized at 1 kHz."

NPL: A revision of reported results was requested by the NPL and accepted by the DPLA in October 2003, before the circulation of the microphones had finished. The changes reported by the NPL are included in appendix A.

NPL's measurement description: *"The calculation method used at NPL follows IEC 1094-2 except that the air density and speed of sound are calculated according to the methods agreed by EUROMET rather than the model given in the informative Annex. This has been shown to result in a difference in the sensitivity of a microphone of less than 0 .005 dB at all frequencies.*

The effective volumes and cavity depths of the microphones were measured and nominal values were assumed for the acoustical impedance parameters. The models for the temperature and pressure coefficients given in IEC 1094-2 were used to correct the results to reference environment conditions. This requires the low frequency value for the temperature and pressure coefficients which are shown in [table 2 (a)]*, and the resonance frequency which was calculated from the acoustical compliance and mass parameters . The data used in the calculation of the sensitivity levels quoted in the certificates are shown in* [table 2 (a and b)]*."*

NRC: *"The reciprocity system for pressure calibration of LS2P microphones at NRC follows the recommendations of IEC 61094-2 (1992-03), except in the following aspects:*

- *The polarizing voltage is measured at a port on the reciprocity calibration apparatus, instead of at the terminals of the microphone.*
- *The value of the diaphragm equivalent volume of the microphone is taken from the manufacturer's nominal value for the model of microphone, instead of being determined by an acoustical method.*
- *In the calculation of sensitivity levels, the factor Δ to compensate for dispersion is taken to be 1.0001 by the 'mp.exe' calculation software, instead of the acknowledged incorrect values referred to in Annex F of IEC 61094-2.*

The measurements were performed in a controlled environment: 23 °C, 101.325 kPa and 50% RH. Pressure, temperature and humidity corrections were negligibly small (of the order of 10^{-5} dB), and were not applied.

Methods for obtaining microphone parameters

The front cavity depth of each microphone is calibrated by the Dimensional Metrology Program of our Institute. The measurements are performed using a Coordinate Measuring Machine (CMM) equipped with a video probe head; the locations of the front of the coupler mounting ring and of the diaphragm are sensed using the optical depth-of-focus of the video probe, and their separation is measured by the Z-axis of the CMM.

The front cavity volume is calculated as the volume of a right cylinder whose height is the calibrated front cavity depth and whose diameter is the nominal diameter (9.30 mm) of an IEC type LS2aP microphone.

The diaphragm equivalent volume is taken from the manufacturer's data for the model of microphone.

The resonance frequency is taken from the manufacturer's data for the model of microphone.

For IEC type LS2P microphones, a default value for the loss factor of 1.03 is used."

PTB: *"The calibration was performed according to IEC 61094-2, using three microphones coupled in pairs by air filled plane wave couplers of different lengths (4.7; 6; 9.4 mm).*

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 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.

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 3 couplers. Due to longitudinal resonances the 6 mm coupler was excluded from the average at 16 kHz and the 9.4 mm coupler at 25 kHz."

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

The microphones were coupled in pairs using two air filled plane-wave couplers with nominal lengths 4,7 mm and 9,4 mm. Actual dimensions of the couplers were determined by using Coordinate Measuring Machine at UME Dimension

Laboratory. The polarizing voltage applied to the microphone was (200,00 ± 0,05) VDC. The variation of the polarization voltage during the measurements was monitored by 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 calculation of microphone sensitivity was performed using software MP.EXE developed at DTU in accordance with IEC 61094-2. 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 volumes were determined by data fitting of microphone sensitivities obtained for two couplers in the low frequency range.

Final sensitivity values were corrected to the reference environmental conditions given below:

Static pressure: 101,325 kPa
Temperature: 23,0 °C
Relative Humidity: % 50,0 RH"

VNIIFTRI: *"The microphones sensitivity was determined by reciprocity technique in accordance with IEC 61094-2. A plane-wave coupler with the nominal length 4.7 mm (Bruel&Kjaer type UA0951) was used. The capillary tube of the coupler was blocked and no grease was applied to the microphones.*

The front cavity depth, L_{fc} *, of the microphones was measured by an optical method. The front cavity volume,* V_{fc}*, was then calculated from the expression:* V_{fc} *[mm*^{3}*] = 68.0•*L_{fc}*. The following typical microphone parameters were used: the equivalent volume of 9.2 mm3, the resonance frequency of 22 kHz and the loss factor of 1.05.*

The measurements were performed at ambient environmental conditions and then corrected to the reference temperature and static pressure. The static pressure and temperature coefficients of the microphones were calculated as described in (K. Rasmussen. The Influence of Environmental Conditions on the Pressure Sensitivity of Measurement Microphones. Bruel&Kjaer Technical Review. No 1. 2001).

The radial wave motion correction was applied according to (K. Rasmussen. Radial wave motion in cylindrical plane-wave couplers. Acta Acustica. No 1. 1993) assuming that the velocity of the microphone membrane is described by Bessel function.

The physical properties of air were calculated from the expressions given in (K. Rasmussen. Calculation methods for the physical properties of air used in the calibration of microphones. Report PL-11b, 1997. Dept of Acoustic Technology, Technical University of Denmark)"

3.4. Measurement results

The reported sensitivity measurements for all microphones and laboratories are shown in table 4. Results from the LNE, NIM and the INMETRO have been corrected for nominal frequencies as described in section. 3.2.

Frequency (Hz)	CENAM	DPLA	GUM	KRISS	LNE	NIST	NMIJ	NPL	PTB
31,5	-38,35	-38,378	-	-38,369	-38,365	-38,366	-38,39	-38,36	-38,37
63	-38,38	-38,408	-38,43	-38,393	-38,387	-38,399	-38,42	-38,41	-38,40
125	-38,40	-38,436	-38,45	-38,418	-38,413	-38,427	-38,45	-38,44	-38,43
250	-38,43	-38,459	-38,46	-38,441	-38,436	-38,454	-38,47	-38,46	-38,45
500	-38,45	-38,479	-38,49	-38,460	-38,456	-38,476	-38,50	-38,48	-38,47
1000	-38,46	-38,489	-38,49	-38,471	-38,468	-38,488	-38,51	-38,48	-38,48
2000	-38,44	-38,470	-38,47	-38,452	-38,449	-38,472	-38,49	-38,47	-38,46
4000	-38,32	-38,342	-38,34	-38,317	-38,321	-38,347	-38,36	-38,34	-38,33
6300	-38,07	-38,085	-38,10	-38,066	-38,069	-38,102	-38,10	-38,09	-38,08
8000	-37,84	-37,851	-37,86	-37,829	-37,832	-37,873	-37,85	-37,86	-37,85
10000	-37,56	-37,567	-37,57	-37,548	-37,549	-37,598	-37,57	-37,58	-37,57
12500	-37,33	-37,322	-37,33	-37,311	-37,313	-37,368	-37,33	-37,34	-37,32
16000	-37,59	-37,559	-37,59	-37,574	-37,566	-37,650	-37,59	-37,58	-37,60
20000	-39,09	-39,050	-39,15	-39,042	-39,015	-39,170	-39,07	-39,07	-39,08
25000	-41,77	-41,764	-	-41,677	-41,556	-41,879	-41,69	-42,28	-41,84
31500	-44,76	-44,687	-	-46,113	-47,045	-	-46,43	-45,40	-

Table 4 (a). Reported pressure sensitivity (dB re 1 V/Pa) for microphone 4180 1395456.

Frequency (Hz)	CENAM	DPLA	GUM	KRISS	LNE	NIST	NMIJ	NPL	PTB
31,5	-38,75	-38,724	-	-38,725	-38,709	-38,713	-38,74	-38,72	-38,72
63	-38,74	-38,741	-38,78	-38,734	-38,725	-38,736	-38,75	-38,74	-38,73
125	-38,75	-38,757	-38,79	-38,747	-38,738	-38,752	-38,77	-38,75	-38,75
250	-38,76	-38,771	-38,79	-38,760	-38,750	-38,765	-38,78	-38,77	-38,76
500	-38,77	-38,779	-38,79	-38,768	-38,760	-38,775	-38,79	-38,77	-38,77
1000	-38,77	-38,780	-38,80	-38,769	-38,762	-38,777	-38,80	-38,77	-38,77
2000	-38,75	-38,758	-38,77	-38,747	-38,740	-38,756	-38,77	-38,75	-38,75
4000	-38,64	-38,653	-38,67	-38,635	-38,635	-38,649	-38,67	-38,65	-38,65
6300	-38,45	-38,457	-38,48	-38,442	-38,434	-38,460	-38,46	-38,45	-38,46
8000	-38,28	-38,290	-38,30	-38,267	-38,263	-38,293	-38,27	-38,29	-38,29
10000	-38,09	-38,095	-38,10	-38,075	-38,068	-38,102	-38,08	-38,10	-38,10
12500	-37,95	-37,958	-37,95	-37,944	-37,926	-37,978	-37,95	-37,96	-37,97
16000	-38,22	-38,210	-38,21	-38,231	-38,200	-38,294	-38,23	-38,22	-38,25
20000	-39,45	-39,438	-39,47	-39,429	-39,447	-39,512	-39,43	-39,37	-39,45
25000	-41,68	-41,716	-	-41,664	-41,816	-41,724	-41,72	-41,64	-41,74
31500	-44,39	-44,443	-	-45,585	-45,250	-	-46,07	-45,13	-

Table 4 (b). Reported pressure sensitivity (dB re 1 V/Pa) for microphone 4180 1627783.

Frequency (Hz)	CENAM	CSIRO	DPLA	INMETRO	NIM	NRC	UME	VNIIFTRI
31,5	-38,038	-38,06	-38,056	-38,057	-38,065	-	-38,050	-38,08
63	-38,054	-38,08	-38,079	-38,078	-38,086	-38,084	-38,073	-38,09
125	-38,066	-38,09	-38,092	-38,093	-38,102	-38,097	-38,087	-38,11
250	-38,076	-38,10	-38,103	-38,103	-38,112	-38,109	-38,098	-38,12
500	-38,081	-38,11	-38,108	-38,108	-38,118	-38,116	-38,104	-38,12
1000	-38,082	-38,11	-38,107	-38,108	-38,118	-38,116	-38,104	-38,12
2000	-38,064	-38,09	-38,088	-38,088	-38,099	-38,099	-38,085	-38,10
4000	-37,979	-38,00	-38,003	-38,001	-38,014	-38,019	-37,998	-38,02
6300	-37,825	-37,84	-37,846	-37,846	-37,859	-37,875	-37,839	-37,86
8000	-37,697	-37,71	-37,720	-37,715	-37,729	-37,755	-37,712	-37,73
10000	-37,565	-37,57	-37,584	-37,576	-37,595	-37,634	-37,568	-37,59
12500	-37,510	-37,51	-37,519	-37,513	-37,544	-37,592	-37,508	-37,52
16000	-37,857	-37,84	-37,873	-37,840	-37,880	-37,944	-37,815	-37,84
20000	-39,060	-39,02	-39,020	-38,988	-39,063	-39,134	-38,997	-39,00
25000	-41,195	-41,22	-41,209	-41,104	-41,231	-	-41,226	-41,09
31500	-43,938	-43,84	-43,914	-	-	-	-	-45,79

Table 4 (c). Reported pressure sensitivity (dB re 1 V/Pa) for microphone 4180 1124046.

Frequency (Hz)	CENAM	CSIRO	DPLA	INMETRO	NIM	NRC	UME	VNIIFTRI
31,5	-38,352	-38,35	-38,348	-38,347	-38,355	-	-38,338	-38,37
63	-38,373	-38,37	-38,372	-38,370	-38,379	-38,376	-38,363	-38,38
125	-38,390	-38,39	-38,392	-38,390	-38,399	-38,395	-38,382	-38,40
250	-38,404	-38,40	-38,409	-38,404	-38,414	-38,411	-38,397	-38,42
500	-38,414	-38,41	-38,417	-38,414	-38,424	-38,420	-38,407	-38,42
1000	-38,415	-38,41	-38,419	-38,415	-38,426	-38,423	-38,408	-38,43
2000	-38,389	-38,38	-38,394	-38,389	-38,401	-38,399	-38,383	-38,40
4000	-38,269	-38,26	-38,274	-38,267	-38,279	-38,284	-38,262	-38,28
6300	-38,041	-38,04	-38,047	-38,041	-38,053	-38,071	-38,031	-38,06
8000	-37,841	-37,83	-37,851	-37,841	-37,853	-37,880	-37,839	-37,86
10000	-37,615	-37,60	-37,623	-37,612	-37,623	-37,666	-37,599	-37,63
12500	-37,456	-37,44	-37,462	-37,450	-37,476	-37,524	-37,436	-37,47
16000	-37,794	-37,78	-37,783	-37,780	-37,810	-37,882	-37,740	-37,79
20000	-39,238	-39,22	-39,202	-39,194	-39,261	-39,316	-39,185	-39,20
25000	-41,774	-41,76	-41,755	-41,681	-41,760	-	-41,820	-41,68
31500	-44,692	-44,57	-44,508	-	-	-	-	-46,54

Table 4 (d). Reported pressure sensitivity (dB re 1 V/Pa) for microphone 4180 1395455.

The uncertainties declared by all the laboratories are listed in Table 5. The declared uncertainties were identical in all the certificates issued by the same laboratory.

Frequency (Hz)	CENAM	CSIRO	DPLA	GUM	INMETRO	KRISS	LNE	NIM	NIST	NMIJ	NPL	NRC	PTB	UME	VNIIFTRI
31,5	0,05	0,06	0,08	-	0,059	0,06	0,042	0,08	0,08	0,30	0,06	-	0,04	0,08	0,14
63	0,05	0,04	0,04	0,05	0,046	0,04	0,034	0,05	0,06	0,10	0,03	0,05	0,04	0,08	0,07
125	0,06	0,04	0,03	0,05	0,046	0,03	0,031	0,05	0,06	0,09	0,03	0,05	0,04	0,08	0,04
250	0,06	0,04	0,03	0,05	0,045	0,03	0,030	0,05	0,04	0,09	0,03	0,04	0,04	0,08	0,04
500	0,06	0,04	0,03	0,05	0,045	0,03	0,030	0,05	0,04	0,09	0,03	0,04	0,04	0,08	0,04
1000	0,06	0,04	0,03	0,05	0,045	0,03	0,031	0,05	0,04	0,09	0,03	0,04	0,04	0,08	0,04
2000	0,06	0,04	0,03	0,05	0,045	0,03	0,033	0,05	0,04	0,09	0,03	0,04	0,04	0,08	0,04
4000	0,06	0,04	0,03	0,05	0,045	0,03	0,040	0,05	0,04	0,09	0,03	0,04	0,04	0,08	0,04
6300	0,06	0,04	0,03	0,05	0,047	0,03	0,052	0,05	0,05	0,09	0,04	0,04	0,04	0,08	0,04
8000	0,05	0,04	0,03	0,06	0,055	0,03	0,063	0,05	0,05	0,09	0,05	0,04	0,04	0,09	0,05
10000	0,05	0,05	0,03	0,07	0,074	0,04	0,080	0,05	0,06	0,09	0,06	0,10	0,06	0,10	0,06
12500	0,05	0,05	0,04	0,08	0,085	0,05	0,100	0,10	0,06	0,09	0,08	0,12	0,08	0,11	0,09
16000	0,07	0,05	0,05	0,09	0,115	0,06	0,140	0,10	0,08	0,09	0,10	0,14	0,12	0,12	0,13
20000	0,17	0,06	0,08	0,17	0,126	0,08	0,190	0,10	0,13	0,15	0,18	0,17	0,12	0,17	0,18
25000	0,21	0,08	0,14	-	0,167	0,20	0,290	0,12	0,26	0,19	0,66	-	0,15	0,20	0,31
31500	0,37	0,22	0,20	-	-	1,20	0,820	-	-	0,67	0,75	-	-	-	0,96

Table 5. Declared measurement uncertainties (dB) with k = 2.

4. ANALYSIS OF THE RESULTS

4.1. Discussion

In CCAUV key comparisons, it is common practice to define a single KCRV and single degrees of equivalence per laboratory and frequency. The present comparison consists of two different measurement circulations, or loops, with two sets of standards. This is a novelty from previous CCAUV comparisons that made possible the participation of a relatively large number of laboratories in a reasonable time. However, in order to establish adequate degrees of equivalence per laboratory and between any given pair of laboratories, the analysis must be able to consider the existence of two measurement loops and link their results.

Comparison evaluation is not yet a well settled matter. Several references touch upon this subject; for example, Nielsen [1], Cox [2] and the European Guide EAL-P7 [3]. In the present case, it is not possible to follow an approach such as in the CCAUV.A-K1 [4] comparison. Only two laboratories (DPLA and CENAM) measured all four standards, while the remaining laboratories measured two of them.

In this report the linear least squares approach, as described in reference [1], is adopted for the analysis. It provides means to test: i) equivalence of all the results, ii) consistency of every one of the reported data in order to detect outliers, and iii) reported correlation between measurements, which is useful to validate the link between loops.

The linear least squares computation of the results leads to estimates of the circulated standards, deviations of any measurement from the standards and a covariance matrix of such deviations, all of it considering links between loops. We have set the goal of obtaining degrees of equivalence for the laboratories, not only for every measurement result. To do that the deviations were averaged and combined, as will be shown in the following. This analysis is repeated for the reported results at every one of the nominal frequencies.

4.2. Linear least squares minimization

On reading reference [1], it becomes obvious that the whole covariance matrix of the comparison must be supplied, including off-diagonal elements, the covariances. It can be assumed as a hypothesis that no correlation exists between the measurements made by different laboratories, but it is apparent that those measurements made by the same laboratory should in principle be correlated to some extent. Unfortunately, the protocol did not require the laboratories to estimate the covariances between their measurements. In the CCAUV.A-K1 comparison [4] full correlation (equal to one) was assumed between measurements made by the same laboratory.

In this analysis, a high degree of correlation is assumed. However, total correlations (equal to one) affect the least squares calculation in the sense that measurements are linked with no uncertainty, making the minimization unsolvable. Besides, the results of the equivalence and consistency tests tend to reject very high correlations, as discussed below. With all these considerations, a correlation value of 0,7 is chosen, somewhat arbitrarily, for the results presented here. This value applies to any pair of measurements made by the same laboratory. All other correlations are set to zero.

The linear model of the comparison is **E(y)** = **X·a**, where **a** is a vector of parameters of the model, **E(y)** the expectations of the measurements and **X** is the design matrix. In our case, the model takes the form in equation (2).

$$\begin{bmatrix} E(y_{11}) \\ \vdots \\ E(y_{19}) \\ E(y_{21}) \\ \vdots \\ E(y_{29}) \\ E(y_{31}) \\ \vdots \\ E(y_{38}) \\ E(y_{41}) \\ \vdots \\ E(y_{48}) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} \qquad (2)$$

$E(y_{ij})$ stands for the the i-th standard being measured by the j-th laboratory in the loop. The parameters a_i are the values of the four standards to be estimated. The laboratories provide at least two measurements in (2). This procedure is applied to the results at every one of the 16 nominal frequencies specified in the protocol. At some frequencies, in particular the lower and higher of the range, not all laboratories provided results. The model must reflect it, reducing the size of (2) accordingly.

The model can take into account the instability of the standards. However, in this comparison the standards are considered stable and no correction is made.

Following notation in [1], the input data for the model are the measurement results $\mathbf{y_i}$ and the covariance matrix $\mathbf{\Sigma}$. The covariance matrix has in its main diagonal the variances: the declared uncertainties in table 5, divided by two and squared. The off-diagonal elements of $\mathbf{\Sigma}$ are only non-zero when they represent the covariance of measurements by the same laboratory. These covariances are calculated assuming a correlation of 0,7 as previously discussed.

The estimated values of the standards $\hat{\mathbf{y}}$ and their covariance matrix $\mathbf{V}(\hat{\mathbf{y}})$ are obtained using:

$$\hat{\mathbf{a}} = \mathbf{C} \cdot \mathbf{X}^{\mathbf{T}} \cdot \mathbf{\Sigma}^{-1} \cdot \mathbf{y} \qquad \textit{where} \quad \mathbf{C} = \mathbf{V}(\hat{\mathbf{a}}) = \left(\mathbf{X}^{\mathbf{T}} \cdot \mathbf{\Sigma}^{-1} \cdot \mathbf{X}\right)^{-1} \tag{3}$$

$$\hat{\mathbf{y}} = \mathbf{X} \cdot \hat{\mathbf{a}} \qquad \textit{and} \quad \mathbf{V}(\hat{\mathbf{y}}) = \mathbf{X} \cdot \mathbf{V}(\hat{\mathbf{a}}) \cdot \mathbf{X}^{\mathbf{T}} \tag{4}$$

The deviations of the measurements from the estimated values of the standards and the covariance matrix of such deviations are then:

$$\mathbf{y} - \hat{\mathbf{y}} = \mathbf{y} - \mathbf{X} \cdot \hat{\mathbf{a}} \qquad \textit{and} \quad \mathbf{V}(\mathbf{y} - \hat{\mathbf{y}}) = \mathbf{V}(\mathbf{y}) - \mathbf{V}(\hat{\mathbf{y}}) \tag{5}$$

4.3. Degrees of equivalence

The previous result must be processed to obtain single degrees of equivalence per laboratory and pairs of laboratories. At first sight, the linear least squares minimization could be applied again to the measurement deviations and their covariance matrix in (5). Unfortunately, the covariance matrix of the deviations is singular because the calculation of the differences introduces an additional constraint. It cannot be inverted, and another approach must be found.

The procedure adopted was advised by Lars Nielsen, author of reference [1]. The deviations per laboratory are obtained using simple averages of the measurement deviations obtained in (5). In practice, an averaging matrix **A** is used, with as many rows as measurements (up to 34) and with fifteen columns or less, that is, the number of laboratories providing measurements at the frequency under study. Every laboratory's column has values on the rows corresponding to its measurements, the values being ½ or ¼ for laboratories measuring twice or four times, respectively. The expressions for the averaged differences and their covariance matrix are given in equation (6).

$$\mathbf{D_{ii}} = \mathbf{A}^T \cdot (\mathbf{y} - \hat{\mathbf{y}}) \qquad and \qquad \mathbf{V}(\mathbf{D_{ii}}) = \mathbf{A}^T \cdot \mathbf{V}(\mathbf{y} - \hat{\mathbf{y}}) \cdot \mathbf{A} \tag{6}$$

The degrees of equivalence per laboratory $\mathbf{D_{ii}}$ are given in (6). The uncertainties are obtained from the diagonal of the averaged covariance matrix $\mathbf{V(D_{ii})}$. The inter-laboratory degrees of equivalence can be obtained by taking differences of this last result and calculating their uncertainties, as shown in equation (7).

$$D_{ij} = D_{ii} - D_{jj} \qquad and \qquad V(D_{ij}) = u_{ii} + u_{jj} - u_{ij} - u_{ji} \tag{7}$$

The D_{ij} represent the inter-laboratory deviations and, along with its variance $V(D_{ij})$, form the inter-laboratory degrees of equivalence. The u_{xx} are elements of the $\mathbf{V(D_{ii})}$ matrix obtained in (6).

4.4. Equivalence of the results

The participating laboratories are supposed to be measuring the same item and their results are assumed to be drawn from a normal distribution. This hypothesis is tested by means of an observed χ^2-distributed estimator, as described in [1]. The degrees of freedom of the χ^2 distribution are $\nu=n-k$, where n is the number of measurements (34 for most frequencies) and k the number of standards (4 LS2P microphones). To accept the hypothesis with a significance of 5%, the probability $P\{\chi^2(\nu)>\chi^2_{obs}\}$ has to be larger than 5%.

Frequency (Hz)	$P\{\chi^2(\nu)>\chi^2_{obs}\}$ (%)				
	Correlation 0,7	***Correlation 0,8***	***Correlation 0,9***	***Correlation 0,95***	***Correlation 0,99***
31,5	100,0	99,3	66,2	1,5	0,0
63	100,0	100,0	97,3	46,5	0,0
125	100,0	99,8	89,6	17,8	0,0
250	100,0	100,0	99,7	86,9	0,0
500	100,0	100,0	98,9	62,9	0,0
1000	100,0	100,0	99,6	81,1	0,0
2000	100,0	100,0	98,9	61,7	0,0
4000	100,0	100,0	99,2	74,4	0,0
6300	100,0	100,0	99,4	84,0	0,0
8000	100,0	99,9	99,1	84,7	0,0
10000	100,0	100,0	99,9	95,5	0,0
12500	100,0	100,0	99,9	91,3	0,0
16000	99,9	99,6	93,8	44,0	0,0
20000	100,0	99,9	97,6	58,6	0,0
25000	69,8	25,4	0,1	0,0	0,0
31500	0,0	0,0	0,0	0,0	0,0

Table 6. Results of the χ^2 test as described in [1]. The correlation used in the calculations is 0,7.

Table 6 shows the results of the equivalence test applied to the comparison results for several values of the correlation within the laboratories. The only frequency that fails the test in all cases is 31,5 kHz. However, the number of laboratories measuring at this frequency is smaller. Besides, the measurement using plane wave couplers at such a high frequency is quite challenging, therefore the lack of equivalence is expected.

The result of this test has been considered satisfactory when a correlation between measurements of the same laboratory of 0,7 is assumed. If the correlation is closer to one, the test tends to fail, as shown in table 6.

4.5. Consistency of individual results and pairs of results

Anomalous results need to be identified by the pilot laboratory. Those laboratories showing deviations judged to be excessive must be contacted in order to have an opportunity to revise their results. On a first examination, the deviations of the results from the mean were compared with their declared uncertainties. None of the results fell outside bounds, therefore no laboratory was asked to review its reported results.

Later, the analysis method in [1] was implemented. In order to test consistency, this method uses the normalized deviations, which were calculated for every frequency and measurement. The normalized deviations are distributed as $N(0,1)$. Therefore, if the modulus of a particular normalized deviation is greater than 2, the corresponding measurement can be considered an outlier with a significance of 5%. Only nine measurements at 31,5 kHz fell outside bounds. As mentioned before, this is to be expected considering the difficulties associated with measurements at such a high frequency. In consequence, there is enough consistency of the results with their declared uncertainties, when the correlations between measurements from a laboratory are set to 0,7. At higher correlation values, inconsistencies begin to appear.

Finally, it is possible to test the correlations by means of the normalized deviations between pairs of measurements. As shown in [1], these normalized deviations are distributed as well as $N(0,1)$. Their values depend on the correlation previously assigned to the pairs. With the correlation of 0,7 used in this analysis, the pairs of results can be considered as consistent. If a higher correlation is used, the normalized deviations become too large, indicating that such correlation is probably excessive. This behavior is more obvious for the measurements reported by CENAM. The results from the other linking laboratory, DPLA, seem to admit a higher correlation. However, the value of 0,7 has been applied to all the laboratories.

Consistency tests produce a large amount of figures. For this reason only the conclusions are presented in this section.

5. RFERENCE VALUES AND DEGREES OF EQUIVALENCE

5.1. Reference values

This comparison does not have a single key comparison reference value. There are four circulating standards and four reference values per frequency are calculated for them using equations (3) and (4). The values are listed in table 7.

Frequency (Hz)	4180.1395456		4180.1627783		4180.1124046		4180.1395455	
	Sensiti-vity	Uncerta-inty, *k* = 2	Sensiti-vity	Uncerta-inty, *k* = 2	Sensiti-vity	Uncerta-inty, *k* = 2	Sensiti-vity	Uncerta-inty, *k* = 2
31,5	-38,367	0,019	-38,725	0,019	-38,049	0,022	-38,345	0,022
63	-38,402	0,013	-38,740	0,013	-38,077	0,015	-38,372	0,015
125	-38,430	0,012	-38,753	0,012	-38,092	0,014	-38,391	0,014
250	-38,451	0,012	-38,766	0,012	-38,102	0,013	-38,406	0,013
500	-38,472	0,012	-38,773	0,012	-38,107	0,013	-38,414	0,013
1000	-38,481	0,012	-38,775	0,012	-38,107	0,013	-38,416	0,013
2000	-38,464	0,012	-38,753	0,012	-38,089	0,013	-38,390	0,013
4000	-38,335	0,012	-38,649	0,012	-38,004	0,013	-38,271	0,013
6300	-38,084	0,013	-38,456	0,013	-37,849	0,014	-38,048	0,014
8000	-37,850	0,013	-38,285	0,013	-37,720	0,014	-37,848	0,014
10000	-37,567	0,016	-38,091	0,016	-37,581	0,016	-37,619	0,016
12500	-37,328	0,019	-37,955	0,019	-37,519	0,020	-37,459	0,020
16000	-37,579	0,024	-38,223	0,024	-37,866	0,024	-37,795	0,024
20000	-39,073	0,036	-39,444	0,036	-39,030	0,034	-39,224	0,034
25000	-41,760	0,061	-41,714	0,061	-41,206	0,049	-41,756	0,049
31500	-44,920	0,144	-44,579	0,144	-44,035	0,132	-44,706	0,132

Table 7. Reference values of the four microphones (dB re 1 V/Pa).

5.2. Degrees of equivalence per laboratory

The deviations of the measurements, that is, the reported measurements in table 4 minus their respective reference values in table 7, are plotted in figure 4.

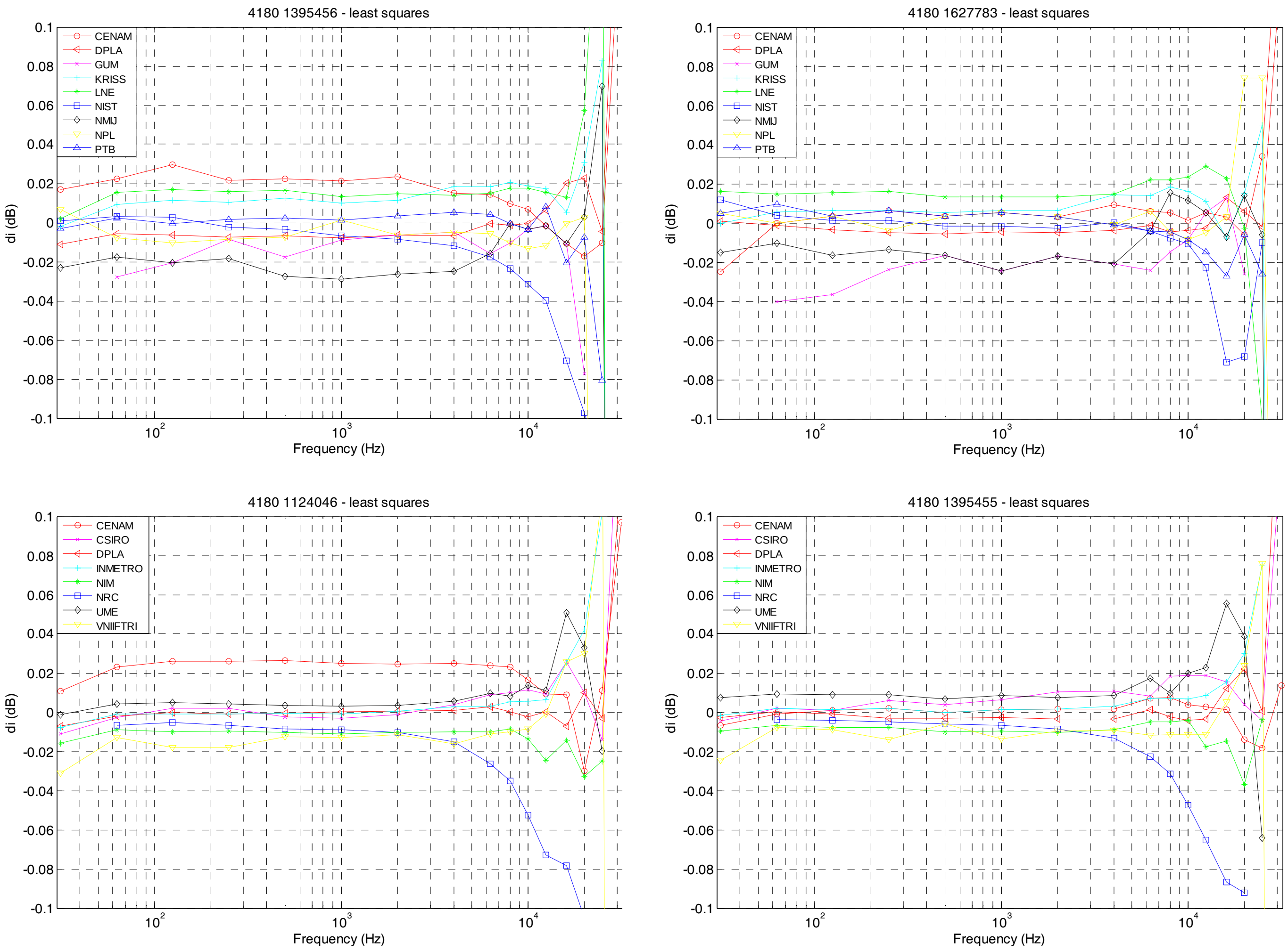

Figure 4. Deviations of the reported measurements.

The covariance matrix of the deviations obtained from equation (5) is employed in equation (6) for obtaining degrees of equivalence per laboratory, shown in table 8 and plotted in figure 5.

Frequency (Hz)	CENAM	CSIRO	DPLA	GUM	INMETRO	KRISS	LNE	NIM	NIST	NMIJ	NPL	NRC	PTB	UME	VNIIFTRI
31,5	-0,001	-0,008	-0,005	-	-0,005	-0,001	0,009	-0,013	0,006	-0,019	0,006	-	0,001	0,003	-0,028
63	0,011	0,000	-0,002	-0,034	0,001	0,008	0,015	-0,008	0,004	-0,014	-0,004	-0,005	0,006	0,007	-0,010
125	0,015	0,001	-0,003	-0,028	0,000	0,009	0,016	-0,009	0,002	-0,018	-0,003	-0,005	0,002	0,007	-0,014
250	0,014	0,004	-0,004	-0,016	0,001	0,008	0,016	-0,009	-0,001	-0,016	-0,006	-0,006	0,004	0,007	-0,016
500	0,013	0,001	-0,004	-0,017	0,000	0,009	0,015	-0,010	-0,003	-0,022	-0,002	-0,007	0,003	0,005	-0,009
1000	0,013	0,002	-0,004	-0,017	0,000	0,008	0,013	-0,010	-0,004	-0,027	0,003	-0,008	0,003	0,006	-0,013
2000	0,013	0,005	-0,004	-0,012	0,001	0,009	0,014	-0,010	-0,006	-0,022	-0,002	-0,009	0,003	0,006	-0,010
4000	0,013	0,007	-0,003	-0,013	0,003	0,016	0,014	-0,009	-0,006	-0,023	-0,003	-0,014	0,002	0,007	-0,013
6300	0,013	0,008	0,001	-0,020	0,005	0,016	0,019	-0,007	-0,011	-0,010	0,000	-0,025	0,000	0,013	-0,012
8000	0,011	0,014	-0,002	-0,013	0,006	0,019	0,020	-0,007	-0,016	0,007	-0,008	-0,033	-0,003	0,009	-0,011
10000	0,007	0,015	-0,003	-0,006	0,006	0,017	0,021	-0,009	-0,021	0,004	-0,011	-0,050	-0,006	0,017	-0,010
12500	0,004	0,014	0,000	0,002	0,007	0,014	0,022	-0,021	-0,031	0,002	-0,008	-0,069	-0,003	0,017	-0,006
16000	0,001	0,021	0,010	0,001	0,021	-0,001	0,018	-0,014	-0,071	-0,009	0,001	-0,082	-0,024	0,053	0,016
20000	-0,017	0,007	0,015	-0,052	0,036	0,023	0,027	-0,035	-0,083	0,008	0,038	-0,098	-0,007	0,036	0,027
25000	0,004	-0,009	-0,002	-	0,089	0,066	0,051	-0,014	-0,065	0,032	-0,223	-	-0,053	-0,042	0,096
31500	0,115	0,165	0,172	-	-	-1,099	-1,398	-	-	-1,500	-0,515	-	-	-	-1,795

Table 8 (a). Degrees of equivalence per laboratory and frequency: deviations (dB).

Frequency (Hz)	CENAM	CSIRO	DPLA	GUM	INMETRO	KRISS	LNE	NIM	NIST	NMIJ	NPL	NRC	PTB	UME	VNIIFTRI
31,5	0,041	0,052	0,069	-	0,051	0,053	0,035	0,071	0,072	0,276	0,053	-	0,033	0,071	0,128
63	0,043	0,034	0,033	0,045	0,040	0,035	0,029	0,044	0,054	0,091	0,025	0,044	0,035	0,072	0,063
125	0,052	0,035	0,024	0,045	0,041	0,025	0,026	0,044	0,054	0,082	0,025	0,044	0,035	0,073	0,035
250	0,052	0,035	0,025	0,045	0,040	0,026	0,026	0,045	0,035	0,082	0,026	0,035	0,035	0,073	0,035
500	0,052	0,035	0,025	0,045	0,040	0,026	0,026	0,045	0,035	0,082	0,026	0,035	0,035	0,073	0,035
1000	0,052	0,035	0,025	0,045	0,040	0,026	0,027	0,045	0,035	0,082	0,026	0,035	0,035	0,073	0,035
2000	0,052	0,035	0,025	0,045	0,040	0,026	0,028	0,045	0,035	0,082	0,026	0,035	0,035	0,073	0,035
4000	0,052	0,035	0,025	0,045	0,040	0,025	0,035	0,044	0,035	0,082	0,025	0,035	0,035	0,073	0,035
6300	0,052	0,035	0,024	0,045	0,042	0,025	0,046	0,044	0,045	0,082	0,035	0,035	0,035	0,073	0,035
8000	0,043	0,035	0,024	0,054	0,049	0,025	0,057	0,044	0,044	0,082	0,044	0,035	0,035	0,082	0,044
10000	0,042	0,044	0,023	0,063	0,067	0,034	0,072	0,044	0,053	0,082	0,053	0,091	0,053	0,091	0,053
12500	0,041	0,042	0,031	0,072	0,076	0,043	0,091	0,090	0,053	0,081	0,072	0,109	0,072	0,100	0,081
16000	0,059	0,041	0,040	0,080	0,104	0,051	0,127	0,090	0,071	0,080	0,090	0,127	0,109	0,108	0,118
20000	0,147	0,046	0,065	0,153	0,112	0,066	0,172	0,087	0,115	0,134	0,163	0,154	0,106	0,154	0,163
25000	0,180	0,059	0,116	-	0,147	0,176	0,262	0,101	0,233	0,167	0,606	-	0,127	0,179	0,282
31500	0,304	0,163	0,132	-	-	1,099	0,745	-	-	0,604	0,679	-	-	-	0,877

Table 8 (b). Degrees of equivalence per laboratory and frequency: uncertainties (dB), k = 2.

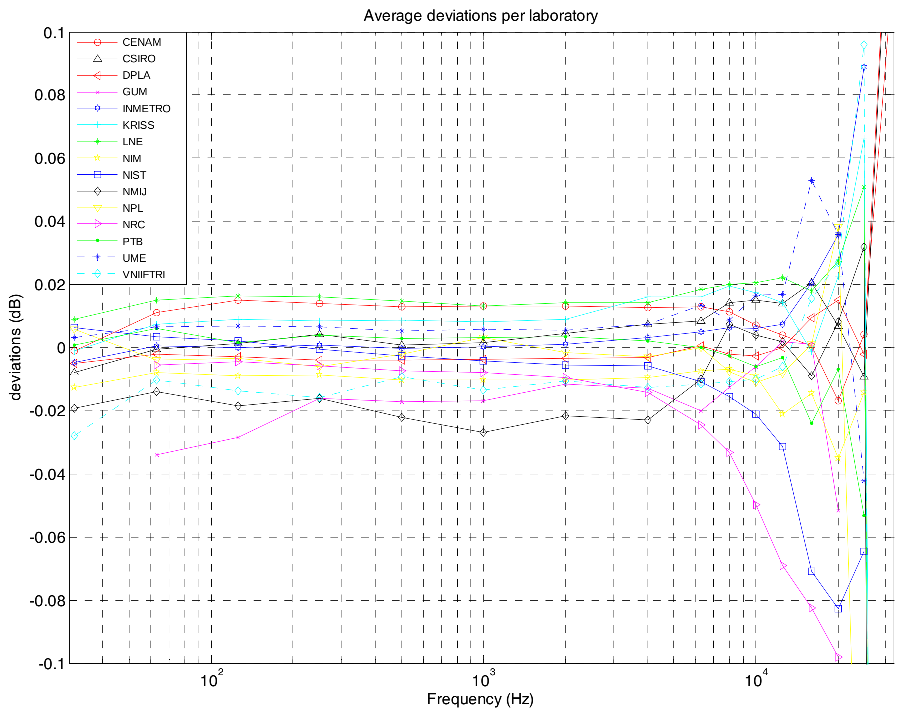

Figure 5(a). Deviations per laboratory and frequency (dB).

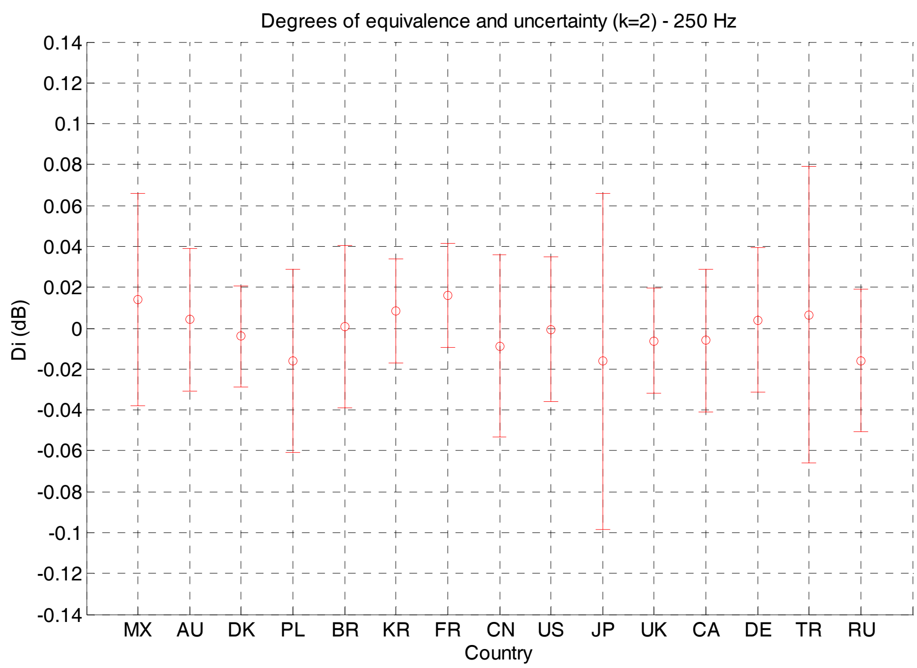

Figure 5 (b). Degrees of equivalence per laboratory at 250 Hz (dB).

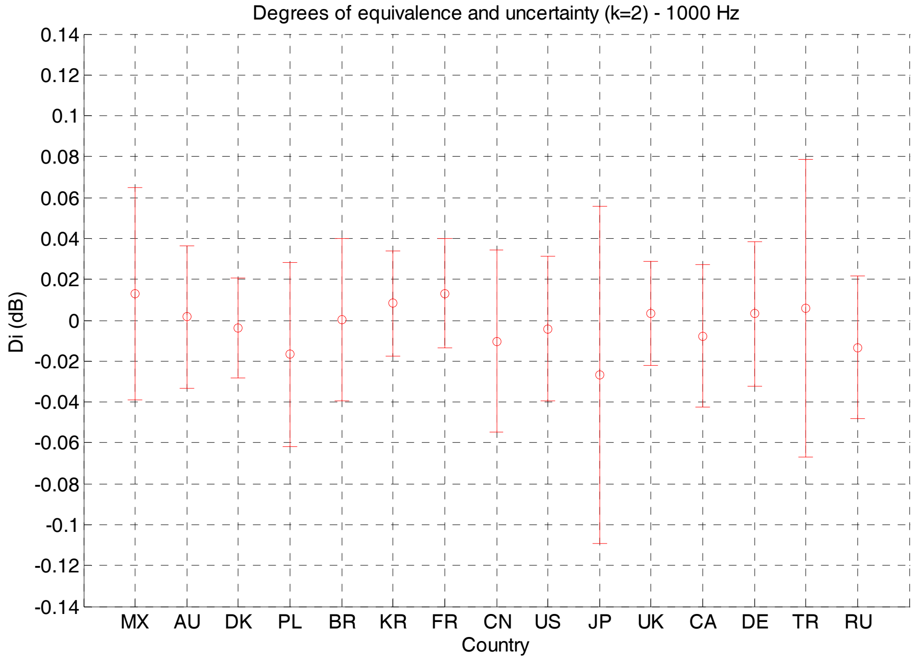

Figure 5 (c). Degrees of equivalence per laboratory at 1000 Hz (dB).

Although there is no significant difference in this case, the degrees of equivalence at 1000 Hz are supposed more adequate for LS2P microphone comparisons, for several reasons: lesser effect of power lines, use of 1 kHz calibrators and no A-weighting correction. These considerations do not necessarily hold for LS1P microphones, therefore 250 Hz is still recommended for LS1P. The 1000 Hz values in figure 5 (c) are therefore considered as the reference results of this comparison.

5.3. Inter-laboratory degrees of equivalence

Table 9 contains the inter-laboratory degrees of equivalence of this key comparison at 250 Hz and 1000 Hz. Again, 1000 Hz is considered a more suitable reference for LS2P microphones and therefore the results in table 9 (b) are considered as the reference for this comparison.

250 Hz	CENAM	CSIRO	DPLA	GUM	INMETRO	KRISS	LNE	NIM	NIST	NMIJ	NPL	NRC	PTB	UME	VNIIFTRI
CENAM	-	0,010	0,018	0,030	0,013	0,006	-0,002	0,023	0,015	0,030	0,020	0,020	0,010	0,007	0,030
CSIRO	0,064	-	-0,008	-0,020	0,003	0,004	0,012	0,013	-0,005	-0,020	-0,010	0,010	0,000	-0,003	0,020
DPLA	0,059	0,045	-	0,012	-0,005	-0,012	-0,020	0,005	-0,003	0,012	0,002	0,002	-0,008	-0,011	0,012
GUM	0,070	0,058	0,053	-	-0,017	-0,025	-0,032	-0,007	-0,016	0,000	-0,010	-0,010	-0,020	-0,023	0,000
INMETRO	0,067	0,056	0,049	0,061	-	0,008	0,015	0,010	-0,001	-0,017	-0,007	0,007	0,003	-0,006	0,017
KRISS	0,059	0,044	0,038	0,054	0,048	-	-0,008	0,017	0,009	0,025	0,015	0,014	0,005	0,002	0,024
LNE	0,059	0,044	0,038	0,054	0,048	0,039	-	0,025	0,017	0,032	0,022	0,022	0,012	0,009	0,032
NIM	0,070	0,059	0,053	0,064	0,062	0,052	0,052	-	0,008	-0,007	0,003	-0,003	0,013	-0,015	0,007
NIST	0,064	0,051	0,045	0,059	0,054	0,046	0,046	0,058	-	0,016	0,006	0,005	-0,005	-0,007	0,015
NMIJ	0,098	0,090	0,087	0,095	0,092	0,087	0,087	0,094	0,091	-	-0,010	-0,010	-0,020	-0,023	0,000
NPL	0,059	0,044	0,038	0,054	0,048	0,039	0,039	0,052	0,046	0,087	-	0,000	-0,010	-0,013	0,010
NRC	0,064	0,052	0,045	0,058	0,056	0,044	0,044	0,059	0,051	0,090	0,044	-	0,010	-0,013	0,010
PTB	0,064	0,051	0,045	0,059	0,054	0,046	0,046	0,058	0,052	0,091	0,046	0,051	-	-0,003	0,020
UME	0,091	0,082	0,078	0,086	0,085	0,078	0,078	0,087	0,082	0,110	0,078	0,082	0,082	-	0,023
VNIIFTRI	0,064	0,052	0,045	0,058	0,056	0,044	0,044	0,059	0,051	0,090	0,044	0,052	0,051	0,082	-

Table 9 (a). Inter-laboratory degrees of equivalence at 250 Hz. Upper triangle: differences. Lower triangle: uncertainties, k = 2.

1000 Hz	CENAM	CSIRO	DPLA	GUM	INMETRO	KRISS	LNE	NIM	NIST	NMIJ	NPL	NRC	PTB	UME	VNIIFTRI
CENAM	-	0,012	0,017	0,030	0,013	0,005	0,000	0,024	0,017	0,040	0,010	0,021	0,010	0,008	0,027
CSIRO	0,064	-	-0,005	-0,018	0,002	0,007	0,012	0,012	-0,006	-0,028	0,002	0,010	0,002	-0,004	0,015
DPLA	0,059	0,045	-	0,013	-0,004	-0,012	-0,017	0,007	0,000	0,023	-0,007	0,004	-0,007	-0,009	0,010
GUM	0,070	0,058	0,053	-	-0,017	-0,025	-0,030	-0,006	-0,013	0,010	-0,020	-0,009	-0,020	-0,022	-0,003
INMETRO	0,067	0,056	0,049	0,061	-	0,008	0,013	0,011	-0,004	-0,027	0,003	0,008	0,003	-0,006	0,014
KRISS	0,059	0,044	0,038	0,054	0,048	-	-0,005	0,019	0,013	0,035	0,005	0,016	0,005	0,003	0,022
LNE	0,060	0,045	0,038	0,054	0,049	0,040	-	0,024	0,018	0,040	0,010	0,021	0,010	0,008	0,027
NIM	0,070	0,059	0,053	0,064	0,062	0,052	0,053	-	0,006	-0,016	0,014	-0,003	0,014	-0,016	0,003
NIST	0,064	0,051	0,045	0,059	0,054	0,046	0,047	0,058	-	0,023	-0,008	0,004	-0,008	-0,010	0,009
NMIJ	0,098	0,090	0,087	0,095	0,092	0,087	0,088	0,094	0,091	-	-0,030	-0,019	-0,030	-0,032	-0,013
NPL	0,059	0,044	0,038	0,054	0,048	0,039	0,040	0,052	0,046	0,087	-	0,011	0,000	-0,002	0,017
NRC	0,064	0,052	0,045	0,058	0,056	0,044	0,045	0,059	0,051	0,090	0,044	-	0,011	-0,014	0,006
PTB	0,064	0,051	0,045	0,059	0,054	0,046	0,047	0,058	0,052	0,091	0,046	0,051	-	-0,002	0,017
UME	0,091	0,082	0,078	0,086	0,085	0,078	0,078	0,087	0,082	0,110	0,078	0,082	0,082	-	0,019
VNIIFTRI	0,064	0,052	0,045	0,058	0,056	0,044	0,045	0,059	0,051	0,090	0,044	0,052	0,051	0,082	-

Table 9 (b). Inter-laboratory degrees of equivalence at 1000 Hz. Upper triangle: differences. Lower triangle: uncertainties, k = 2.

6. RECALCULATION OF RESULTS

As a result of the discussion that took place after the measurement phase, it was decided to run an experiment. The laboratories would recalculate their results using a common set of microphone parameters. The motivation was to investigate the effect of removing parameter estimation from the results. The chosen set of parameters was supplied by DPLA. The outcome of this exercise is included in Appendix B.

7. CONCLUSIONS

In this CCAUV.A-K3 comparison, the existence of two loops with two different sets of circulating standards has been a novelty in the series of CCAUV key comparisons. The analysis of the results has been challenging and raises some new questions that should be considered carefully in future comparisons:

- The correlation between measurement results from the same laboratory or different laboratories should be estimated as carefully as possible. In this comparison, a figure of 0,7 was used for measurements by the same laboratory. This figure is based on the results of consistency and equivalence tests.
- The laboratories participating in all loops are fundamental to provide a link. There should be a sufficient number of them.
- An elaborate analysis is required to reach a single degree of equivalence per laboratory and pair of laboratories. The whole process may imply larger uncertainties, but this is the price to pay for a shorter and simpler measurement phase with more participants and less danger of drifts in the standards.

The results of the comparison are in general quite satisfactory. They are close enough to make the use of three decimal places desirable. The protocol recommended that no grease should be used to seal couplers and microphones. Each laboratory followed this recommendation, which has proved to be a good choice, as shown by the results.

8. ACKNOWLEDGEMENT

The authors wish to thank Lars Nielsen from the Danish Institute of Fundamental Metrology for the useful advice about methods for comparison analysis.

9. REFERENCES

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APPENDIX A - NPL corrections to reported results

The corrections to reported data requested by NPL are listed below. Table A-1 contains the original and revised sensitivities of the two microphones, table A-2 has the original and corrected measured effective volumes and table A-3 has the original and corrected values of the capillary corrections.

The reasons given by NPL for this correction are two:

- A defective piece of equipment led to an incorrect determination of the effective volumes of the microphones.
- Capillary corrections were derived from software under development instead of validated software.

Frequency (Hz)	Sensitivity level (dB)			
	4180 1395456		4180 1627783	
	original	revised	original	revised
31,5	-38,34	-38,36	-38,70	-38,72
63	-38,42	-38,41	-38,75	-38,74
125	-38,45	-38,44	-38,77	-38,75
250	-38,48	-38,46	-38,79	-38,77
500	-38,50	-38,48	-38,79	-38,77
1000	-38,50	-38,48	-38,80	-38,77
2000	-38,49	-38,47	-38,77	-38,75
4000	-38,36	-38,34	-38,67	-38,65
5000	-38,26	-38,25	-38,59	-38,58
6300	-38,11	-38,09	-38,47	-38,45
8000	-37,88	-37,86	-38,30	-38,29
10000	-37,59	-37,58	-38,11	-38,10
12500	-37,34	-37,34	-37,97	-37,96
16000	-37,57	-37,58	-38,21	-38,22
20000	-39,02	-39,07	-39,31	-39,37
25000	-41,93	-42,28	-41,32	-41,64
31500	-45,50	-45,40	-45,24	-45,13

Table A-1. Original and revised sensitivity level data for the two microphones

Microphone	Original volume measurement (mm^3)	Revised volume measurement (mm^3)
4180 1395456	42,96	44,03
4180 1627783	39,41	40,52

Table A-2. Original and revised effective volumes for the two microphones.

Frequency (Hz)	Original capillary correction (dB)	Revised capillary correction (dB)
31,5	0,037	0,070
63	0,001	0,013
125	-0,009	-0,004
250	-0,010	-0,009
500	-0,007	-0,007
1000	0,000	0,000
2000	0,006	0,007
4000	0,000	0,000
5000	0,001	0,002
6300	0,000	0,000
8000	0,001	0,001
10000	0,000	0,000
12500	0,000	0,000
16000	0,000	0,000
20000	0,000	0,000
25000	0,000	0,000
31500	0,000	0,000

Table A-3. Original and revised capillary correction used in the analysis.

APPENDIX B – Recalculation of measurement results

During the 3rd CCAUV meeting in September 2004, the CCAUV.A-K3 participants decided that the laboratories would recalculate their measurement results with a unique set of microphone parameters. This does not imply new measurements; the existing results held by every laboratory would just be processed using a single set of parameters.

Microphone parameters

The purpose of the exercise is to remove the effect of the different parameter estimation methods, and examine its influence. The set of parameters employed was supplied by DPLA and is listed in table B-1.

Microphone	Front cavity depth (mm)	Equivalent volume (mm^3)	Front volume (mm^3)	Resonance frequency (kHz)	Loss factor	Temperature coefficient at 250 Hz (dB/K)	Pressure coefficient at 250 Hz (dB/kPa)
4180.1395456	0,514	9,30	34,60	21,20	0,98	0,0004	-0,00594
4180.1627783	0,469	8,50	31,70	22,70	1,05	-0,0031	-0,00537
4180.1124046	0,481	9,20	32,60	23,50	1,10	-0,0031	-0,00577
4180.1395455	0,488	9,60	33,00	21,80	1,03	-0,0015	-0,00570

Table B-1.DPLA set of microphone parameters used for the recalculation.

The values of acoustic mass, acoustic compliance and acoustic resistance have been calculated using equations (1) in this report, for those laboratories needing microphone parameters in this form. They are listed in table B-2.

Microphone	Acoustic mass (kg/m^4)	Acoustic compliance (m^5/N)	Acoustic resistance ($N{\cdot}s/m^5$)
4180.1395456	860,1	$6{,}552\cdot10^{-14}$	$1{,}123\cdot10^{8}$
4180.1627783	820,8	$5{,}989\cdot10^{-14}$	$1{,}229\cdot10^{8}$
4180.1124046	707,6	$6{,}482\cdot10^{-14}$	$1{,}149\cdot10^{8}$
4180.1395455	788,0	$6{,}764\cdot10^{-14}$	$1{,}112\cdot10^{8}$

Table B-2.DPLA converted microphone parameters.

Reported recalculated results

The reported recalculated results are listed in table B-3. The DPLA column is filled with its original results.

Frequency (Hz)	CENAM	DPLA	GUM	KRISS	LNE	NIST	NMIJ	NPL	PTB
31,5	-38,368	-38,378		-38,372	-38,375	-38,369	-38,40	-38,358	-38,378
63	-38,397	-38,408	-38,42	-38,395	-38,398	-38,402	-38,42	-38,413	-38,406
125	-38,422	-38,436	-38,44	-38,421	-38,425	-38,430	-38,46	-38,439	-38,434
250	-38,446	-38,459	-38,45	-38,444	-38,448	-38,457	-38,48	-38,461	-38,457
500	-38,465	-38,479	-38,48	-38,464	-38,467	-38,479	-38,50	-38,478	-38,478
1000	-38,477	-38,489	-38,48	-38,475	-38,480	-38,492	-38,52	-38,485	-38,488
2000	-38,461	-38,470	-38,46	-38,455	-38,461	-38,475	-38,50	-38,470	-38,469
4000	-38,335	-38,342	-38,33	-38,321	-38,334	-38,349	-38,37	-38,343	-38,341
6300	-38,083	-38,085	-38,09	-38,067	-38,083	-38,105	-38,11	-38,088	-38,084
8000	-37,849	-37,851	-37,85	-37,828	-37,846	-37,875	-37,86	-37,857	-37,848
10000	-37,568	-37,567	-37,57	-37,547	-37,564	-37,599	-37,57	-37,576	-37,564
12500	-37,331	-37,322	-37,33	-37,311	-37,328	-37,369	-37,33	-37,342	-37,319
16000	-37,590	-37,559	-37,58	-37,586	-37,584	-37,650	-37,59	-37,603	-37,593
20000	-39,082	-39,050	-39,01	-39,089	-39,055	-39,149	-39,06	-39,066	-39,061
25000	-41,757	-41,764		-41,881	-41,715	-41,792	-41,72	-41,429	-41,782
31500	-44,701	-44,687		-45,533			-46,51	-45,474	

Table B-3 (a). Recalculated pressure sensitivity (dB re 1 V/Pa) for microphone 4180 1395456.

Frequency (Hz)	CENAM	DPLA	GUM	KRISS	LNE	NIST	NMIJ	NPL	PTB
31,5	-38,747	-38,724		-38,713	-38,720	-38,721	-38,75	-38,722	-38,724
63	-38,744	-38,741	-38,76	-38,722	-38,735	-38,744	-38,76	-38,745	-38,737
125	-38,752	-38,757	-38,78	-38,735	-38,749	-38,760	-38,77	-38,760	-38,754
250	-38,762	-38,771	-38,78	-38,748	-38,761	-38,774	-38,79	-38,772	-38,768
500	-38,770	-38,779	-38,78	-38,757	-38,771	-38,783	-38,80	-38,778	-38,777
1000	-38,772	-38,780	-38,78	-38,758	-38,773	-38,785	-38,81	-38,780	-38,780
2000	-38,750	-38,758	-38,75	-38,736	-38,751	-38,764	-38,79	-38,754	-38,759
4000	-38,644	-38,653	-38,66	-38,625	-38,645	-38,656	-38,68	-38,652	-38,655
6300	-38,449	-38,457	-38,47	-38,430	-38,444	-38,473	-38,47	-38,453	-38,460
8000	-38,277	-38,290	-38,29	-38,254	-38,272	-38,304	-38,28	-38,286	-38,289
10000	-38,083	-38,095	-38,09	-38,062	-38,076	-38,111	-38,09	-38,093	-38,099
12500	-37,948	-37,958	-37,95	-37,932	-37,934	-37,982	-37,96	-37,965	-37,968
16000	-38,221	-38,210	-38,21	-38,231	-38,205	-38,295	-38,23	-38,255	-38,259
20000	-39,465	-39,438	-39,39	-39,479	-39,425	-39,524	-39,43	-39,455	-39,465
25000	-41,686	-41,716		-41,867	-41,617	-41,768	-41,73	-41,465	-41,758
31500	-44,415	-44,443		-45,009			-45,98	-45,018	

Table B-3 (b). Recalculated pressure sensitivity (dB re 1 V/Pa) for microphone 4180 1627783.

Frequency (Hz)	CENAM	CSIRO	DPLA	INMETRO	NIM	NRC	UME	VNIIFTRI
31,5	-38,057	-38,079	-38,056	-38,064	-38,086		-38,061	-38,087
63	-38,073	-38,099	-38,079	-38,085	-38,107	-38,089	-38,084	-38,097
125	-38,085	-38,111	-38,092	-38,100	-38,123	-38,102	-38,098	-38,111
250	-38,093	-38,121	-38,103	-38,110	-38,133	-38,114	-38,108	-38,119
500	-38,098	-38,127	-38,108	-38,116	-38,140	-38,122	-38,114	-38,128
1000	-38,099	-38,126	-38,107	-38,116	-38,140	-38,122	-38,114	-38,127
2000	-38,080	-38,107	-38,088	-38,096	-38,121	-38,104	-38,095	-38,108
4000	-37,995	-38,020	-38,003	-38,010	-38,034	-38,025	-38,008	-38,022
6300	-37,840	-37,864	-37,846	-37,853	-37,876	-37,881	-37,847	-37,866
8000	-37,711	-37,731	-37,720	-37,722	-37,743	-37,762	-37,719	-37,731
10000	-37,576	-37,591	-37,584	-37,581	-37,602	-37,640	-37,571	-37,592
12500	-37,517	-37,521	-37,519	-37,514	-37,553	-37,596	-37,500	-37,523
16000	-37,856	-37,834	-37,873	-37,839	-37,877	-37,943	-37,806	-37,845
20000	-39,057	-39,001	-39,020	-39,001	-39,052	-39,134	-38,982	-39,016
25000	-41,190	-41,194	-41,209	-41,135	-41,174		-41,206	-41,141
31500	-44,069	-43,797	-43,914					-45,298

Table B-3 (c). Recalculated pressure sensitivity (dB re 1 V/Pa) for microphone 4180 1124046.

Frequency (Hz)	CENAM	CSIRO	DPLA	INMETRO	NIM	NRC	UME	VNIIFTRI
31,5	-38,357	-38,366	-38,348	-38,351	-38,367		-38,349	-38,360
63	-38,377	-38,388	-38,372	-38,374	-38,391	-38,379	-38,373	-38,374
125	-38,395	-38,405	-38,392	-38,394	-38,411	-38,399	-38,392	-38,392
250	-38,408	-38,419	-38,409	-38,408	-38,426	-38,415	-38,407	-38,407
500	-38,419	-38,430	-38,417	-38,418	-38,437	-38,424	-38,417	-38,417
1000	-38,419	-38,429	-38,419	-38,419	-38,438	-38,427	-38,419	-38,418
2000	-38,394	-38,403	-38,394	-38,393	-38,413	-38,403	-38,393	-38,393
4000	-38,274	-38,281	-38,274	-38,271	-38,291	-38,288	-38,271	-38,273
6300	-38,046	-38,053	-38,047	-38,044	-38,062	-38,074	-38,038	-38,048
8000	-37,845	-37,848	-37,851	-37,843	-37,860	-37,884	-37,843	-37,850
10000	-37,618	-37,615	-37,623	-37,612	-37,627	-37,670	-37,600	-37,623
12500	-37,457	-37,448	-37,462	-37,450	-37,481	-37,526	-37,428	-37,465
16000	-37,788	-37,774	-37,783	-37,778	-37,807	-37,876	-37,737	-37,793
20000	-39,208	-39,206	-39,202	-39,181	-39,233	-39,278	-39,158	-39,197
25000	-41,692	-41,734	-41,755	-41,618	-41,647		-41,705	-41,652
31500	-44,502	-44,517	-44,508					-46,585

Table B-3 (d). Recalculated pressure sensitivity (dB re 1 V/Pa) for microphone 4180 1395455.

Conversion of results at exact frequencies to nominal frequencies

A correction was applied to the results reported by the LNE, NIM and the INMETRO at exact frequencies in order to convert the measurements to nominal frequencies. The process is the same used for the first reported results, already described in subsection 3.2 of this report. Table B-4 lists the corrections added to the reported recalculations to produce the consistent data in table B-3.

Nominal frequency (Hz)	LNE			NIM			INMETRO		
	Reported frequency (Hz)	Correction to reported sensitivity (x0,01 dB)		Reported frequency (Hz)	Correction to reported sensitivity (x0,01 dB)		Reported frequency (Hz)	Correction to reported sensitivity (x0,01 dB)	
		4180 1395456	4180 1627783		4180 1124046	4180 1395455		4180 1124046	4180 1395455
31,5	31,62	0,0000	0,0000	31,62	0,0000	0,0000	31,62	0,0000	0,0000
63	63,09	0,0000	0,0000	63,1	0,0000	0,0000	63,1	0,0000	0,0000
125	125,88	0,0000	0,0000	125,89	0,0000	0,0000	125,89	0,0000	0,0000
250	251,17	0,0000	0,0000	251,19	0,0000	0,0000	251,19	0,0000	0,0000
500	501,14	0,0000	0,0000	501,19	0,0000	0,0000	501,19	0,0000	0,0000
1000	999,9	0,0000	0,0000	1000	0,0000	0,0000	1000	0,0000	0,0000
2000	1995,1	0,0000	0,0000	1995,3	0,0000	0,0000	1995,3	0,0000	0,0000
4000	3980,7	0,2000	0,1000	3981,1	0,1000	0,2000	3981,1	0,1000	0,2000
6300	6309	-0,1000	-0,1000	6309,6	-0,1000	-0,1000	6309,6	-0,1000	-0,1000
8000	7942,5	0,8000	0,6000	7943,3	0,4000	0,7000	7943,3	0,4000	0,7000
10000	9999	0,0000	0,0000	10000	0,0000	0,0000	10000	0,0000	0,0000
12500	12588	-0,4000	-0,1000	12589	0,1000	-0,1000	12589	0,1000	-0,1000
16000	15847	-3,2000	-2,7000	15849	-2,8000	-3,3000	15849	-2,8000	-3,3000
20000	19951	-2,4000	-2,0000	19953	-1,8000	-2,2000	19953	-1,8000	-2,2000
25000	25116	6,2000	5,4000	25119	5,4000	5,9000	25119	5,4000	5,9000

Table B-4. Correction of sensitivity results from exact to nominal frequencies.

Discussion

The recalculated results have been processed using the method described in this report, linear least squares and averaging. Table B-5 contains the reference values obtained for the four microphones, using the recalculated results. Figure B-1 shows the new deviations per microphone, that is, the reported results in table B-3 minus the reference values in table B-5. Table B-6 lists the new degrees of equivalence per laboratory, which are plotted in figure B-2. The data presented here should be compared with the results in subsections 5.1 and 5.2.

For a number of laboratories, the recalculated deviations turn out to be smaller. However, this is not the general rule. The uncertainty of this measurement is the result of the contributions from several independent groups of factors: pure electrical measurements, electrical impedance value, coupler dimensions, calculation procedure, environmental conditions, polarising voltage, skill and experience of the operator, and finally the microphone parameters. Only the latter group has been isolated with this exercise.

Frequency (Hz)	4180.1395456		4180.1627783		4180.1124046		4180.1395455	
	Sensiti-vity	Uncerta-inty, *k* = 2	Sensiti-vity	Uncerta-inty, *k* = 2	Sensiti-vity	Uncerta-inty, *k* = 2	Sensiti-vity	Uncerta-inty, *k* = 2
31,5	-38,375	0,019	-38,728	0,019	-38,062	0,022	-38,352	0,022
63	-38,408	0,013	-38,743	0,013	-38,087	0,015	-38,377	0,015
125	-38,434	0,012	-38,756	0,012	-38,099	0,014	-38,394	0,014
250	-38,456	0,012	-38,769	0,012	-38,109	0,013	-38,409	0,013
500	-38,477	0,012	-38,777	0,012	-38,116	0,013	-38,418	0,013
1000	-38,487	0,012	-38,779	0,012	-38,115	0,013	-38,420	0,013
2000	-38,469	0,012	-38,756	0,012	-38,096	0,013	-38,395	0,013
4000	-38,341	0,012	-38,651	0,012	-38,011	0,013	-38,275	0,013
6300	-38,088	0,013	-38,456	0,013	-37,856	0,014	-38,049	0,014
8000	-37,852	0,013	-38,284	0,013	-37,726	0,014	-37,851	0,014
10000	-37,569	0,016	-38,090	0,016	-37,586	0,016	-37,620	0,016
12500	-37,330	0,019	-37,955	0,019	-37,523	0,020	-37,460	0,020
16000	-37,581	0,024	-38,225	0,024	-37,865	0,024	-37,794	0,024
20000	-39,068	0,036	-39,454	0,036	-39,026	0,034	-39,213	0,034
25000	-41,753	0,061	-41,720	0,061	-41,194	0,049	-41,711	0,049
31500	-44,822	0,146	-44,537	0,146	-43,993	0,133	-44,627	0,133

Table B-5. Recalculated reference values of the four microphones (dB re 1 V/Pa).

In the general case, one can conclude that those laboratories showing a clear improvement in their recalculated result can consider their parameter estimation as a major uncertainty contribution. On the other hand, if no improvement is observed, other sources of uncertainty must be examined rather than parameter estimation.

The results of the exercise do not allow clear and general conclusions. However, the data obtained provides information to all laboratories to help isolate uncertainty contributions.

It is expected that the results of this exercise will be used in the future to analyze different aspects of the calibration methods employed. The amount of data collected should make it possible to study the effect of a particular practice or equipment on the results. However, extending the analysis here would fall outside the scope of this report and therefore we will leave it to new contributions.

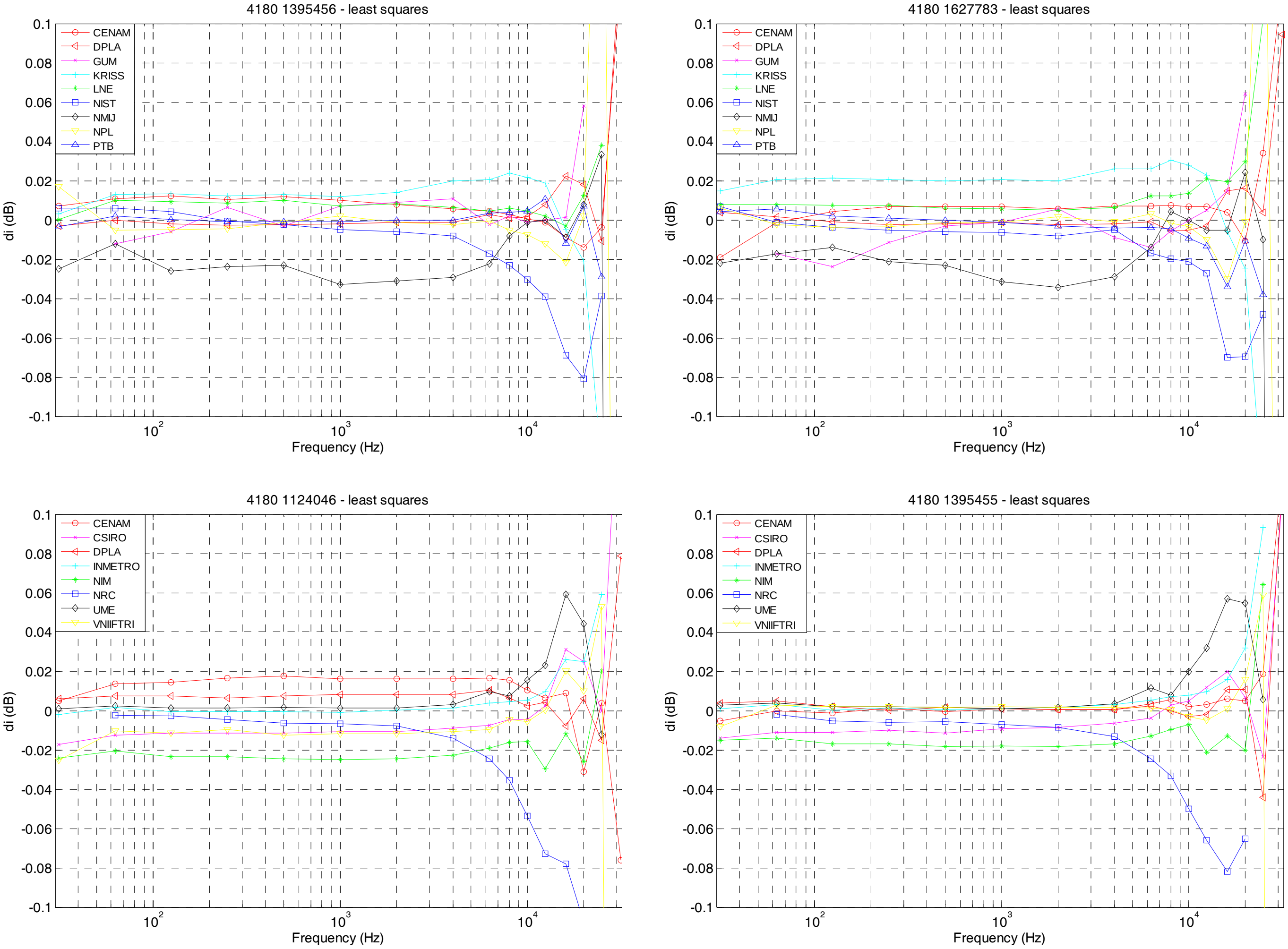

Figure B-1. Deviations of the recalculated measurements.

Frequency (Hz)	CENAM	CSIRO	DPLA	GUM	INMETRO	KRISS	LNE	NIM	NIST	NMIJ	NPL	NRC	PTB	UME	VNIIFTRI
31,5	-0,003	-0,016	0,003	-	-0,001	0,009	0,004	-0,020	0,006	-0,024	0,011	-	0,000	0,002	-0,017
63	0,006	-0,012	0,003	-0,015	0,002	0,017	0,009	-0,017	0,002	-0,015	-0,004	-0,002	0,004	0,003	-0,004
125	0,007	-0,011	0,002	-0,015	0,000	0,017	0,008	-0,020	0,000	-0,020	-0,004	-0,004	0,001	0,002	-0,005
250	0,009	-0,011	0,000	-0,003	0,000	0,016	0,008	-0,020	-0,003	-0,023	-0,004	-0,005	0,000	0,002	-0,004
500	0,009	-0,011	0,001	-0,003	0,000	0,016	0,008	-0,021	-0,004	-0,023	-0,001	-0,006	-0,001	0,002	-0,005
1000	0,008	-0,010	0,001	0,003	0,000	0,016	0,006	-0,021	-0,006	-0,032	0,000	-0,007	-0,001	0,001	-0,005
2000	0,008	-0,010	0,001	0,007	0,001	0,017	0,006	-0,021	-0,007	-0,033	0,000	-0,008	-0,002	0,001	-0,005
4000	0,007	-0,008	0,001	0,001	0,002	0,023	0,006	-0,020	-0,007	-0,029	-0,002	-0,014	-0,002	0,003	-0,005
6300	0,008	-0,006	0,004	-0,008	0,004	0,023	0,008	-0,016	-0,017	-0,018	0,001	-0,025	0,000	0,010	-0,004
8000	0,008	-0,001	0,000	-0,002	0,006	0,027	0,009	-0,013	-0,021	-0,002	-0,003	-0,034	0,000	0,008	-0,002
10000	0,005	0,000	-0,001	-0,001	0,007	0,025	0,009	-0,011	-0,026	-0,001	-0,005	-0,052	-0,002	0,018	-0,004
12500	0,004	0,007	0,002	0,002	0,010	0,021	0,011	-0,025	-0,033	-0,003	-0,011	-0,069	-0,001	0,028	-0,002
16000	0,002	0,025	0,010	0,008	0,021	-0,005	0,008	-0,013	-0,069	-0,007	-0,026	-0,080	-0,023	0,058	0,010
20000	-0,013	0,016	0,013	0,061	0,029	-0,023	0,021	-0,023	-0,075	0,016	0,001	-0,087	-0,002	0,049	0,013
25000	0,013	-0,012	-0,017	-	0,076	-0,137	0,071	0,042	-0,043	0,012	0,290	-	-0,033	-0,003	0,056
31500	0,073	0,153	0,107	-	-	-0,591	-	-	-	-1,565	-0,566	-	-	-	-1,632

Table B-6 (a). Recalculated degrees of equivalence per laboratory and frequency: deviations (dB).

Frequency (Hz)	CENAM	CSIRO	DPLA	GUM	INMETRO	KRISS	LNE	NIM	NIST	NMIJ	NPL	NRC	PTB	UME	VNIIFTRI
31,5	0,041	0,052	0,069	-	0,051	0,053	0,035	0,071	0,072	0,276	0,053	-	0,033	0,071	0,128
63	0,043	0,034	0,033	0,045	0,040	0,035	0,029	0,044	0,054	0,091	0,025	0,044	0,035	0,072	0,063
125	0,052	0,035	0,024	0,045	0,041	0,025	0,026	0,044	0,054	0,082	0,025	0,044	0,035	0,073	0,035
250	0,052	0,035	0,025	0,045	0,040	0,026	0,026	0,045	0,035	0,082	0,026	0,035	0,035	0,073	0,035
500	0,052	0,035	0,025	0,045	0,040	0,026	0,026	0,045	0,035	0,082	0,026	0,035	0,035	0,073	0,035
1000	0,052	0,035	0,025	0,045	0,040	0,026	0,027	0,045	0,035	0,082	0,026	0,035	0,035	0,073	0,035
2000	0,052	0,035	0,025	0,045	0,040	0,026	0,028	0,045	0,035	0,082	0,026	0,035	0,035	0,073	0,035
4000	0,052	0,035	0,025	0,045	0,040	0,025	0,035	0,044	0,035	0,082	0,025	0,035	0,035	0,073	0,035
6300	0,052	0,035	0,024	0,045	0,042	0,025	0,046	0,044	0,045	0,082	0,035	0,035	0,035	0,073	0,035
8000	0,043	0,035	0,024	0,054	0,049	0,025	0,057	0,044	0,044	0,082	0,044	0,035	0,035	0,082	0,044
10000	0,042	0,044	0,023	0,063	0,067	0,034	0,072	0,044	0,053	0,082	0,053	0,091	0,053	0,091	0,053
12500	0,041	0,042	0,031	0,072	0,076	0,043	0,091	0,090	0,053	0,081	0,072	0,109	0,072	0,100	0,081
16000	0,059	0,041	0,040	0,080	0,104	0,051	0,127	0,090	0,071	0,080	0,090	0,127	0,109	0,108	0,118
20000	0,147	0,046	0,065	0,153	0,112	0,066	0,172	0,087	0,115	0,134	0,163	0,154	0,106	0,154	0,163
25000	0,180	0,059	0,116	-	0,147	0,176	0,262	0,101	0,233	0,167	0,606	-	0,127	0,179	0,282
31500	0,304	0,162	0,131	-	-	1,099	-	-	-	0,604	0,679	-	-	-	0,877

Table B-6 (b). Recalculated degrees of equivalence per laboratory and frequency: uncertainties (dB), k=2.

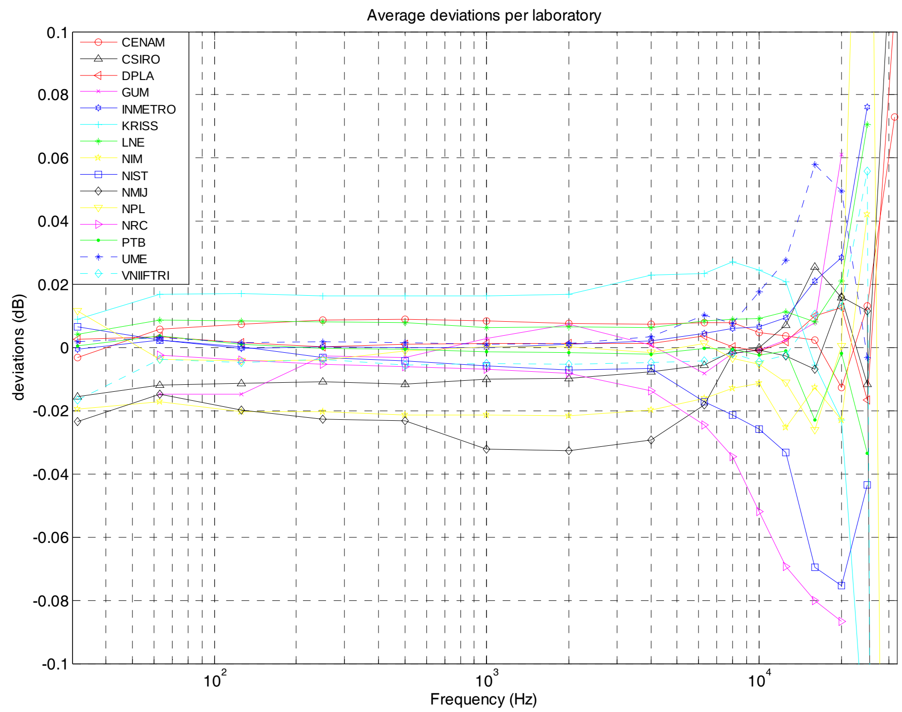

Figure B-2(a). Recalculated results: deviations per laboratory and frequency (dB).

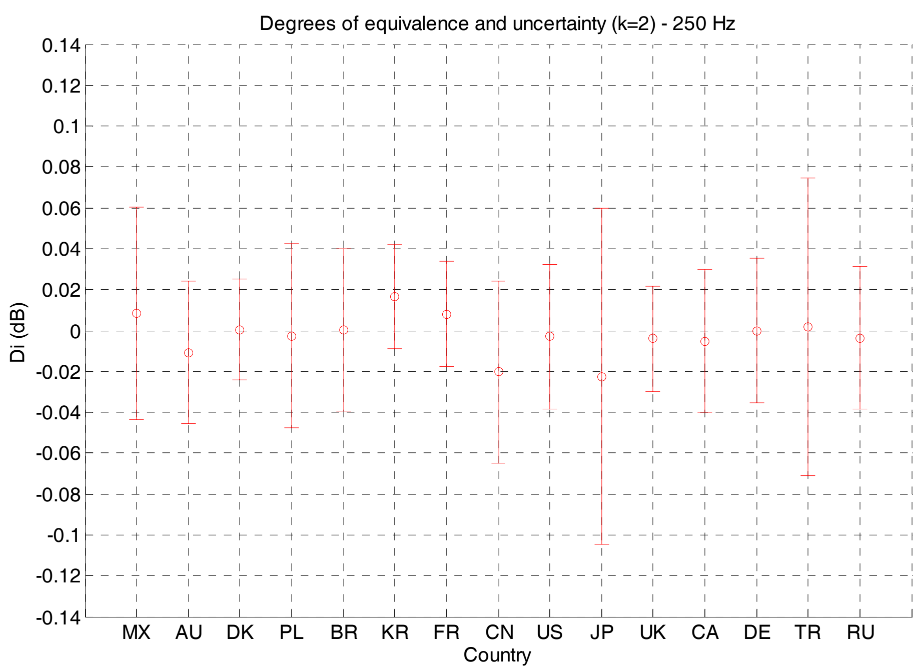

Figure B-2 (b). Recalculated results: degrees of equivalence per laboratory at 250 Hz (dB).

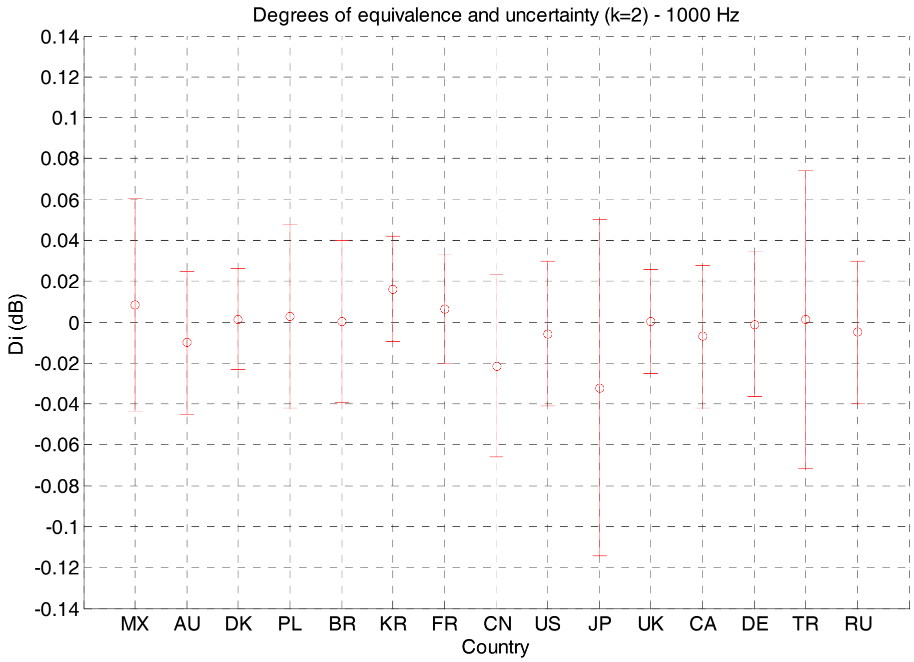

Figure B-2 (c). Recalculated results: degrees of equivalence per laboratory at 1000 Hz (dB).

APPENDIX C – Uncertainty budgets

Uncertainty budgets were requested of the participants in the protocol. They are reproduced here as they were received by the pilot laboratory.

CENAM: Summary of uncertainty analysis for LS2P microphones

	Measurement quantities							Microphone quantities							Coupler quantities				Capillary tubes		Others			
	Voltage ratios, R_{ij}	Ref. capacitor, C	Ref. resistor, R	Stattic pressure, p_s	Temperature, T	Relative Humidity, RH	Frequency, f	Front Volume, V_f	Cavity depth, l_f	Equivalent volume, V_e	Resonance frequency, f_0	Loss factor, d	Static pressure Coeff, C_{ps}	Temperature Coeff, C_t	Coupler length, l_{cpl}	Coupler diameter, D_{cpl}	Coupler volume, V_{cpl}	Coupler Surface, S_{cpl}	capillary tube length, l_{ct}	capillary tube diameter, D_{ct}	Polarization voltage, V_{pol}	Combined std uncertainty Type B	Std uncertainty Type A	Expanded uncertainty, $U_{95,45}$, k=2
0,0315	8,91	1,46	1,19	3,15	1,09	1,09	1,27	206,99	6,05	130,55	1,11	1,16	1,25	8,61	10,56	13,03	1,93	2,02	2,24	104,64	13,00	0,027	0,0044	0,05
0,0630	8,84	1,39	1,05	3,50	1,03	1,03	1,10	228,22	4,45	138,65	1,05	1,10	1,20	8,54	10,95	13,40	1,60	1,66	1,18	15,13	13,00	0,027	0,0017	0,05
0,1250	8,76	1,31	0,95	3,63	0,94	0,94	0,98	237,54	3,29	141,79	0,97	1,02	1,12	8,46	11,01	13,43	1,34	1,38	1,32	11,04	13,00	0,028	0,0024	0,06
0,2500	8,57	1,11	0,75	3,79	2,95	1,55	0,77	263,55	2,64	153,07	0,77	0,82	0,98	8,02	11,63	13,05	1,07	1,08	1,38	16,50	13,00	0,031	0,0026	0,06
0,5000	8,49	1,04	0,68	3,81	2,75	1,42	0,68	265,89	1,97	153,51	0,68	0,70	0,92	7,95	11,54	12,95	0,90	0,91	1,25	10,57	13,00	0,031	0,0032	0,06
1,0000	8,52	1,06	0,74	3,73	2,74	1,40	0,70	266,24	1,59	153,29	0,77	0,90	0,93	7,97	11,50	12,94	0,85	0,86	1,09	2,13	13,00	0,031	0,0037	0,06
2,0000	8,38	0,93	0,57	3,89	3,00	1,28	0,59	264,32	1,12	152,06	1,21	2,11	0,80	7,84	11,26	12,80	0,68	0,68	0,82	2,25	13,00	0,031	0,0039	0,06
4,0000	8,29	0,84	0,47	4,16	4,51	1,24	0,56	256,64	0,59	148,16	4,71	10,35	0,70	7,74	10,84	12,84	0,55	0,55	0,70	0,72	13,00	0,030	0,0038	0,06
6,3000	8,20	0,75	0,38	4,54	6,04	1,30	0,63	238,24	0,54	139,12	47,28	24,71	0,63	7,66	10,05	12,98	0,45	0,45	0,46	0,43	13,00	0,028	0,0032	0,06
8,0000	8,21	0,75	0,39	4,85	8,17	1,40	0,77	218,32	0,72	129,30	52,68	36,29	0,63	7,66	9,31	13,22	0,44	0,45	0,54	0,48	13,00	0,026	0,0026	0,05
10,0000	8,17	0,78	0,39	5,80	42,00	1,70	2,50	187,01	1,38	114,10	81,12	46,50	0,59	7,63	8,11	13,57	0,41	0,41	0,37	0,45	13,00	0,024	0,0030	0,05
12,5000	8,14	0,76	0,33	5,83	45,00	1,83	2,71	172,77	2,42	89,85	90,72	45,00	0,57	7,60	6,11	14,17	0,37	0,38	0,39	0,50	13,00	0,023	0,0057	0,05
16,0000	8,12	0,78	0,30	5,60	50,00	2,32	5,08	123,93	3,68	53,61	74,65	20,00	0,54	7,58	4,05	15,35	0,34	0,35	0,35	0,34	13,00	0,017	0,0296	0,07
20,0000	8,09	0,81	0,28	3,62	46,00	3,03	9,84	316,01	4,20	52,59	282,35	42,93	0,51	7,55	12,82	17,38	0,31	0,31	0,33	0,35	13,00	0,043	0,0737	0,17
25,0000	8,03	0,88	0,21	0,34	35,00	5,56	14,61	635,46	6,53	132,16	374,56	150,66	0,43	7,22	24,47	19,83	0,24	0,24	0,23	0,26	13,00	0,077	0,0687	0,21
31,5000	8,15	0,75	0,33	1,83	44,00	14,40	24,66	1343,17	28,81	274,39	270,79	385,24	0,55	7,21	52,48	26,76	0,36	0,36	0,35	0,35	13,00	0,145	0,1158	0,37
	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dBx10^{-4}	dB	dB	dB

Uncertainty analysis of the NML Wideband Reciprocity System

Forward

The NML wideband reciprocity system is based on the Bruel & Kjaer type 5998 microphone reciprocity apparatus which is part of the Bruel & Kjaer type 9669 reciprocity calibration system. The NML system is functionally the same as the 9669 system but differs only in the generator used. The control software supplied by B&K is used and the data calculation is carried out by the program MP.EXE from Danish Technical University. This program implements the standard IEC 61094-2 with a series of 2 port couplers.

Local atmospheric pressure is measured by means of a Digiquartz precision aneroid barometric reference. Laboratory air temperature and relative humidity are determined by means of a Rotronic DV2 RH/T system; both of these systems are described in NML procedure AUVAP04.

The type B uncertainty components can be separated into 5 main categories and subcategories, the type A uncertainties obtained from repeated calibration are listed in section 5.3:

1. Electrical parameters and measurement
   - 1.1 Series Impedance
   - 1.2 Voltage ratio
   - 1.3 Frequency
   - 1.4 Inherent noise
   - 1.5 Distortion
   - 1.6 Cross talk
   - 1.7 Polarising voltage

2. Coupler dimensions
   - 2.1 Coupler length
   - 2.2 Coupler diameter
   - 2.3 Coupler volume
   - 2.4 Coupler surface area

3. Microphone parameters
   - 3.1 Front cavity depth
   - 3.2 Front cavity volume
   - 3.3 Equivalent volume
   - 3.4 Resonant frequency
   - 3.5 Loss factor

4. Ambient conditions
   - 4.1 Static pressure determination
   - 4.2 Drift in static pressure during a measurement
   - 4.3 Lack of knowledge of the pressure co-efficient of the microphone
   - 4.4 Coupler (microphone) temperature
   - 4.5 Lack of knowledge of the temperature co-efficient of the microphone
   - 4.6 Humidity measurement

5. Measurement limitations
   - 5.1 Imperfections in the theory
   - 5.2 Rounding errors
   - 5.3 Type A errors

Of these components, many are frequency dependant. To summarise the analysis, a spreadsheet entitled LS2P 9669 U95 is used. This has been inserted as the last page of this document.

Note! As all values are small (<0.05 dB), the analysis is carried out by reducing all quantities to dB.

1. Electrical parameters and measurement

1.1 Series Impedance, *parameter* $u_{1.1}$

For the determination of the current injection to the transmitting microphone, the voltage developed across a series capacitor is measured. In the 9669 system the capacitor is an integral part of the ZE0796 transmitter unit and has a nominal value of 4.66 ηFd. This is calibrated at 1 kHz on an annual basis using a General Radio type 1615 3-terminal capacitance bridge using the B&K UA1436 BNC access unit in conjunction with the NML 2 to 3 terminal adaptor The 1615 bridge is checked before use against a General Radio type 1404 1 ηFd standard air capacitor which is used as a transfer standard. The 1404 has a calibration uncertainty of 3.2 ppm. Allowance is made for stray capacitance in the procedure that is described in the document 5998 XCAP.doc where the measured values are listed; these have been stable at 4.656 ηFd over 3 years.

An estimated standard uncertainty of 0.001 ηFd which becomes in dB ratio:

$u_{1.1} = 0.0019$ dB with $\nu_{1.1} \geq 30$

1.2 Voltage ratio, *parameter* $u_{1.2}$

A Hewlett Packard 3458A digital voltmeter is used in conjunction with a B&K 1617 bandpass filter for noise reduction. The worst case uncertainty from the NML calibration report, for a voltage range 0.05 V to 10 V over the frequency range 0.02 to 50 kHz, is 80 ppm of the reading which may have a correction of ≤ 10 ppm over those ranges. Hence a conservative uncertainty of 90 ppm at 1 V (0.0008 dB) will apply for any voltage measurement. For each microphone pair in a given coupler, a set of 4 measurements of voltage are made at each frequency. For a sensitivity calculation, the square root of 3 sets of voltage measurements are used. Then the uncertainty of the voltage ratio will be 2 x √3 of the 3458A uncertainty.

$u_{1.2} = 0.0027$ dB with $\nu_{1.2} \geq 30$

1.3 Frequency, *parameter* $u_{1.3}$

The error in the frequency of the generated signal is ≤ 5 ppm. There are no elements in the system that have a significant effect due to frequency accuracy other than the injection capacitor. The impedance has a direct relationship with frequency so an uncertainty will arise in the measured voltage of:

$u_{1.3} = 0.043 \times 10^{-3}$ dB with $\nu_{1.3} \geq 30$

1.4 Inherent noise, *parameter* $u_{1.4}$

The acoustic and electrical noise levels in the acoustics laboratory are minimized by electrical filtering and the acoustic shielding of the B&K 9669 cover. The typical standard deviation of the measured voltage ratio for each set of measurements is given by the measurement summary report and is frequency dependant. At low frequencies up to 30 samples are taken. For a signal to noise ratio of <46 dB the effect on sensitivity is reckoned to be <0.0001 dB. As for item 1.2 above, 3 sets are used for each sensitivity determination so the results for one set are multiplied by √3.

Typical results for $u_{1.4}$ are tabulated below together with the degrees of freedom:

Freq	31.5	63	125	250	500	1k	2k	4k	6.3k	8k	10k	12.5k	16k	20k	25k
Sdev ppm	300	200	140	105	85	50	50	50	45	45	45	45	45	45	45
N Samples	30	20	10	10	10	10	10	10	10	10	10	10	10	10	10
SEOM dB*E-06	55	45	44	33	27	16	16	16	14	14	14	14	14	14	14
SEOM*√3 *E-06 dB	95	78	77	58	47	28	28	28	25	25	25	25	25	25	25

1.5 Distortion, *parameter* $u_{1.5}$

The signal source has less a THD of approximately 0.2% (-53dB) at lowest frequency and is reckoned to affect the sensitivity by <0.0001 dB (from B&K sources).

1.6 Cross talk, *parameter* $u_{1.6}$

Cross talk of <-66 dB is reckoned to affect the sensitivity result by no more than 0.0025 dB (from B&K sources).

1.7 Polarising voltage, *parameter* $u_{1.7}$

The NML calibration report for the HP3458A DMM states that the maximum error is – 2 ppm at 200 Volts applied ± 7ppm for voltages up to 1 kV. An uncertainty of 10 ppm will be assigned for reading.
At the start of each calibration run the polarising voltage is checked and is generally within 2 mV or 10 ppm. Thus the uncertainty in the polarising voltage is estimated to be 15 ppm or a maximum error of 3 mV.
The 4180 is estimated to have a sensitivity to polarising voltage of approximately –0.05 dB/Volt so an uncertainty in sensitivity arising from polarising voltage is estimated to be:
$u_{1.7} = 0.00015$ dB with $\nu_{1.7} \geq 30$

2. Coupler dimensions

There are 6 couplers for LS2P calibration in the NML system. The NML calibration report states an uncertainty of 2.5 µm in length, and 2 µm in diameter. The sensitivity factors are frequency dependant so for indicative purposes a worst case both for coupler (the shortest) and the frequency is tabulated below together with the estimated uncertainty on the sensitivity result:

Table 1.
Worst case uncertainty for coupler dimensions.

Coupler identification	**2171**	**2172**	**2173**	**2174**	**2175**	**2176**
2.1 Length, mm	9.4	6.0	5.0	4.7	4.0	3.0
Uncertainty in length %	0.027	0.042	0.05	0.053	0.063	0.083
Sensitivity factor, [worst] dB/%		0.0109	0.0197		0.034	0.076
Uncertainty in Length (dB)		**0.0005**	**0.001**		**0.0021**	**0.0067**
2.2 Diameter, mm	9.3	9.3	9.3	9.3	9.3	9.3
Uncertainty in diameter %	0.022	0.022	0.022	0.022	0.022	0.022
Sensitivity factor, [worst] dB/%		0.0257	0.0372		0.0618	0.179
Uncertainty in Diameter (dB)		**0.0006**	**0.0008**		**0.0014**	**0.0039**
2.3 Volume mm^3	638.53	407.57	339.65	319.27	271.72	203.79
Uncertainty in volume %	0.000588	0.000925	0.00111	0.00118	0.00139	0.00185
Sensitivity factor, [worst] dB/%		0.0005	0.0006		0.0005	0.0006
Uncertainty in Volume (dB)		**1E-6**	**1E-6**		**1E-6**	**1E-6**
2.4 Surface area mm^2	411.82	311.07	281.46	273.94	252.67	223.30
Uncertainty in area %	0.00115	0.00152	0.00168	0.00172	0.00187	0.00211
Sensitivity factor, [worst] dB/%		0.0005	0.0006		0.0006	0.0007
Uncertainty in Area (dB)		**1E-6**	**1E-6**		**1E-6**	**1E-6**

To determine the frequency dependant sensitivity factor for each coupler parameter, the parameter (or dimension) for each cavity was modulated by a small increment and the differences in the calculated sensitivity for one microphone at each frequency noted to obtain the "sensitivity factor" at each frequency which was then resolved as an uncertainty. When all 4 cavities in the measurement set were treated in this way, an RMS addition of the 4 uncertainties was made at each frequency. The worst case for each coupler is shown above under each parameter. The actual uncertainties as a function of frequency have been included in the spreadsheet "LS2P 9669 U95.xls"

For coupler Length, *parameter* $u_{2.1}$.

For coupler Diameter, *parameter* $u_{2.2}$.

For coupler Volume, *parameter* $u_{2.3}$.

For coupler Surface Area, *parameter* $u_{2.4}$.

3. Microphone parameters

To determine the uncertainty of each microphone parameter, that parameter was modulated by a small known percentage to assess the sensitivity co-efficient. This was then combined with the uncertainty in the measurement of that parameter to provide a frequency dependant uncertainty for that parameter for each coupler and at each frequency. As the same uncertainty applies to the other 2 microphones in the triad and each will affect the other, the uncertainty is multiplied by √3. The microphone parameters are further "adjusted" during the data reduction process by adjusting each in turn to reduce the effects when using different couplers on the mean result.

3.1 Front cavity depth, *parameter* $u_{3.1}$.

The measurement uncertainty is ± 10 µm in a nominal depth of 0.5 mm, normally distributed which amounts to 2%.

3.2 Front cavity volume, *parameter* $u_{3.2}$.

The fixed volume is calculated from the depth and diameter. As above, the uncertainty in depth is ± 10 µm and the uncertainty of the diameter is assessed as ± 20 µm due to taper, roughness and the sealing ring. The standard IEC 61094-1 lists the dimension and tolerance for diameter as 9.3 mm ± 0.03 mm. This leads to an uncertainty of 30 μm^3 in a nominal volume of 33.5 mm^3 or 0.895% of volume.

3.3 Equivalent volume, *parameter* $u_{3.3}$.

For the 4180 it is difficult to determine the equivalent volume by any means other than an iterative process using changes in V_{eq} and observing the results at low frequencies and at frequencies above the resonant frequency. The nominal value of 9.2mm^3 is used as the staring point. From experiment it appears possible to determine the value to within ±0.5 mm^3.

3.4 Resonant frequency, *parameter* $u_{3.4}$.

The resonant frequency is determined by a measurement of the phase relationship between the stimulation from an electrostatic actuator and the output signal. The phase passes through 90° at the resonant frequency. The actuator however loads the diaphragm to some degree and will slightly lower the resonant frequency. For a nominal frequency of 22 kHz the uncertainty is thought to be approximately 0.2 kHz or 0.843%.

3.5 Loss factor, *parameter* $u_{3.5}$.

The loss factor is determined from an observation of the microphone response between the asymptote to the low frequency sensitivty and the resonance peak. The nominal value is approximately 1.05 and it is thought possible to determine this to within 0.02 or 2%.

4. Ambient conditions

4.1 Static pressure determination, *parameter* $u_{4.1}$.

The ambient pressure in the acoustics lab at NML is determined by a "Digiquartz" barometric reference. This transducer, its calibration, maintenance and uncertainty budget is described in the NML procedure AUVAP04 "Atmospheric Pressure and Microphone corrections". The estimated uncertainty for this transducer is 0.0072% or 0.073 hPa at STP.
The static pressure co-efficient is frequency dependant and generally lies between –0.003 and –0.008 dB/kPa for LS2P microphones [IEC61094-2 1992 Annex D] (-0.0003 and –0.0008 dB/hPa).
The pressure is logged at the start of the measurement cycle of each microphone pair but may drift (see 4.2 below).

4.2 Drift in static pressure during a measurement cycle, *parameter* $u_{4.2}$.

The complete cycle for a microphone pair may take up to 30 minutes and within this time there will be pressure fluctuations and there may also be drift in the ambient pressure. Experience indicates that this may be up to 0.5 hPa in extreme conditions. The RMP.EXE program that controls the data collection from the voltage ratio measurements interpolates between the pressure logged at the start of the cycle and the pressure logged at the start of the next cycle. Thus the pressure is unlikely to be in error by more than 0.1 hPa, probably with a normal distribution (k=2). From the nominal pressure co-efficient of the LS2P microphone (-0.0008 dB/hPa)an uncertainty of less than -0.00004 or 4E-5 dB

4.3 Lack of knowledge of the pressure co-efficient of the microphone, *parameter* $u_{4.3}$.

The nominal low frequency pressure co-efficient is used by the MP.EXE program to derive a frequency dependant correction. The pressure coefficient may differ from the stated nominal by up to 25 % .

4.4 Coupler (microphone) temperature, *parameter* $u_{4.4}$.

The Acoustics laboratory at NML is controlled for temperature and humidity to reasonable levels with the aim to maintain the ambient conditions at 22.5°C ± 0.5°C and 50 % ± 5% RH. The air conditions are monitored with a Rotronic RH/T probe which is described in the NML procedure AUVAP04 "Atmospheric Pressure and Microphone corrections". The stated uncertainty on the NML calibration report for the Rotronic system is 0.6%RH and 0.12°C .

In the NML implementation of the B&K 9669 system the coupler temperature is not directly monitored but must be entered at the start of each cycle. The B&K control software "RMP.EXE" uses the stated air temperature and coupler temperature to adjust the humidity, see 4.6 below. During the input of temperature at the start of each cycle the local air temperature in the laboratory is entered and an "educated guess" at the coupler temperature is made. This by local protocol set at Ambient +0.5°C. This could however be in error by as much as ± 0.3°C with an assumed normal distribution. Thus the combination of the calibration report uncertainty

(0.12°C at 95% k=2) and the coupler temperature error (0.3°C, k=2) gives an estimated standard uncertainty of $u_{4.4} = 0.16$ with $v_{4.4} \geq 30$.

4.5 Lack of knowledge of the temperature co-efficient of the microphone, *parameter* $u_{4.5}$.

The B&K handbook for the 4180 microphone and the manual for the 9669 reciprocity system state a low frequency temperature co-efficient of –0.002 dB/hPa. From experience unless this is characterised for the individual microphones it may be up to 50% in error from the nominal value.

4.6 Humidity measurement, *parameter* $u_{4.6}$.

The stated uncertainty for the NML acoustics lab RH/T measurement system is 0.6% RH. The figure is observed on the laboratory RH/T system and logged into the measurement control program "RMP.EXE" at the start of the cycle. The control program adjusts the RH value in the coupler based on the anticipated temperature rise of the coupler relative to the surrounding air.

5. Measurement limitations

5.1 Imperfections in the theory, *parameter* $u_{5.1}$.

The uncertainty imposed by imperfections in the theory, corrections and calculations obtained from IEC 61094-2 are unknown so an educated guess must be made. This will probably be worst at low frequencies due to heat conduction theory and at high frequencies from the radial wave motion corrections. As the reliability is poor a low dof will be assigned from R=25% hence $\nu_{5.1}$ will be assigned a value of 8 dof.

5.2 Rounding errors, *parameter* $u_{5.2}$.

These are constant with frequency and where values are rounded up to 0.001 an error of 0.00029 dB with rectangular distribution and dof ≥ 30.

5.3 Type A errors, *parameter* $u_{5.3}$.

There were 4 complete measurements carried, each with 4 couplers. The ESDM of the values at each frequency are tabulated as item 5.3 in the spreadsheet. As a result a dof of $\nu_{5.3}$ =3 is used.

B. H. Meldrum
CSIRO NML 22 May 2003

		Uncertainty Estimates					CCAUV-K3 Key Comparison on LS2P Microphones							CSIRO NML		Apr-03			Meldrum/Bell			
	Component	Symbol	Unit	Source	31.5	63	125	250	500	1000	2000	4000	6300	8000	10000	12500	16000	20000	25000	31500	Dof	Distrib'n
	Electrical measurements				31.5	63	125	250	500	1k	2k	4k	6.3k	8k	10k	12.5k	16k	20k	25k	31.5k		
1.1	Series Z	C	nFd	NML	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	30	Rect
1.2	Voltage ratio	Vr	V	NML	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	30	Rect
1.3	Frequency	f	Hz	NML	4.3E-05	4.3E-05	4.3E-05	4.3E-05	4.3E-05	4.3E-05	4.3E-05	4.3E-05	4.3E-05	4.3E-05	4.3E-05	4.3E-05	4.3E-05	4.3E-05	4.3E-05	4.3E-05	30	Rect
1.4	Noise		V	NML	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	9	Normal
1.5	distortion	D	ratio	B&K	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	30	Rect
1.6	Cross talk		ratio	B&K	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	30	Rect
1.7	Polarising V	Pv	V	NML	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	0.00015	30	Rect
	Coupler dimensions																					
2.1	Length	Cl	mm	NML	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0009	0.0008	0.0007	0.0005	0.0006	0.0011	0.0023	0.0067	30	Normal
2.2	Diameter	Cd	mm	NML	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0008	0.0008	0.0008	0.0008	0.0009	0.0010	0.0013	0.0019	0.0039	30	Normal
2.3	Volume	Cv	mm^2	NML	2.E-06	1.E-06	1.E-06	1.E-06	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	30	Normal
2.4	Area	CA	mm^2	NML	2.E-06	1.E-06	1.E-06	1.E-06	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	0.E+00	30	Normal
	Microphone parameters																					
3.1	Front depth	Fd	mm	NML	0.0022	0.0016	0.0011	0.0008	0.0006	0.0004	0.0002	0.0001	0.0002	0.0004	0.0008	0.0012	0.0018	0.0025	0.0042	0.0198	30	Normal
3.2	Front volume	Fv	mm^3	NML	0.0013	0.0013	0.0013	0.0014	0.0014	0.0014	0.0014	0.0013	0.0012	0.0011	0.0009	0.0006	0.0001	0.0008	0.0018	0.0036	30	Normal
3.3	Equiv volume	Ve	mm^3	NML	0.0181	0.0185	0.0187	0.0189	0.0190	0.0190	0.0189	0.0182	0.0166	0.0149	0.0122	0.0078	0.0007	0.0004	0.0055	0.0553	30	Normal
3.4	Resonance freq	Fr	Hz	NML	5.9E-06	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.9E-06	1.8E-05	0.0001	0.0001	0.0001	0.0001	4.8E-05	0.0005	0.0022	0.0050	0.0148	30	Normal
3.5	Loss factor	Loss	ratio	NML	2.6E-06	0.0E+00	2.6E-06	0.0E+00	2.6E-06	2.4E-05	0.0001	0.0004	0.0010	0.0015	0.0019	0.0019	0.0001	0.0011	0.0026	0.0076	30	Rect
	Ambient Conditions																					
4.1	Static Pressure	Pamb	hPa	NML	0.0026	0.0026	0.0026	0.0026	0.0025	0.0025	0.0026	0.0027	0.0028	0.0030	0.0033	0.0036	0.0035	0.0024	0.0004	0.0007	30	Triangular
4.2	Drift in pressure	Pdrift	hPa	NML	4.E-05	4.E-05	4.E-05	4.E-05	4.E-05	4.E-05	4.E-05	4.E-05	4.E-05	4.E-05	4.E-05	4.E-05	4.E-05	4.E-05	4.E-05	4.E-05	30	Rect
4.3	Pcoeft unknown	Pcoeft	dB/hPa	NML	0.0086	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0029	0.0017	0.0002	30	Rect
4.4	Mic Temperature	Tmic	DegC	NML	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0003	0.0001	0.0001	30	Normal
4.5	Tcoeft unknown	Tcoeft	IB/Deg(	NML	0.0072	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0051	0.0006	0.0019	30	Rect
4.6	Humidity Meas't	RH%	%	NML	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0004	0.0014	30	Normal
	Measurement Limitations																					
5.1	Theory limitations		dB	NML	0.0050	0.0040	0.0030	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0030	0.0050	0.0100	8	Normal
5.2	Rounding Errors		dB	NML	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	0.00290	30	Rect
5.3	Type A	uA	dB	NML	0.0020	0.002	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.004	0.006	0.008	0.008	0.013	0.064	3	Normal
	Combined Uncertainty, uc				0.023	0.020	0.020	0.020	0.020	0.020	0.020	0.019	0.018	0.017	0.015	0.012	0.011	0.012	0.018	0.090		
	EffDoff				69.5	41.2	39.0	37.8	37.7	37.6	37.7	39.1	41.2	44.8	55.1	38.9	9.5	17.0	10.3	10.9		
	k factor				1.996	2.022	2.026	2.028	2.028	2.028	2.028	2.026	2.022	2.017	2.006	2.026	2.252	2.115	2.228	2.211		
	Expanded Uncertainty, U95 for k=2				**0.046**	**0.040**	**0.040**	**0.040**	**0.040**	**0.040**	**0.040**	**0.039**	**0.036**	**0.033**	**0.029**	**0.024**	**0.021**	**0.025**	**0.036**	**0.179**		
	U95 rounded to 2 dP				**0.05**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.03**	**0.03**	**0.02**	**0.03**	**0.04**	**0.18**		
	Stated Uncertainty				**0.06**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.06**	**0.06**	**0.05**	**0.06**	**0.08**	**0.22**		

Danish Primary Laboratory of Acoustics

Condensed uncertainty budget for type 4180 microphones

The condensed uncertainty budget for a pressure reciprocity calibration of B&K Type 4180 microphones are given in the table below. The background for the budget is given in the following remarks:

Item 1: The figures represent the combined effects of the uncertainty on the coupler length (3 µm) and diameter (4 µm) including the resulting changes in heat conduction corrections.

Item 2: The figures represent the combined effects of the uncertainty on the microphone resonance frequency (500 Hz), loss factor (0.05), cavity depth (10 µm), front cavity (0.5 mm^3) and equivalent volume (0.2 mm^3).

Item 3: The figures represent the combined effects of the uncertainty on the measurement impedance, voltage ratios (3 ratios each derived from 4 voltage measurements), cross-talk (< 66 dB) and noise (S/N < 46 dB). It is assumed that cross-talk and noise affects all voltage ratios in the same way.

Item 4: The figures represent the combined effects of the measurement uncertainties on static pressure (40 Pa), temperature (1 K) and relative humidity (5 %).

Item 5: The figures represent the uncertainty on the polarizing voltage (40 mV) and the non-linear relation between polarizing voltage and microphone sensitivity.

Item 6: The figures represent the uncertainty on the applied radial wave-motion correction.

Item 7: The figures represent the estimated error committed by not taking viscosity effects into account.

Item 8: The figures represent the uncertainty on the equations for calculating the speed of sound (0.05 m/s), density of air (10^4 $kg/m^{3)}$ and ratio of specific heats (0.0005).

Item 11: The figures represent the uncertainty on applying a correction for dependence of static pressure and temperature on the microphone sensitivity. (Uncertainty on resonance frequency 500 Hz, on low-frequency value of static pressure coefficient 0.0005 dB/kPa and on temperature coefficient 0.002 dB/K, allowed deviation from reference conditions 2 kPa respectively 1 K).

Uncertainty budget for pressure reciprocity calibration of type B&K 4180 microphones

Components of type B uncertainties in dB*1000

Frequency Hz

Source	20	25	31.5	63	125	250	500	1000	4000	6300	8000	10000	12500	16000	20000	25000	31500
1 Coupler dimensions	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	4	5	7	10	15	25
2 Microphone parameters	10	10	10	10	10	10	10	10	10	10	10	12	15	20	30	50	80
3 Electrical transfer impedance	35	25	20	10	7	5	4	4	4	4	4	4	4	4	7	8	10
4 Environmental parameters	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.7	2.1	2.7	3.7	5.6	8.8	15	20	30
5 Polarizing voltage	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
6 Radial wave-motion correction	0	0	0	0	0	0	0	0	0	1	2	3	5	10	15	20	30
7 Viscosity losses	0	0	0	0	0	0	0	0	0	0.2	0.5	1	3	5	10	15	20
8 Equations of environmental parameters	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.3	1.3	1.2
9 Rounding of results	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
$\sigma_B = \left(\sum u^2 / 3\right)^{1/2}$	21,4	16,1	13,5	9,1	8,1	7,6	7,4	7,4	7,4	7,5	7,6	8,8	11	15,3	23,3	35,8	55,8
Components of type A uncertainties in dB*1000																	
10 Allowed reproducibility σ_A	35	25	18	15	12	10	10	10	10	10	10	10	12	15	20	30	50
Overall uncertainty in dB*10000 at measurement conditions ($k = 2$)																	
$\sigma = 2\left(\sigma_A^2 + \sigma_B^2\right)^{1/2}$	82,0	59,4	45,0	35,1	28,9	25,1	24,9	24,9	24,9	25,0	25,1	26,6	32,6	42,8	61,4	93,4	149,9
Uncertainty on corrections to reference environmental conditions in dB*1000 ($k = 2$)																	
11 Correction to reference conditions	3	3	3	3	3	3	3	3	4	5	7	10	15	20	25	35	50
Overall uncertainty in dB*1000 at reference conditions ($k = 2$)																	
	82,1	59,5	45,1	35,2	29,1	25,3	25,1	25,1	25,2	25,4	26,1	28,4	35,8	47,2	66,3	99,8	158,0
Resulting uncertainty in dB																	
	0,09	0,06	0,05	0,04	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,04	0,05	0,07	0,10	0,16
Uncertainty stated in the CMC in dB																	
CMC values	0,1	0,08	0,08	0,04	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,04	0,05	0,08	0,14	na

Central Office of Measures (GUM)
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Uncertainty evaluation for the reciprocity calibration of LS2 microphones

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

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	4 kHz	5 kHz	6.3 kHz	8 kHz	10 kHz	12.5 kHz	16 kHz	20 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	0.05	0.05
2	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	0.50	0.50
3	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	0.50	0.50
4	Radius of coupler	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.19	0.19	0.19	0.19
5	Velocity of sound (dry air)	0	0	0	0	0	0	0	0.01	0.01	0.02	0.04	0.06	0.11	0.22
6	Velocity of sound change with humidity	0	0	0	0	0	0	0.01	0.01	0.03	0.04	0.07	0.12	0.23	0.47
7	Ratio of specific heats	0.26	0.27	0.28	0.29	0.29	0.29	0.29	0.30	0.30	0.30	0.30	0.31	0.31	0.31
8	Ambient pressure	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
9	Length of coupler	0.38	0.38	0.38	0.38	0.38	0.38	0.34	0.33	0.30	0.24	0.16	0.01	0.31	1.04
10	Cavity depth	0	0	0	0	0	0	0	0	0	0.02	0.04	0.04	0.04	0
11	Front cavity volume	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.16	0.14	0.12	0.08	0.02	0.14	0.50
12	Theory of adding volume	0	0	0	0	0	0.01	0.01	0.03	0.04	0.07	0.12	0.20	0.39	0.83
13	Acoustic compliance	0	0	0	0	0	0.04	0.14	0.25	0.38	0.58	0.68	0.11	3.41	11.04
14	Acoustic mass	0	0	0	0	0	0.02	0.07	0.08	0.12	0.13	0.09	0.02	0.86	4.23
15	Acoustic resistance	0	0	0	0	0	0.04	0.14	0.23	0.33	0.44	0.44	0.09	0.78	0.38
16	Heat conduction theory	1.28	0.92	0.65	0.45	0.30	0.15	0.09	0.21	0.38	0.64	1.00	1.55	2.60	4.70
17	Thermal diffusivity	0.41	0.29	0.20	0.14	0.10	0.07	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.02
18	Capillary radius	0.30	0.50	0.50	0.40	0.12	0.10	0.03	0.02	0.01	0.01	0.01	0	0	0
19	Air viscosity	0.09	0.10	0.10	0.09	0.03	0.01	0	0	0	0	0	0	0	0
20	Humidity determination	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.06	0.10	0.19
21	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	0.44	0.44
22	Temperature	0	0	0	0	0	0	0.01	0.02	0.03	0.05	0.08	0.14	0.16	0.53
23	Pressure radial non-uniformity	0	0	0	0	0	0.01	0.05	0.08	0.11	0.18	0.26	0.38	0.54	0.60
24	Temperature dependence of microphone parameters	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
25	Static pressure dependence of microphone parameters	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
26	Transmitter ground shield	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
27	Receiver ground shield	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
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	0.50	0.50
Resultant Type B uncertainty expressed as distribution halfwidth		1.84	1.63	1.48	1.37	1.26	1.23	1.23	1.27	1.36	1.54	1.76	1.99	4.66	12.90
Resultant Type B uncertainty expressed as standard deviation		1.06	0.94	0.86	0.79	0.73	0.71	0.71	0.74	0.79	0.89	1.02	1.15	2.69	7.45

2. Overall uncertainty evaluation

Type of uncertainty	Uncertainty value (mB) at frequency													
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	5 kHz	6.3 kHz	8 kHz	10 kHz	12.5 kHz	16 kHz	20 kHz
Resultant Type B uncertainty expressed as standard deviation	1.06	0.94	0.86	0.79	0.73	0.71	0.71	0.74	0.79	0.89	1.02	1.15	2.69	7.45
Typical Type A uncertainty due to repeatability, expressed as standard deviation	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.50	3.00	3.50	3.50	3.50
Type A uncertainty of front volume determination, expressed as standard deviation	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.32	0.28	0.24	0.16	0.04	0.28	1.00
Resultant Type A uncertainty expressed as standard deviation	2.03	2.03	2.03	2.03	2.03	2.03	2.03	2.03	2.02	2.51	3.00	3.50	3.51	3.64
Expanded Type B uncertainty at k=2	2.12	1.88	1.71	1.58	1.46	1.43	1.42	1.47	1.57	1.78	2.04	2.30	5.38	14.89
Expanded Type A uncertainty at k = 2	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.05	4.04	5.02	6.01	7.00	7.02	7.28
Overall uncertainty at k=2	4.58	4.48	4.41	4.36	4.32	4.31	4.31	4.31	4.33	5.33	6.34	7.37	8.85	16.58
Overall uncertainty at k=2 rounded as entier(x) + 1	5	5	5	5	5	5	5	5	5	6	7	8	9	17

INMETRO: Uncertainty Budget - LS2P Microphone Calibration (Sound Pressure Level)

Type B uncertainty																				
Source of uncertainty - Rectangular distribution as semi-ranges (10^{-4} dB)																				
Frequencies(Hz)	31,5	40	50	63	80	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
Measurement																				
Capacitor	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48	48
Polarization Voltage	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Microphone parameters																				
Acoustic impedance (fit)	270	250	220	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
Couplers																				
Diameter	40	40	40	40	40	40	30	30	30	30	30	30	30	30	30	30	40	40	40	40
Length	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Correction of results to normal environmental conditions																				
Static pressure	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Temperature	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Environmental conditions																				
Static pressure	49	49	49	49	49	49	49	49	49	49	49	49	49	49	49	49	49	49	49	49
Temperature	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Humidity	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Rounding error	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Estimate of type B uncertainty, k=1	284	265	237	219	219	219	217	217	217	217	217	217	217	217	217	217	219	219	219	219
Type A uncertainty																				
Type A uncertainty as Normal distribution (10^{-4} dB)																				
Repeatibility	70	70	70	70	70	70	60	60	60	60	60	60	60	60	60	60	60	60	60	60
Estimate of type A uncertainty, k=1	70	70	70	70	70	70	60	60	60	60	60	60	60	60	60	60	60	60	60	60
Overall uncertainty (10^{-4} dB)																				
Type A, k=2	140	140	140	140	140	140	120	120	120	120	120	120	120	120	120	120	120	120	120	120
Type B, k=2	569	531	475	438	438	438	435	435	435	435	435	435	435	435	435	435	438	438	438	438
Overall uncertainty, k=2	**586**	**549**	**495**	**460**	**460**	**460**	**451**	**451**	**451**	**451**	**451**	**451**	**451**	**451**	**451**	**451**	**454**	**454**	**454**	**454**

INMETRO: Uncertainty Budget - LS2P Microphone Calibration (Sound Pressure Level)

Type B uncertainty

Source of uncertainty - Rectangular distribution as semi-ranges (10^{-4} dB)

Frequencies(Hz)	4000	5000	6300	8000	10000	12500	16000	20000	25000
Measurement									
Capacitor	48	48	48	48	48	48	48	48	48
Polarization Voltage	20	20	20	20	20	20	20	20	20
Microphone parameters									
Acoustic impedance (fit)	200	200	200	250	350	400	550	600	800
Couplers									
Diameter	40	40	40	40	40	40	40	45	50
Length	20	20	20	20	20	25	30	40	70
Correction of results to normal environmental conditions									
Static pressure	15	25	25	25	25	25	25	25	25
Temperature	20	20	20	20	20	20	20	20	20
Environmental conditions									
Static pressure	49	49	49	49	49	49	49	49	49
Temperature	8	8	8	8	15	25	30	30	35
Humidity	8	15	20	25	30	30	30	30	35
Rounding error	3	3	3	3	3	3	3	3	3
Estimate of type B uncertainty, k=1	219	220	221	267	363	412	559	610	810

Type A uncertainty

Type A uncertainty as Normal distribution (10^{-4} dB)

Repeatibility	60	60	60	60	70	110	140	150	200
Estimate of type A uncertainty, k=1	60	60	60	60	70	110	140	150	200

Overall uncertainty (10^{-4} dB)

Type A, k=2	120	120	120	120	140	220	280	300	400
Type B, k=2	438	440	441	534	726	825	1119	1219	1620
Overall uncertainty, k=2	**454**	**456**	**457**	**548**	**740**	**853**	**1153**	**1256**	**1669**

KRISS: Uncertainty Budget for LS2P

MEASURED QUANTITY	Symbol	Unc.	Unit	31,5	63	125	250	500	1000	2000	3150	4000	5000	6300	8000	10000	12500	16000	20000	25000	31500
Electrical Transfer Impedance				0,0112	0,0109	0,0107	0,0067	0,0054	0,0050	0,0055	0,0067	0,0067	0,0067	0,0067	0,0067	0,0083	0,0117	0,0117	0,0117	0,0117	0,0159
Series Capacitance	C	Table	nF	0,0102	0,0098	0,0097	0,0048	0,0029	0,0019	0,0029	0,0048	0,0048	0,0048	0,0048	0,0048	0,0048	0,0095	0,0095	0,0095	0,0095	0,0095
Voltage Ratio	VR	Table		0,0031	0,0029	0,0028	0,0028	0,0028	0,0028	0,0029	0,0029	0,0029	0,0029	0,0029	0,0029	0,0057	0,0057	0,0057	0,0057	0,0057	0,0122
Cross-talk				0,0035	0,0035	0,0035	0,0035	0,0035	0,0035	0,0035	0,0035	0,0035	0,0035	0,0035	0,0035	0,0035	0,0035	0,0035	0,0035	0,0035	0,0035
Inherent Noise				0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009	0,0009
Distortion				0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0004	0,0005	0,0005	0,0006	0,0006	0,0004	0,0003	0,0011	0,0000	0,0000	0,0000
Frequency	f		Hz	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Reveiver Ground Shield		B&K		0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003
Transmitter Ground Shield		B&K		0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003
Coupler Properties				0,0039	0,0039	0,0039	0,0039	0,0040	0,0039	0,0039	0,0039	0,0039	0,0039	0,0039	0,0039	0,0040	0,0042	0,0050	0,0069	0,0141	0,0663
Coupler Length	lcoup	0,0020	mm	0,0014	0,0014	0,0014	0,0014	0,0015	0,0014	0,0014	0,0014	0,0014	0,0013	0,0012	0,0011	0,0008	0,0004	0,0003	0,0017	0,0058	0,0345
Coupler Diameter	dcoup	0,0030	mm	0,0022	0,0022	0,0022	0,0022	0,0022	0,0022	0,0022	0,0022	0,0022	0,0022	0,0022	0,0022	0,0023	0,0023	0,0023	0,0023	0,0022	0,0017
Coupler Volume	Vcoup	0,2470	mm3	0,0027	0,0027	0,0027	0,0027	0,0027	0,0027	0,0027	0,0027	0,0027	0,0027	0,0027	0,0027	0,0027	0,0027	0,0028	0,0028	0,0026	0,0020
Coupler Surface Area	Scoup	0,1440	mm2	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Static Pressure	Ps	0,0275	kPa	0,0012	0,0012	0,0011	0,0011	0,0011	0,0011	0,0011	0,0011	0,0011	0,0011	0,0011	0,0011	0,0012	0,0012	0,0012	0,0012	0,0011	0,0008
Temperature	T	0,3464	K	0,0001	0,0001	0,0001	0,0001	0,0000	0,0000	0,0001	0,0001	0,0002	0,0003	0,0004	0,0007	0,0011	0,0018	0,0030	0,0053	0,0119	0,0548
Relative Humidity	RH	3,3164	%	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0002	0,0003	0,0004	0,0005	0,0006	0,0010	0,0016	0,0033	0,0141
Microphone Parameters				0,0096	0,0097	0,0099	0,0099	0,0100	0,0100	0,0099	0,0098	0,0099	0,0100	0,0105	0,0117	0,0128	0,0121	0,0120	0,0519	0,1353	0,8243
Front Cavity Depth	Lf	0,0030	mm	0,0001	0,0001	0,0001	0,0000	0,0000	0,0000	0,0001	0,0002	0,0003	0,0005	0,0007	0,0012	0,0019	0,0032	0,0054	0,0097	0,0216	0,1006
Front Cavity Volume	Vf	0,2100	mm3	0,0045	0,0045	0,0045	0,0045	0,0045	0,0045	0,0045	0,0045	0,0045	0,0045	0,0045	0,0046	0,0046	0,0047	0,0047	0,0047	0,0044	0,0035
Equivalent Volume	Veq	0,4200	mm3	0,0085	0,0086	0,0088	0,0088	0,0089	0,0089	0,0088	0,0086	0,0085	0,0081	0,0076	0,0068	0,0053	0,0029	0,0002	0,0004	0,0130	0,0564
Resonance Frequency	fo	2440	Hz	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0001	0,0002	0,0005	0,0010	0,0022	0,0042	0,0055	0,0078	0,0494	0,1018	0,7684
Loss Factor	D	0,1800		0,0000	0,0000	0,0000	0,0000	0,0000	0,0001	0,0006	0,0015	0,0024	0,0037	0,0056	0,0079	0,0097	0,0087	0,0057	0,0118	0,0854	0,2751
Additional Heat Conduction Caused by Front Cavity Thread				0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Polarizing Voltage	Uo	0,0048	V	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003
Imperfection of Theory				0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Heat Conduction Theory				0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Adding of Excess Volume				0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Radial Wave Motion				0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Processing of Results				0,0152	0,0125	0,0117	0,0117	0,0117	0,0117	0,0117	0,0118	0,0118	0,0119	0,0122	0,0129	0,0154	0,0190	0,0221	0,0262	0,0345	0,0417
Rounding Error		0,0050	dB	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058	0,0058
Repeatability of Measurements			dB	0,0140	0,0110	0,0100	0,0100	0,0100	0,0100	0,0100	0,0100	0,0100	0,0100	0,0100	0,0100	0,0110	0,0120	0,0150	0,0180	0,0210	0,0240

Static Pressure Corrections	0,0011	0,0011	0,0011	0,0011	0,0012	0,0012	0,0011	0,0010	0,0009	0,0007	0,0003	0,0006	0,0020	0,0032	0,0004	0,0107	0,0261	0,0308
Temperature Corrections	0,0009	0,0009	0,0009	0,0009	0,0009	0,0010	0,0014	0,0019	0,0023	0,0028	0,0038	0,0056	0,0089	0,0132	0,0152	0,0146	0,0061	0,0132
Sum	0,0216	0,0196	0,0191	0,0171	0,0168	0,0166	0,0167	0,0172	0,0173	0,0174	0,0178	0,0190	0,0221	0,0257	0,0282	0,0597	0,1408	0,8282
Total Uncertainty with Residual Effects	0,0270	0,0245	0,0238	0,0214	0,0209	0,0208	0,0209	0,0215	0,0216	0,0217	0,0223	0,0238	0,0276	0,0322	0,0353	0,0746	0,1760	1,0352
Stated Uncertainty	0,06	0,04	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,04	0,05	0,06	0,08	0,20	1,20

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4. Sensitivity level uncertainties

The microphone sensitivity level uncertainties are directly computed in dB and estimated in two steps :

- Evaluation of the influence of the parameters directly involved in the formulation of the sensitivity product.
- Influence of the parameters not taken into account in the formulation of the sensitivity product.

4.1. Parameters directly involved in the formulation of the sensitivity product.

The influence of the parameters involved in the sensitivity product calculation, is estimated by using the same software as the one used for the calculation of the sensitivity product.
A set of mean parameters is first given by experimental values. An estimation of the effect of an individual parameter on the sensitivity product can be obtained by increasing its own value. These coefficients are then mixed in order to obtain the influence coefficients for the sensitivity level of one microphone.

Evaluation of the parameter uncertainties

Parameter	Unit	Mean value	U	k	u
Absolute pressure	hPa	1000	1	2	0,5
Temperature	°C	23	1	2	0,5
Humidity	%	50	5	2	2,5
Transfer function (U_e/U_r)	dB	-	0,005	1	0,005
Serie capacitor	F	4744.10^{-12}	5.10^{-12}	2	$2,5.10^{-12}$
Polarisation	V	200	0,1	1	0,1
Frequency	Hz	-	$0,01+10^{-5}.f$	1	
Cavity diameter	mm	9,319	0,01	2	0,005
Cavity length	mm	4,698	0,01	2	0,005
Microphone eq. volume	mm^3	8	2	2	1
Front cavity volume	mm^3	32,8	1	2	0,5
Front cavity depth	mm	0,49	0,05 *	2	0,025
Loss factor		1	0,5	1,7	0,29
Resonance frequency	Hz	23000	1000	1,7	577
Static pressure coefficient	dB/kPa	-0,005	0,001	1,7	0,00058
Temperature coefficient	dB/°C	-0,002	0,001	1,7	0,00058
Excess volume	mm^3	-	0,6	1	0,6
Excess area	mm^2	-	1,2	1	1,2

* **Note** : During this calibration, the optical device was out of order (problem of focusing). So, measurements of the front cavity depth were carried out using a comparison method with a known microphone and using a microscope. The front cavity depth expanded uncertainty (originally 0,01 mm) is increased consequently to 0,05 mm.

4.2. Parameters not directly involved in the formulation of the sensitivity product

Parameter	Unit	Mean value	U	k	u
Rounding errors	dB	-	0,0005	1,7	0,00029
Distortion	dB	-	0,001	1	0,001

Heat conduction theory	Standard uncertainty estimated at 1% of the effective correction
Acoustic leakage	Resistor effect for a standard uncertainty of 0,015 dB (LS2p) or 0,0015 dB (LS1p) at 20 Hz.
Inherent noise	Standard uncertainty estimated with the Lp 10% measured in the cavity over a long period.
Repetability	Standard uncertainty estimated on several calibrations
Cross-talk	Standard uncertainty for each component estimated at 0,001 dB + a f^2 in order to obtain 0,08 dB at 20 kHz
Ground shield	
Viscosity / radial waves	

4.3. Expanded uncertainties

The expanded uncertainties are computed and reported in the following table :

Nominal frequency (Hz)	Expanded uncertainties k=2 (dB)	Nominal frequency (Hz)	Expanded uncertainties k=2 (dB)
31,5	0,042	6300	0,052
63	0,034	8000	0,063
125	0,031	10000	0,08
250	0,030	12500	0,10
500	0,030	15000	0,14
1000	0,031	20000	0,19
2000	0,033	25000	0,29
4000	0,040	31500	0,82

The Head of Accredited Laboratory

Jean-Noël Durocher

NIM:

Table: uncertainty budget of LS2aP

No.	resource	symbol	20Hz	31.5Hz	50Hz	63Hz	125Hz	250Hz	1kHz	2kHz	4kHz	8kHz	10kHz	12.5kHz	16kHz	20kHZ	25kHz
1	Sensitive calibration	$\nu_1=S_1$	0.0118	0.0101	0.0100	0.0077	0.0093	0.0086	0.0085	0.0085	0.0089	0.0113	0.0133	0.0159	0.0194	0.0219	0.0271
2	Polarization volt.	ν_2	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004
3	Volt. Ratio	ν_3	0.0009	0.0009	0.0007	0.0007	0.0004	0.0004	0.0004	0.0004	0.0007	0.0007	0.0007	0.0024	0.0024	0.0024	0.0024
4	Cross talk	ν_3	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025
5	Noise	ν_5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
6	Distortion	ν_6	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
7	Frequency	ν_7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
8	Length of coupler	ν_8	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0006	0.0010	0.0016	0.0026	0.0046	0.0100
9	Diameter of coupler	ν_9	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
10	Surface area of coupler	ν_{10}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
11	Volume of coupler	ν_{11}	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037
12	Leak of coupler	ν_{12}	0.0217	0.0087	0.0050	0.0022	0.0011	0.0003	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
13	Length of front cavity of microphone	ν_{13}	0.0002	0.0002	0.0002	0.0001	0.0001	0.0000	0.0000	0.0000	0.0004	0.0016	0.0026	0.0045	0.0075	0.0100	0.0140
14	Affix front cavity	ν_{14}	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

15	Equivalent front cavity volume	v_{15}	0.0067	0.0068	0.0069	0.0069	0.0070	0.0070	0.0070	0.0070	0.0068	0.0058	0.0040	0.0035	0.0014	0.0013	0.0075
16	Diaphragm Resonance frequency	v_{16}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0010	0.0022	0.0026	0.0060	0.0140	0.0290
17	Diaphragm damp coefficient	v_{17}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0010	0.0010	0.0020	0.0022	0.0044	0.0040	0.0070	0.0150
18	Capacitance in serial C	v_{18}	0.0190	0.0093	0.0050	0.0050	0.0050	0.0050	0.0013	0.0017	0.0017	0.0020	0.0021	0.0025	0.0031	0.0038	0.0074
19	Static pressure	v_{19}	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
20	Temperature	v_{20}	0.0004	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0002	0.0013	0.0022	0.0040	0.0072	0.0112	0.0120
21	Humidity	v_{21}	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0004	0.0006	0.0008	0.0012	0.0020	0.0040
22	Complete figure	v_{22}	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
23	Microphone Static pressure correct	v_{23}	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0009	0.0019	0.0019	0.0019	0.0080	0.0090	0.0080
24	Temperature. correct of microphone	v_{24}	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024	0.0025	0.0036	0.0036	0.0043	0.0042	0.0060	0.0064
Standard uncertainty		**u_c**	**0.0323**	**0.0184**	**0.0151**	**0.0129**	**0.0138**	**0.0133**	**0.0123**	**0.0124**	**0.0126**	**0.0146**	**0.0161**	**0.0197**	**0.0258**	**0.0337**	**0.0500**
Expand uncertainty k=2		U	**0.065**	**0.037**	**0.030**	**0.026**	**0.028**	**0.027**	**0.025**	**0.025**	**0.025**	**0.029**	**0.032**	**0.039**	**0.052**	**0.067**	**0.100**

Above are our details of uncertainty budget, which is obtained during experiment. But we'd like to submit the uncertainty budget as follows.

Frequency range	Uncertainty
31.5Hz~50Hz	0.08dB (k=2)
63Hz~10kHz	0.05dB (k=2)
12.5kHz~20kHz	0.10dB (k=2)
25kHz	0.12db (k=2)

Best regard

chenjianlin and zhengxiaoyuan

NIST Uncertainty Budget for CCAUV.A-K3	Standard Uncertainty (%) in Given Frequency Range (ALL are Type B except where noted otherwise)														
Source of uncertainty	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	6.3 kHz	8 kHz	10 kHz	12.5 kHz	16 kHz	20 kHz	25 kHz
acoustic transfer impedance 1 (includes effects of coupler length, temperature, microphone impedance parameters)	0,006	0,004	0,004	0,002	0,002	0,004	0,018	0,035	0,025	0,052	0,104	0,131	0,208	0,392	0,85
acoustic transfer impedance 2 (as above)	0,006	0,004	0,004	0,002	0,002	0,004	0,018	0,035	0,025	0,052	0,104	0,131	0,208	0,392	0,85
acoustic transfer impedance 3 (as above)	0,006	0,004	0,004	0,002	0,002	0,004	0,018	0,035	0,025	0,052	0,104	0,131	0,208	0,392	0,85
volume of coupler including microphone front cavity and matching procedure	0,125	0,125	0,125	0,125	0,125	0,125	0,125	0,125	0,227	0,227	0,227	0,227	0,227	0,227	0,227
heat conduction correction	0,200	0,150	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,150	0,200	0,200
ambient barometric pressure (including effects of variations during measurement runs)	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,029	0,003	0,029	0,029	0,029	0,029	0,029
allowance for acoustical leakage	0,250	0,070	0,030												
voltage ratio 1 (including s/n, crosstalk)	0,170	0,170	0,170	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,192
voltage ratio 2(including s/n, crosstalk)	0,170	0,170	0,170	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,192
voltage ratio 3 (including s/n, crosstalk)	0,170	0,170	0,170	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,071	0,192
capacitor value used to determine current, including effect of stray capacitance	0,043	0,043	0,043	0,043	0,043	0,043	0,043	0,043	0,043	0,043	0,043	0,043	0,043	0,043	0,043
polarizing voltage	0,006	0,006	0,006	0,006	0,006	0,006	0,006	0,006	0,006	0,006	0,006	0,006	0,006	0,006	0,006
Estimate of combined standard uncertainty (%)	0,46	0,36	0,34	0,21	0,21	0,21	0,21	0,22	0,29	0,29	0,33	0,36	0,47	0,76	1,54
Estimate of expanded uncertainty (%) with coverage factor equal to 2	0,91	0,73	0,68	0,42	0,42	0,42	0,42	0,43	0,57	0,59	0,67	0,72	0,94	1,51	3,08
Estimate of expanded uncertainty (dB) with coverage factor equal to 2	0,08	0,06	0,06	0,04	0,04	0,04	0,04	0,04	0,05	0,05	0,06	0,06	0,08	0,13	0,26

Uncertainty Budget for CCAUV.A-K3 (NMIJ/AIST)

Uncertainty components			31,5	63	125	250	500	1000	2000	4000	6300	8000	10000	12500	16000	20000	25000	31500
static pressure	A	normal	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001
specific heat ratio	A	normal	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002
coupler volume (including front cavity volumes)	A	normal	0,050	0,050	0,050	0,050	0,050	0,050	0,050	0,050	0,050	0,050	0,050	0,050	0,050	0,050	0,050	0,050
equivalent volumes	A	normal	0,016	0,016	0,016	0,016	0,016	0,016	0,016	0,016	0,016	0,016	0,016	0,016	0,016	0,016	0,016	0,016
voltage transfer function between input terminal of transmitter and output terminal of receiver		combined	0,010	0,007	0,010	0,007	0,007	0,007	0,007	0,006	0,006	0,006	0,005	0,004	0,004	0,060	0,060	0,060
cross-talk	B	rectangular	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001
distortion (linearlity of FFT analyzer)	B	rectangular	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001
attenuator	B	rectangular	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001
transmitter and receiver ground shield	A	normal	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003	0,003
repeatability	A	normal	0,009	0,006	0,009	0,006	0,006	0,006	0,006	0,005	0,005	0,005	0,004	0,003	0,003	0,060	0,060	0,060
leakage of sound	A	normal	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
electrical impedance of transmitter		combined	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002
distortion (linearlity of FFT analyzer)	B	rectangular	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001
repeatability	A	normal	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002	0,002
polarizing voltage	A	normal	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001
uncertainty of device (microphone)	A	normal	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030	0,030
rounding error	B	rectangular	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001
static pressure coefficient of pressure sensitivity	A	normal	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,002	0,003	0,003	0,001
temperature coefficient of pressure sensitivity	A	normal	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,001	0,001	0,002	0,002	0,001	0,002	0,000
coupler correction(heat conduction, capillary tube and wave motion)		combined	0,142	0,025	0,016	0,020	0,011	0,006	0,006	0,006	0,006	0,006	0,007	0,010	0,017	0,031	0,068	0,324
static pressure, temperature and relative humidity	A	normal	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,001	0,003	0,006	0,026
coupler length and diameter	A	normal	0,006	0,002	0,001	0,001	0,001	0,001	0,001	0,002	0,003	0,004	0,006	0,010	0,017	0,030	0,067	0,303
capillary tube length and diameter	A	normal	0,142	0,025	0,015	0,019	0,009	0,002	0,001	0,001	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
resonance frequency, quality factor and tension of microphone diaphragm	A	normal	0,005	0,005	0,005	0,006	0,006	0,006	0,006	0,005	0,005	0,004	0,004	0,002	0,001	0,008	0,012	0,111
Combined standard uncertainty of pressure sensitivity			0,148	0,048	0,044	0,045	0,042	0,041	0,041	0,041	0,041	0,041	0,041	0,041	0,044	0,073	0,095	0,330
Expanded uncertainty of pressure sensitivity (coverage factor : *k*=2)			0,30	0,10	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,15	0,19	0,67

in dB

NPL:

COMPONENTS OF TYPE B UNCERTAINTY EXPRESSED AS SEMI-RANGES (10^{-4} dB)																	
SOURCE	Frequency (Hz)																
Rectangular distribution applies unless stated	31.5	63	125	250	500	1k	2k	4k	5k	6.3k	8k	10k	12.5k	16k	20k	25k	31.5k
Resistance Box Accuracy	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Stray Capacitance	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Non Linearity	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Radius of Coupler	15	15	15	15	15	15	15	16	16	16	16	17	18	21	26	61	5
Velocity of Sound (dry air)	41	42	42	42	42	42	42	40	39	38	35	30	22	5	37	354	137
Ratio of Specific Heats	7	5	3	2	2	1	1	1	0	0	0	0	0	0	0	0	0
Ambient Pressure	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	10	13
Density of Air	10	11	11	11	11	11	11	11	11	11	11	11	11	11	11	8	11
Length of Coupler	36	37	38	38	38	38	37	35	33	30	24	16	1	31	106	674	205
Cavity Depth	2	0	0	0	0	0	0	0	0	0	0	2	2	2	0	4	6
Front Cavity Volume	18	18	18	18	18	18	18	18	16	14	12	8	2	14	52	328	98
Theory of Adding Volume	0	0	0	0	0	0	0	2	3	4	7	12	20	39	82	406	94
Compliance	0	0	0	0	0	0	4	16	26	42	62	72	12	362	1164	4742	1332
Mass	0	0	0	0	0	0	2	4	6	8	8	6	2	58	296	514	40
Resistance	0	0	0	0	0	2	6	22	32	46	60	60	12	102	50	2382	382
Heat Conduction Theory	174	126	91	64	45	30	15	9	21	39	65	101	156	261	474	1288	548
Thermal Diffusivity	66	45	31	22	15	11	8	5	5	4	4	3	3	3	2	2	2
Capillary Radius	292	27	49	63	46	14	9	3	2	1	1	1	0	0	0	0	0
Air Viscosity	23	2	9	10	7	3	0	1	0	0	0	0	0	0	0	0	0
Humidity Determination	1	1	1	1	1	1	1	2	2	2	3	4	5	8	15	67	14
Polarising Voltage	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22
Temperature	2	2	2	1	1	1	1	2	3	4	6	10	16	29	59	280	66
Pressure Radial Non-Unif	0	0	0	0	0	1	2	9	14	22	34	52	76	108	123	43	593
Mic. Temp. Dependence	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Mic. Press. Dependence	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Transmitter Ground Shield	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
Receiver Ground Shield	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19
Rounding Error	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
F0 Press. Dependence	0	0	0	0	0	0	8	12	21	33	42	28	44	222	315	616	5855
F0 Temp. Dependence	0	0	0	0	0	0	11	4	9	19	32	37	16	65	160	229	1743
ESTIMATE OF S.D. (s_B) $s_B = [S(a^2/3)]^{1/2}$	212	105	93	87	79	72	70	71	74	83	98	110	122	312	785	3239	3651

COMPONENTS OF TYPE A UNCERTAINTY EXPRESSED AS STANDARD DEVIATIONS (10^{-4} dB)																	
SOURCE	Frequency (Hz)																
Normal distribution with n®¥ applies unless stated	31.5	63	125	250	500	1k	2k	4k	5k	6.3k	8k	10k	12.5k	16k	20k	25k	31.5k
Allowed Repeatability	150	100	100	100	100	100	100	100	100	150	200	250	350	350	350	350	800
Front Cavity Volume	26	28	28	28	28	28	28	26	24	22	18	12	2	22	78	494	148
ESTIMATE OF S.D. (s_A) $s_A = [S(a^2)]^{1/2}$	152	104	104	104	104	104	104	103	103	152	201	250	350	351	359	605	814

OVERALL UNCERTAINTY (10^{-4} dB)																	
SOURCE	Frequency (Hz)																
	31.5	63	125	250	500	1k	2k	4k	5k	6.3k	8k	10k	12.5k	16k	20k	25k	31.5k
Type B at k=2 ($2s_B$)	424	209	186	175	158	144	141	142	149	167	195	220	244	625	1569	6477	7302
Type A at k=2 ($2s_A$)	304	208	208	208	208	208	208	207	206	303	402	501	700	701	717	1211	1627
Overall Uncertainty at k=2 $s = 2(s_A^2+s_B^2)^{1/2}$	522	295	279	272	261	253	251	251	254	346	446	547	741	939	1725	6589	7481

Table 2 Uncertainty components

R. Barh[illegible].

7 March 2003

NRC Canada
LS2P Pressure Reciprocity Calibration
CCAUV.A-K3

2003-07-08

Sources	*Type*	*Distribution*	Standard uncertainties (dB) for frequency ranges (Hz)					
			40-125	*160-8000*	*10000*	*12500*	*16000*	*20000*
Acoustic transfer impedance	B	Rectangular	0.0144	0.0144	0.0144	0.0231	0.0289	0.0462
Voltage ratio	B	Rectangular	0.0055	0.0035	0.0055	0.0055	0.0055	0.0055
Reference impedance	B	Rectangular	0.0024	0.0024	0.0024	0.0024	0.0024	0.0024
Specific heat ratio	B	Rectangular	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
Density of air	B	Rectangular	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006
Barometric pressure	B	Rectangular	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
Heat-conduction correction	B	Rectangular	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058
Insert voltage	B	Rectangular	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006
Polarizing voltage	B	Rectangular	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Wave motion etc	B	Rectangular	0.0017	0.0017	0.0202	0.0346	0.0462	0.0577
Repeatability	A	Normal	0.0120	0.0100	0.0400	0.0400	0.0400	0.0400
Combined standard uncertainty			0.0207	0.0191	0.0479	0.0584	0.0681	0.0845
Expanded uncertainty (dB) (k=2.00)			**0.05**	**0.04**	**0.10**	**0.12**	**0.14**	**0.17**

PTB:

LS2P microphones		Frequency in Hz											
		63	125	250	500	1k	2k	4k	8k	10k	12.5k	16k	20k
Type A uncertainty, as standard deviation (10^{-4} dB)													
Normal distribution													
Source of uncertainty													
	Repeatability of electrical transfer impedance measurement	100	100	100	100	100	100	100	100	160	200	300	400
Estimate of a type A uncertainty (S.D.), k=1		100	100	100	100	100	100	100	100	160	200	300	400
Type B uncertainty, as semi-ranges (10^{-4} dB)													
Source of uncertainty													
Rectangular distribution													
Measurement	Resistance box	50	50	50	50	50	50	50	50	50	50	50	50
	Polarization Voltage	22	22	22	22	22	22	22	22	22	22	22	22
Microphone parameters	Acoustic impedance (fit)	200	200	200	200	200	200	200	200	400	600	600	800
	Cavity depth	1	1	1	1	1	1	1	2	2	2	1	1
Couplers	Diameter	20	20	20	20	20	20	20	20	22	22	22	22
	Length	40	40	40	40	40	40	40	30	20	10	40	50
Correction of results to normal environmental conditions	Static pressure	10	10	10	10	10	10	10	20	20	20	20	20
	Temperature	30	30	30	30	30	30	30	30	30	30	30	30

		63	125	250	500	1k	2k	4k	8k	10k	12.5k	16k	20k
Environmental conditions	Static pressure	30	30	30	30	30	30	30	30	30	30	30	30
	Temperature	5	5	5	5	5	5	5	5	10	20	30	30
	Humidity	5	5	5	5	5	5	5	10	15	20	20	20
Rounding error		50	50	50	50	50	50	50	50	50	50	50	50
Estimate of type B uncertainty (S.D.), k=1		128	128	128	128	128	128	128	128	237	351	352	466

Overall uncertainty (10^{-4} dB)

	63	125	250	500	1k	2k	4k	8k	10k	12.5k	16k	20k
Type A, k=2	200	200	200	200	200	200	200	200	320	400	600	800
Type B, k=2	257	257	257	257	257	257	257	256	475	701	703	932
Overall uncertainty, k=2	325	325	325	325	325	325	325	325	572	808	925	1229

UME:

Frequency	63	125	250	500	1000	2000	4000	5000	6300	8000	10000	12500	16000	20000	Type of dist.
Ratio Voltmeter Accuracy	50	50	50	50	50	50	100	100	100	100	100	100	100	100	Rectangular
Stray Capacitance	50	50	50	50	50	50	50	50	50	50	50	50	50	50	Rectangular
Non Linearity of ratio voltmeter	100	100	100	100	100	100	100	100	100	100	100	100	100	100	Rectangular
Radius of coupler	100	100	100	100	100	100	100	100	100	100	100	100	100	100	Rectangular
Velocity of Sound	0	0	0	0	0	0	10	10	10	20	25	30	35	60	Rectangular
Change with humidity	10	10	10	10	10	10	10	10	10	10	20	30	40	60	Rectangular
Ratio of specific heat	45	45	45	45	45	45	45	45	45	45	45	45	45	45	Rectangular
Ambient Pressure	43	43	43	43	43	43	43	43	43	43	43	43	43	43	Rectangular
Length of coupler	60	60	60	60	60	60	35	35	30	10	30	10	60	200	Rectangular
Cavity Depth	0	0	0	0	0	0	5	8	8	5	0	5	5	5	Rectangular
Front cavity volume	140	140	140	140	140	140	140	140	100	50	30	200	150	350	Rectangular
Theory of adding volume	0	0	0	1	2	6	22	35	58	60	80	120	200	200	Rectangular
Mass	0	0	0	20	20	60	100	20	100	130	110	125	150	400	Rectangular
Resistance	0	0	10	15	20	60	100	100	125	55	100	130	100	100	Rectangular
Heat Conduction Correction	200	200	200	200	200	200	200	200	200	200	200	200	200	200	Rectangular
Capillary Radius	57	64	51	23	4	3	2	0	0	0	0	0	0	0	Rectangular
Air Viscosity	20	20	16	8	3	0	0	0	0	0	0	0	0	0	Rectangular
Humidity Determination	20	20	20	20	20	20	20	20	20	20	20	20	20	20	Rectangular
Polarization Voltage	22	22	22	22	22	22	22	22	22	22	22	22	22	22	Rectangular
Temperature	2	2	2	2	2	2	2	4	6	10	16	28	32	106	Rectangular
Pressure Radial Non Uniformity	0	0	0	0	0	1	5	8	11	18	26	38	54	60	Rectangular
Transmitter Ground Shield	30	30	30	30	30	30	30	30	30	30	30	30	30	30	Rectangular
Receiver Ground Shield	19	19	19	19	19	19	19	19	19	19	19	19	19	19	Rectangular
Rounding error	50	50	50	50	50	50	50	50	50	50	50	50	50	50	Rectangular
Temperature Correction	50	50	50	50	50	50	50	50	50	50	50	50	50	50	Rectangular

Mic.Pressure Correction	70	70	70	70	70	70	70	70	70	70	70	70	70	70	Rectangular
Heat Conduction Theory	128	92	65	45	30	15	9	21	38	64	100	155	260	470	Rectangular
	204	198	193	190	189	195	210	203	210	202	209	268	313	514	Rectangular

Random Uncertainty Components Expressed as Standard Deviations (x 0,0001 dB)

Allowed Repeatability	300	300	300	300	300	300	300	300	300	400	400	400	400	400	Normal
Compliance	0	0	0	20	40	50	50	50	50	50	20	110	180	300	Normal
Mass	0	0	0	20	20	60	100	20	100	120	110	125	150	400	Normal
Resistance	0	0	10	15	20	60	100	100	125	55	100	130	100	100	Normal
Front Cavity Volume	100	100	100	100	100	100	90	90	80	70	50	50	100	250	Normal
Overall Uncertainty at % 95 CL	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.09**	**0.10**	**0.11**	**0.12**	**0.17**	

VNIIFTRI:

The expression for expanded uncertainty U (for k=2 and P=0.95), dB is:

$$U = 2 \cdot \sqrt{U_A^2 + U_B^2}$$

where:

$$U_A = \sqrt{\frac{\sum_{j=1}^{m} \left(M_j - \overline{M}\right)^2}{m \cdot (m-1)}}$$ is type A uncertainty;

$$\overline{M} = \frac{1}{m} \sum_{j=1}^{m} M_j$$ is the average sensitivity from a number of measurements;

M_j - is the sensitivity level, dB re 1V/Pa ;

m = 5 – numbers of measurements;

$$U_B = \frac{1}{\sqrt{3}} \cdot \sqrt{\sum_{i=1}^{n} C_i \cdot \Theta_i^2}$$ is type B uncertainty;

n =1…9 – identification number of input quantities ;

$$\Theta_i = \left| \frac{\partial M}{\partial X_i} \cdot \Delta X_i \right|$$, dB are components of type B uncertainty;

$$\Delta X_i = \sqrt{\Delta X_{i,ran}^2 + \Delta X_{i,sis}^2}$$ is the uncertainty of input quantity i;

$\Delta X_{i,sis}$ - is the systematic uncertainty of input quantity i;

$\Delta X_{i,ran}$ - is the random uncertainty of input quantity i;

X_1 – is the electrical transfer impedance, dB; ΔX_1 = 0,01; C_1 =3;

X_2 – is the geometrical distance between the microphone diaphragms, m; $\Delta X_2 = 0.02 \cdot 10^{-3}$; C_2 =3;

X_3 – is the geometrical volume of the coupler including the front cavity volumes of a pair of microphones, m^3; $\Delta X_2 = 1 \cdot 10^{-9}$; C_2 =3;

X_4 – is the acoustic compliance of a microphone, m^5/N^4; $\Delta X_4 = 64.9 \cdot 10^{-16}$; C_4 =1;

X_5 – is the acoustic resistance of a microphone, Ns/m^5; $\Delta X_5 = 11.7 \cdot 10^6$; C_5=1;

X_6 – is the acoustic mass of a microphone, kg/m^4; $\Delta X_6 = 80.6$; C_6=1;

X_7 – is the temperature of the gas in the coupler, ^oC; ΔX_7=2; C_7=1;

X_8 – is the atmospheric pressure, mm Hg; ΔX_8=0.15 ; C_8=1;

X_9 – is the relative humidity of the gas in the coupler, %; ΔX_9=20; C_9=1.

Θ_i, U_A and U are given in the table below.

Table

Hz	$\Theta_i \times 10^3$, dB									$U_A \times 10^3$, dB	U_B, dB	U, dB
	Θ_1	Θ_2	Θ_3	Θ_4	Θ_5	Θ_6	Θ_7	Θ_8	Θ_9			
31,5	10,0	0,0	10,7	18,6	0,0	0,0	1,9	0,8	1,2	70,0	0,018	0,145
40	10,0	0,0	10,7	18,7	0,0	0,0	1,7	0,8	1,2	50,0	0,018	0,106
50	10,0	0,0	10,7	18,8	0,0	0,0	1,6	0,8	1,2	37,0	0,018	0,083
63	10,0	0,0	10,7	18,9	0,0	0,0	1,4	0,8	1,2	27,0	0,018	0,065
80	10,0	0,0	10,7	19,0	0,0	0,0	1,3	0,8	1,2	20,0	0,018	0,054
100	10,0	0,0	10,7	19,0	0,0	0,0	1,2	0,8	1,2	15,0	0,018	0,047
125	10,0	0,0	10,7	19,1	0,0	0,0	1,1	0,8	1,2	10,0	0,018	0,042
160	10,0	0,0	10,7	19,2	0,0	0,0	1,0	0,8	1,2	5,0	0,018	0,038
200	10,0	0,0	10,7	19,2	0,0	0,0	1,0	0,8	1,2	5,0	0,018	0,038
250	10,0	0,0	10,7	19,3	0,0	0,0	0,9	0,8	1,2	5,0	0,018	0,038
315	10,0	0,0	10,7	19,3	0,0	0,0	0,8	0,8	1,2	5,0	0,018	0,038
400	10,0	0,0	10,7	19,4	0,0	0,0	0,8	0,8	1,2	5,0	0,018	0,038
500	10,0	0,0	10,7	19,4	0,0	0,0	0,7	0,8	1,2	5,0	0,018	0,038
630	10,0	0,0	10,7	19,4	0,0	0,0	0,7	0,8	1,2	5,0	0,018	0,038
800	10,0	0,0	10,7	19,4	0,1	0,0	0,7	0,8	1,2	5,0	0,018	0,038
1000	10,0	0,1	10,7	19,4	0,1	0,0	0,7	0,8	1,2	5,0	0,018	0,038
1250	10,0	0,1	10,7	19,3	0,1	0,1	0,7	0,8	1,2	5,0	0,018	0,038
1600	10,0	0,2	10,7	19,2	0,2	0,1	0,7	0,8	1,2	5,0	0,018	0,038
2000	10,0	0,2	10,7	19,1	0,3	0,2	0,8	0,8	1,2	7,0	0,018	0,039
2500	10,0	0,4	10,7	18,8	0,5	0,2	0,9	0,8	1,3	7,0	0,018	0,039
3150	10,0	0,6	10,7	18,4	0,9	0,4	1,1	0,8	1,3	7,0	0,018	0,039
4000	10,0	1,0	10,7	17,6	1,3	0,6	1,5	0,8	1,4	8,0	0,018	0,039
5000	10,0	1,5	10,8	16,5	2,1	0,9	2,1	0,8	1,6	10,0	0,018	0,041
6300	10,0	2,4	10,8	14,6	3,1	1,2	3,0	0,8	1,8	12,0	0,017	0,042
8000	10,0	4,0	10,8	11,5	4,5	1,5	4,6	0,8	2,2	15,0	0,017	0,046
10000	10,0	6,4	10,9	6,9	5,7	1,4	7,2	0,8	2,9	25,0	0,018	0,061
12500	10,0	10,7	11,1	1,7	4,7	0,6	11,6	0,8	4,0	40,0	0,020	0,089
16000	10,0	18,2	11,2	3,1	2,2	1,6	19,4	0,9	6,0	60,0	0,026	0,131
20000	10,0	32,9	11,2	24,6	5,3	20,2	34,6	0,9	9,8	80,0	0,046	0,184
22400	10,0	47,0	11,2	37,6	8,9	38,9	49,4	0,9	13,4	90,0	0,066	0,223
25000	10,0	75,0	10,5	42,9	41,4	55,9	78,4	0,8	20,7	120,0	0,101	0,314
31500	10,0	338,5	10,7	151,8	142,2	313,6	352,0	0,8	86,9	150,0	0,454	0,956