Report on the Regional Comparison
COOMET.AUV.A-K3

Summary

COOMET.AUV.A-K3 is a Regional Comparison that supplements the CCAUV.A-K3 Key Comparison organised by the CCAUV. The participating NMI's are GUM (Poland), INM (Romania), VNIIFTRI (Russia), and DP-NDI "Systema" (Ukraine). The rôle of Pilot laboratory was undertaken by DPLA-DFM (Denmark). The measurements took place between May 2005 and February 2006. The time schedule was organised in a single star configuration. Initially, two LS2aP microphones were circulated. However, a sudden change of sensitivity of one of them forced the inclusion of an additional microphone. Nevertheless, the analysis was performed on all microphones involved. This report includes the measurement results from the participants, information about their calibration methods, and the analysis leading to the assignation of equivalence degrees and the link to the CCAUV.A-K3.

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Content

1 Introduction

The CCAUV.A-K3 comparison under the auspices of the CCAUV-BIPM has been underway since 2003. Four countries of the Euro-Asian region were interested on participating in the CCAUV-A.K3. However, the number of participating countries from each metrological region is limited; therefore a supplementary comparison was suggested. COOMET.AUV.A-K3 is a regional key comparison that supplements the CCAUV.A-K3 key comparison organised by the CCAUV.

The standards are LS2aP microphones and they must be calibrated using the reciprocity technique in the frequency range from 20 Hz to 20 kHz in 1/3-octave intervals. Initially, two microphones were circulated. A sudden change of sensitivity of one of them forced the inclusion of an additional microphone. The analysis was performed on all the microphones. The participating NMI's are GUM (Poland), INM (Romania), VNIIFTRI (Russia), and DP-NDI "Systema" (Ukraine). The rôle of Pilot laboratory was undertaken by DPLA-DFM (Denmark). The measurements took place between May 2005 and February 2006. The time schedule was organised in a single star configuration.

This report includes the measurement results from the participants, information about their calibration methods, and the analysis leading to the assignation of equivalence degrees and the link to the CCAUV.A-K3. The reader is referred to the protocol and reports of the CCAUV.A-K3 for further information about the measurement requirements, frequencies of interest, methods used in the treatment of the data, etc.

2 Comparison protocol

The protocol followed in the comparison is based on the CCAUV.A-K3 protocol with some clarifications. It was emphasized that the calibrations shall be performed at the preferred nominal frequencies rather than the exact frequencies. Although not requested by the protocol, only two laboratories declared results using three decimals. In this report, the results are presented in the same way they were declared. The microphones were transported either by hand or by a courier company (DHL). The container used under the courier transportation was provided by DPLA-DFM.

3 Travelling microphones

Two LS2 microphones, Brüel & Kjær 4180, serial numbers 1503926 and 1503933, were supplied by DPLA-DFM and circulated among the participants. In the middle of the comparison a sudden change occurred in the sensitivity of one of the microphones of the original pair. Therefore, a third microphone Brüel & Kjær 4180, serial number 1526170, was introduced in case the microphone remained unstable. DPLA has monitored the microphones since the beginning of the comparison.
Figure 1 shows DPLA's results of the control calibrations for some selected frequencies during the comparison span. It can be clearly seen that microphone 1503926 showed a significant change of sensitivity but remained stable with its new sensitivity after the change. This is further confirmed in figure 2, which shows the results over the whole frequency range of the three microphones. The sensitivity of the microphone 1503926 is shown before and after the change of sensitivity.

Consequently it was decided to conduct the statistical analysis using all measurement results and consider the results for microphone 1503926 before and after the change as two different microphones.

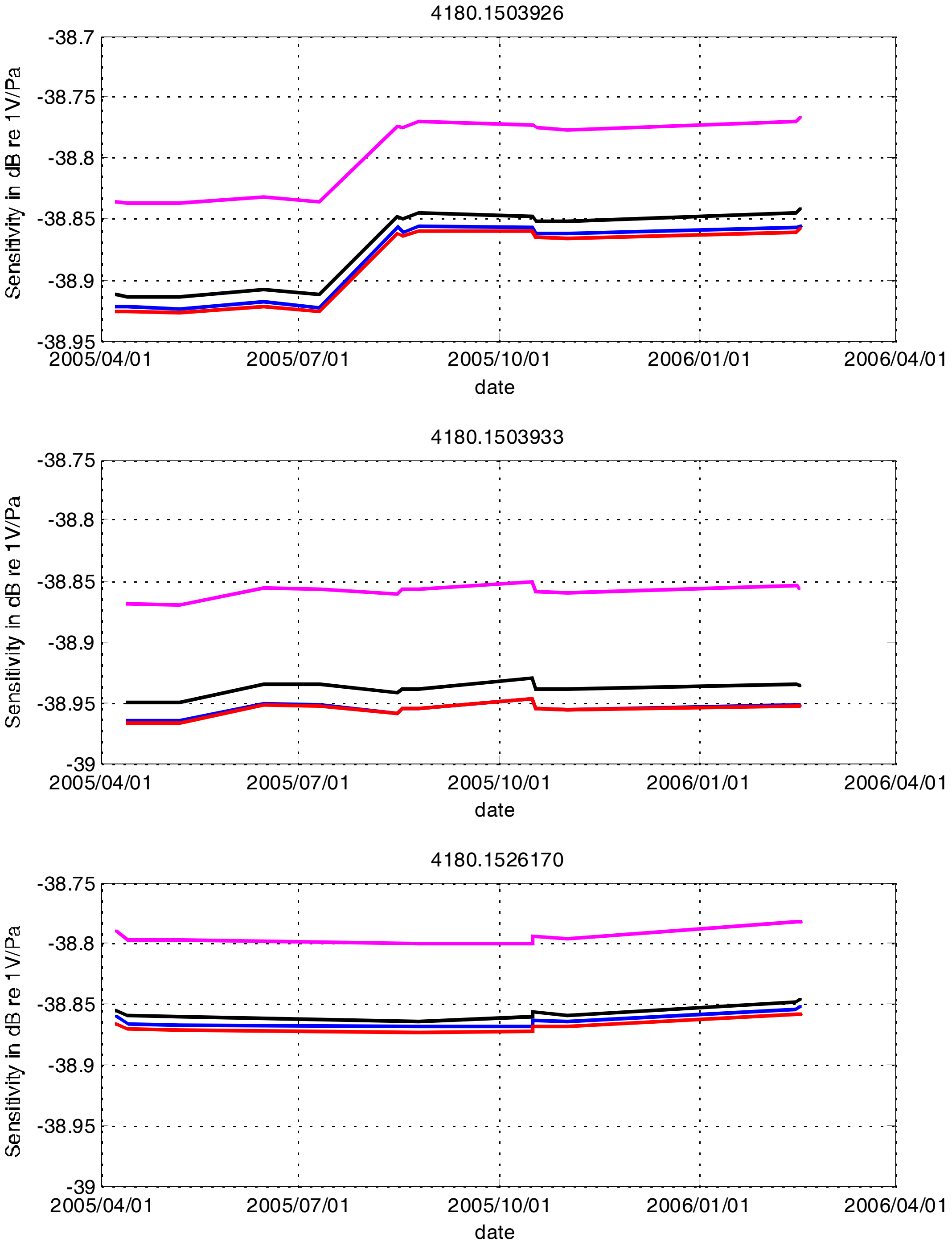

Figure 1. Time history of the calibrations performed at DPLA during the comparison. Blue line: 250 Hz; red line 500 Hz; black line 1 kHz; and magenta line 2 kHz.

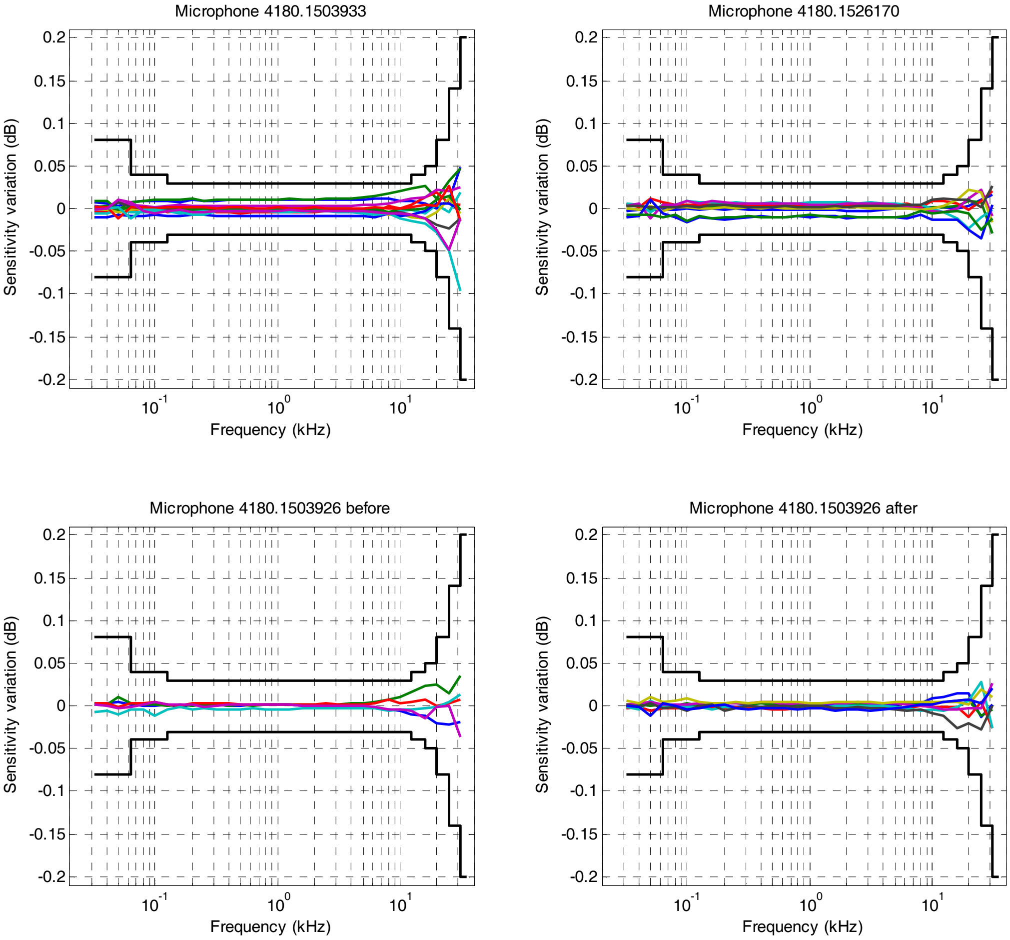

Figure 2 DPLA measurements over frequency, with the DPLA uncertainty bounds. Results of the microphone 1503926 are shown before and after the change of sensitivity.

4 Results

4.1 Calibration methods

A description of the calibration methods and the reporting of results of each laboratory is given below. The description of the methods used in DPLA and GUM are taken from the 'Final Report on the Key Comparison CCAUV.A-K3', see http://www.iop.org/ej/abstract/0026-1394/43/1A/09001/.

DPLA:
"DPLA measured the standards at least once before and after being sent to every other laboratory. The very first measurement round for each microphone reported by DPLA has been used as the officially reported DPLA result.
Measurement principle
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 23.0ºC ± 1.5ºC. Humidity is kept within the range 40% - 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 data fitting 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 are the average of a calibration in only two couplers."

DP NDI "Systema":
"This pressure calibration of the standard microphones was carried out with primary method in accordance with IEC 61094-2 and Technical protocol for key comparison COOMET.A-K3 by means of a semi-automate pressure reciprocity calibration system type УЕ-2П and its software. The type УЕ-2П system consists of a measurement device, power supply, PC computer, filter and the B&K device type 4143.
The acoustic bloc, amplifiers and generator of polarization voltage of device 4143 are used only.
The measurement device is precision two channel digital voltmeter. It measures the transfer impedance of pairs of coupled microphones.
The software is included for calculation of the sensitivity and for measurement control.

The radial wave motion, typical values of the static pressure coefficient and the temperature coefficient, the typical resonance frequency and loss factor were taken into account. Frequency dependence of equivalent volume was calculated via low frequency equivalent volume, resonance frequency and loss factor.
The low frequency equivalent volume was determined as a difference between total volume and front volume. The total volume was determined via the depth of the front cavity. The depth of the front cavity was determined by using the focusing microscope.
The two of plane-wave couplers of known dimensions and different lengths were used to determine the total volume."

GUM:

"Deviations from the recommendations given in IEC 61094-2:

- The speed of sound value equal to 345,87400455 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 optimise 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 · 10^3 kg · m^{-4},
acoustical compliance of the diaphragm: 5,850 · 10^{-14} m^5 · N^{-1};
acoustical resistance of the diaphragm: 1,520 · 10^8 N · s · m^{-5},
front volume of the microphone: 34,5 mm^3,
depth of front cavity: 0,49 mm."

INM:
The calibration was carried out with respect to Technical Protocol for key comparison COOMET.AUV.A-K3, using a primary method. 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 20 kHz as well as 31.5 kHz.
The system used for calibration is Reciprocity Calibration System Type 9699. The microphones sensitivity is calculated using MP.EXE software developed at DTU.
The reciprocity technique is in accordance with IEC 61094-2 and use three microphones pair coupled through two air-filled plane-wave couplers (type UA 1414 and type UA 1430) with nominal length of 4.7 mm end 9.4 mm to cover the entire frequency range.

The polarization voltage during the measurements was monitored by Keithley 2000 Digital Multimeter and was measured at the port of the reciprocity calibration apparatus, instead of the terminals of the microphone.

Nominal values for the microphone cavity depth (0.50 mm), resonance frequency (22 kHz) and loss factor (1.05) declared by the manufacturer were used for the sensitivity calculation. Values for microphone equivalent and front volumes were determined by data fitting of microphone sensitivity obtained for the two couplers in the low frequency range.

No grease was applied to the contacting surfaces between the microphones and the coupler
Measurement conditions:

- Pressure interval : 99.83 - 102.34 kPa ;
- Temperature interval : 24.1 – 25.8 ºC;
- Relative humidity : 23 - 31.5 % RH ;
- Polarisation voltage : 200.00 ± 0.05 V

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

- Static pressure: 101.3250kPa;
- 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 measurements were performed at ambient environmental conditions and then corrected to the reference tempera-

ture 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 a 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)"

4.2 Microphone parameters

The values of the microphone parameters have been reported by the laboratories in two different fashions. All laboratories but GUM reported the equivalent volume, v_{eq}, resonance frequency, f_0, and loss factor, d. GUM reported the acoustic mass, m_{a}, compliance, c_{a}, and resistance, r_{a} instead. These quantities can be used interchangeably by using the following expressions:

$$v_{\mathrm{eq}} = \gamma \cdot p_{\mathrm{s}} \cdot c_{\mathrm{a}},$$

$$f_0 = \frac{1}{2\pi} \frac{1}{\sqrt{m_{\mathrm{a}} \cdot c_{\mathrm{a}}}},$$

$$d = 2\pi \cdot f_0 \cdot c_{\mathrm{a}} \cdot r_{\mathrm{a}},$$

where γ is the specific heat ratio at reference conditions, and p_{s} is the reference static pressure, 101.325 kPa. The values of the acoustic mass, compliance and resistance declared by GUM are in the table below.

Table 1 - Acoustic parameters of the microphones declared by GUM

	4180.1503926	4180.1503933
Acoustic mass (kg/m^4)	1.076e3	1.076e3
Acoustic compliance (m^5/N)	5.85e-14	5.85e-14
Acoustic resistance (Ns/m^5)	1.52e8	1.52e8

The values of the microphone parameters reported by each laboratory are given in the following tables.

Table 2 - Acoustic parameters of the microphone 4180.1503926

	DPLA	GUM	DP NDI	VNIIFTRI	INM
Front volume (mm3)	32.0	33.7	32.44	33.7	34.0
Equivalent volume (mm3)	10.0	8.3	9.34	9.2	9.2
Loss factor	1.0	1.12	1.07	1.03	1.05
Resonance frequency (kHz)	22.6	20.06	22.34	21.93	22.00
Front cavity depth (mm)	0.48	0.485	0.473	0.481	0.5
Temp. coeff. at 250 Hz (dB/K)	-0.00055	-0.0000	-0.0012	-0.0012	-0.002
Static press. coeff. at 250 Hz (dB/kPa)	-0.0055	-0.0055	-0.00519	-0.0055	-0.0055

Table 3 - Acoustic parameters of the microphone 4180.1503933

	DPLA	GUM	DP NDI	VNIIFTRI	INM
Front volume (mm3)	31.8	33.1	32.8	34.3	34.0
Equivalent volume (mm3)	10.0	8.3	9.29	9.5	9.2
Loss factor	1.0	1.12	1.07	1.05	1.05
Resonance frequency (kHz)	22.35	20.06	22.34	22.017	22.00
Front cavity depth (mm)	0.483	0.485	0.480	0.485	0.5
Temp. coeff. at 250 Hz (dB/K)	-0.0008	-0.0000	-0.0012	-0.0012	-0.002
Static press. coeff. at 250 Hz (dB/kPa)	-0.0055	-0.0055	-0.00519	-0.0055	-0.0055

Table 4 - Acoustic parameters of the microphone 4180.1526170

	DPLA	VNIIFTRI	INM
Front volume (mm3)	31.2	33.0	34.0
Equivalent volume (mm3)	9.6	9.3	9.2
Loss factor	1.13	1.05	1.05
Resonance frequency (kHz)	22.9	22.068	22.00
Front cavity depth (mm)	0.476	0.468	0.5
Temp. coeff. at 250 Hz (dB/K)	-0.0013	-0.0012	-0.002
Static press. coeff. at 250 Hz (dB/kPa)	-0.0049	-0.0055	-0.0055

4.3 Microphone sensitivities

The microphone sensitivity reported by each laboratory for each microphone is given in the tables 5 – 8 below. The sensitivity is given in dB re 1 V/Pa

The uncertainties in dB declared by each laboratory are listed in table 9.

Table 5 - Sensitivity in dB re 1V/Pa of the microphone 1503926
***before* the change of sensitivity**

Frequency	DPLA	GUM	DP NDI
31.5	-38.874		-38.920
63	-38.890	-38.900	-38.920
125	-38.906	-38.920	-38.930
250	-38.918	-38.920	-38.950
500	-38.924	-38.930	-38.950
1000	-38.925	-38.920	-38.950
2000	-38.897	-38.900	-38.920
4000	-38.772	-38.780	-38.800
6300	-38.535	-38.560	-38.560
8000	-38.319	-38.340	-38.350
10000	-38.058	-38.090	-38.090
12500	-37.812	-37.840	-37.850
16000	-37.958	-37.960	-38.020
20000	-39.159	-39.130	-39.210
25000	-41.582	---	---
31500	-44.390	---	---

Table 6 - Sensitivity in dB re 1V/Pa of the microphone 1503926 *after* the change of sensitivity

Frequency (Hz)	DPLA	VNIIFTRI	INM
31.5	-38.802	-38.772	-38.790
63	-38.821	-38.783	-38.812
125	-38.839	-38.798	-38.830
250	-38.851	-38.812	-38.843
500	-38.860	-38.821	-38.852
1000	-38.860	-38.823	-38.851
2000	-38.833	-38.797	-38.825
4000	-38.711	-38.675	-38.695
6300	-38.478	-38.443	-38.461
8000	-38.265	-38.231	-38.249
10000	-38.015	-37.977	-37.991
12500	-37.787	-37.751	-37.763
16000	-37.962	-37.933	-37.970
20000	-39.197	-39.175	-39.248
25000	-41.593	-41.605	---
31500	-44.394	-45.111	-45.994

Table 7 - Sensitivity in dB re 1V/Pa of the microphone 1503933

Frequency (Hz)	DPLA	GUM	DP NDI	VNIIFTRI	INM
31.5	-38.915	---	-38.99	-38.851	-38.891
63	-38.934	-38.96	-38.98	-38.859	-38.913
125	-38.950	-38.97	-38.99	-38.872	-38.928
250	-38.960	-38.97	-39.00	-38.882	-38.938
500	-38.966	-38.98	-39.00	-38.889	-38.944
1000	-38.964	-38.97	-39.00	-38.887	-38.941
2000	-38.933	-38.95	-38.96	-38.857	-38.91
4000	-38.803	-38.82	-38.83	-38.728	-38.776
6300	-38.559	-38.58	-38.58	-38.485	-38.53
8000	-38.337	-38.36	-38.36	-38.261	-38.306
10000	-38.062	-38.09	-38.08	-37.988	-38.029
12500	-37.807	-37.82	-37.82	-37.737	-37.776
16000	-37.950	-37.92	-37.99	-37.896	-37.957
20000	-39.186	-39.11	-39.24	-39.206	-39.259
25000	-41.682	---	---	-41.822	---
31500	-44.577	---	---	-45.238	-46.2

Table 8 - Sensitivity in dB re 1V/Pa of the microphone 1526170

Frequency (Hz)	DPLA	VNIIFTRI	INM
31.5	-38.801	-38.767	-38.765
63	-38.826	-38.777	-38.789
125	-38.842	-38.793	-38.807
250	-38.855	-38.807	-38.820
500	-38.863	-38.816	-38.830
1000	-38.865	-38.819	-38.832
2000	-38.842	-38.798	-38.810
4000	-38.738	-38.692	-38.697
6300	-38.543	-38.493	-38.502
8000	-38.371	-38.316	-38.331
10000	-38.175	-38.116	-38.137
12500	-38.031	-37.973	-38.010
16000	-38.298	-38.255	-38.342
20000	-39.523	-39.522	-39.633
25000	-41.840	-41.942	---
31500	-44.565	-45.147	-45.584

Table 9 - Expanded uncertainties in dB using a coverage factor of $k=2$, as declared by the participant laboratories

Frequency (Hz)	DPLA	GUM	DP NDI	VNIIFTRI	INM
31.5	0.08	---	0.09	0.14	0.055
63	0.04	0.05	0.08	0.07	0.055
125	0.03	0.05	0.07	0.04	0.046
250	0.03	0.05	0.07	0.04	0.046
500	0.03	0.05	0.06	0.04	0.046
1000	0.03	0.05	0.06	0.04	0.046
2000	0.03	0.05	0.06	0.04	0.046
4000	0.03	0.05	0.06	0.04	0.046
6300	0.03	0.05	0.06	0.04	0.046
8000	0.03	0.06	0.07	0.05	0.046
10000	0.03	0.07	0.08	0.06	0.046
12500	0.04	0.08	0.09	0.09	0.047
16000	0.05	0.09	0.14	0.13	0.085
20000	0.08	0.17	0.2	0.18	0.126
25000	0.14	---	---	0.31	---
31500	0.20	---	---	0.96	0.218

5 Analysis of the results

The nature of this comparison —5 participants following a single loop with two travelling standards— should make it possible to use simple methods for estimating the comparison reference value such as those used in the comparison CCAUV.A-K1. However, the comparison has to be linked to the CCAUV.A-K3, and during the circulation one of the microphones changed its sensitivity and an additional microphone was introduced into the circulation loop. Therefore a flexible approach should be followed in order to introduce the complexities that arose in the process. Nielsen provides a method based on least-squares approximation [Nielsen2002] that can be used for dealing with instabilities in the standards and the linking of the results to the Key Comparison.

In general a linear model described by $\mathbf{E}(\mathbf{y}) = \mathbf{X} \cdot \mathbf{a}$ has to be solved for each frequency. In the model **a** is a vector of parameters of the model, **E**(**y**) is the expectation of the measurements and **X** is the design matrix [Nielsen2002]; these values are the values that should have been measured in absence of uncertainty. The vector **y** is conformed by the *n* measurement values provided by the participants on at least one of the circulated measurement objects. The elements of the design matrix are known a priori with zero uncertainty. The parameters $a_1 \ldots a_k$, $k \geq 1$, are unknown and have to be estimated from the *n* measurement results provided by the participants **y**, and the associated covariance matrix Σ.

The covariance matrix Σ is the sum of two matrixes: Σ_{meas}, which contains the square of the uncertainties claimed by the participants (diagonal elements) and the covariances between the provided measurement results (off-diagonal elements), and Σ_{object}, which contains only diagonal elements that describe the estimated variance of the value of the measurand due to random instability of the circulated objects. Once these matrices have been built, the unknown parameters in the model and the reference values of the comparison can be estimated following the rest of the procedure described in reference [Nielsen2002].

If the reference values of this particular comparison were to be estimated, the design matrix, the covariance matrix and the matrix of the results of the participants should only be constructed using data from this comparison. However, this comparison should be linked to the CCAUV.A-K3 comparison. Therefore the matrices can be built using data from the CCAUV.A-K3 comparison and COOMET.AUV.A-K3 as if it was a single comparison. As the reference values from the Key Comparison must not change, the participants in the COOMET comparison, except DPLA that will serve as a link, are excluded from the determination of the reference value.

On the other hand, the sensitivity change observed in one of the microphones could be modelled in the corresponding covariance matrix. However, it was chosen to handle the measurement values after the sensitivity change as an *additional* standard since the calibration results from the pilot laboratory indicated that the microphone remained stable after the change. In this way, each laboratory has measured at least two standards. The model looks then as

$$
\begin{bmatrix} E(y_{11}) \\ \vdots \\ E(y_{19}) \\ E(y_{21}) \\ \vdots \\ E(y_{29}) \\ E(y_{31}) \\ \vdots \\ E(y_{38}) \\ E(y_{41}) \\ \vdots \\ E(y_{48}) \\ E(y_{51}) \\ \vdots \\ E(y_{53}) \\ E(y_{63}) \\ \vdots \\ E(y_{65}) \\ E(y_{71}) \\ \vdots \\ E(y_{75}) \\ E(y_{83}) \\ \vdots \\ E(y_{85}) \end{bmatrix}
=
\begin{bmatrix}
1 & 0 & 0 & 0 & & & & \\
\vdots & \vdots & \vdots & \vdots & & & & \\
1 & 0 & 0 & 0 & & & & \\
0 & 1 & 0 & 0 & & & & \\
\vdots & \vdots & \vdots & \vdots & & & & \\
0 & 1 & 0 & 0 & & & & \\
0 & 0 & 1 & 0 & & 0 & & \\
\vdots & \vdots & \vdots & \vdots & & & & \\
0 & 0 & 1 & 0 & & & & \\
0 & 0 & 0 & 1 & & & & \\
\vdots & \vdots & \vdots & \vdots & & & & \\
0 & 0 & 0 & 1 & & & & \\
 & & & & 1 & 0 & 0 & 0 \\
 & & & & \vdots & \vdots & \vdots & \vdots \\
 & & & & 1 & 0 & 0 & 0 \\
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 & & & & \vdots & \vdots & \vdots & \vdots \\
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 & 0 & & & 0 & 0 & 1 & 0 \\
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 & & & & 0 & 0 & 1 & 0 \\
 & & & & 0 & 0 & 0 & 1 \\
 & & & & \vdots & \vdots & \vdots & \vdots \\
 & & & & 0 & 0 & 0 & 1
\end{bmatrix}
\cdot
\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \\ a_7 \\ a_8 \end{bmatrix},
\tag{1}
$$

where $E(y_{ij})$ is the expected value of the i-th standard being measured in the j-th laboratory in the loop. The elements of the vector a_j are the parameters to be estimated for the standard j. The standards $i = 1\ldots 4$ are from the CCAUV.A-K3 comparison. The standard $i = 5$ is the microphone S/N 1503926 *before* the change of sensitivity. The standard $i = 6$ is microphone S/N 1503926 *after* the change of sensitivity.

The covariance matrix is a 48x48 matrix that contains the declared uncertainties from each laboratory in the two comparisons. As well as in the case of the CCAUV-A.K3, the correlation value for measurements carried in the same laboratory is set to 0,7. Once these matrices are complete, the estimates of the unknown parameters of the model can be calculated using:

$$
\begin{aligned}
&\hat{\mathbf{a}} = \mathbf{C}\mathbf{X}_r^T\boldsymbol{\Sigma}_r^{-1}\mathbf{y}_r, \\
&\mathbf{C} = \left(\mathbf{X}_r^T\boldsymbol{\Sigma}_r^{-1}\mathbf{X}_r^T\right).^{-1}
\end{aligned}
\tag{2}
$$

where $\mathbf{y}_r$ and $\mathbf{X}_r$ are obtained from **y** and **X** given in (1) by deleting the rows associated with the laboratories excluded from the calculation of the reference values, and Σ_r is the covariance matrix associated with the reduced data set $\mathbf{y}_r$

The reference values of the comparison and the associated covariance matrix should be calculated using:

$$\begin{aligned} \hat{\mathbf{y}} &= \mathbf{X}\hat{\mathbf{a}}, \\ V(\hat{\mathbf{y}}) &= \mathbf{X}V(\hat{\mathbf{a}})\mathbf{X}^T. \end{aligned} \tag{3}$$

The degrees of equivalence are obtained using:

$$\begin{aligned} \mathbf{D_{ii}} &= \mathbf{A}^T(\mathbf{y}-\hat{\mathbf{y}}), \\ V(\mathbf{D_{ii}}) &= \mathbf{A}^T V(\mathbf{y}-\hat{\mathbf{y}})\mathbf{A}, \end{aligned} \tag{4}$$

where $\mathbf{D_{ii}}$ is the degrees of equivalence per laboratory, **A** is an averaging matrix. The inter-laboratory degrees of equivalence can be estimated using [CCAUV.A-K3]:

$$\begin{aligned} D_{ij} &= D_{ii} - D_{jj}, \\ V\left(D_{ij}\right) &= u_{ii} + u_{jj} - u_{ij} - u_{ji,} \end{aligned} \tag{5}$$

where D_{ij} is the inter-laboratory deviation. The u_{xx} elements are obtained from equation (4).

The consistency of results was tested using the procedure described in [Nielsen2002].

6 Results

6.1 Reference values

As well as in the case of the CCAUV.A-K3 comparison, there is not a single key comparison reference value, but one per frequency associated with each one of the standards circulated. The reference values are listed below in table 10. These values were obtained using the procedure described in the previous section.

Table 10 - Reference values for the comparison.
Sensitivities M_p in dB re 1V/Pa and expanded uncertainty u ($k = 2$) in dB.
Microphone 1503926A corresponds to microphone 1503926 before the change of sensitivity, and microphone 1503926B after the change.

Freq. (Hz)	**4180.1503926A**		**4180.1503926B**		**4180.1503933**		**4180.1526170**	
	M_p	u $k=2$	M_p	u $k=2$	M_p	u $k=2$	M_p	U $k=2$
31.5	-38.869	0.051	-38.798	0.051	-38.910	0.051	-38.797	0.051
63	-38.888	0.026	-38.819	0.026	-38.932	0.026	-38.824	0.026
125	-38.903	0.020	-38.837	0.020	-38.948	0.020	-38.840	0.020
250	-38.914	0.020	-38.848	0.020	-38.957	0.020	-38.852	0.020
500	-38.921	0.020	-38.856	0.020	-38.963	0.020	-38.859	0.020
1000	-38.921	0.020	-38.857	0.020	-38.960	0.020	-38.862	0.020
2000	-38.893	0.020	-38.830	0.020	-38.929	0.020	-38.839	0.020
4000	-38.769	0.020	-38.708	0.020	-38.800	0.020	-38.735	0.020
6300	-38.536	0.020	-38.479	0.020	-38.560	0.020	-38.543	0.020
8000	-38.317	0.021	-38.263	0.021	-38.335	0.021	-38.369	0.021
10000	-38.055	0.022	-38.013	0.022	-38.060	0.022	-38.172	0.022
12500	-37.812	0.028	-37.787	0.028	-37.807	0.028	-38.031	0.028
16000	-37.967	0.035	-37.970	0.035	-37.959	0.035	-38.306	0.035
20000	-39.172	0.054	-39.210	0.054	-39.200	0.054	-39.537	0.054
25000	-41.580	0.093	-41.591	0.093	-41.680	0.093	-41.838	0.093
31500	-44.545	0.161	-44.549	0.161	-44.732	0.161	-44.720	0.161

6.2 Degrees of equivalence per laboratory

The degrees of equivalence per laboratory were determined as mentioned in the previous section (equation (4)). Figure 3 and tables 11 and 12 below shows deviations and the degrees of equivalence per laboratory as a function of frequency.

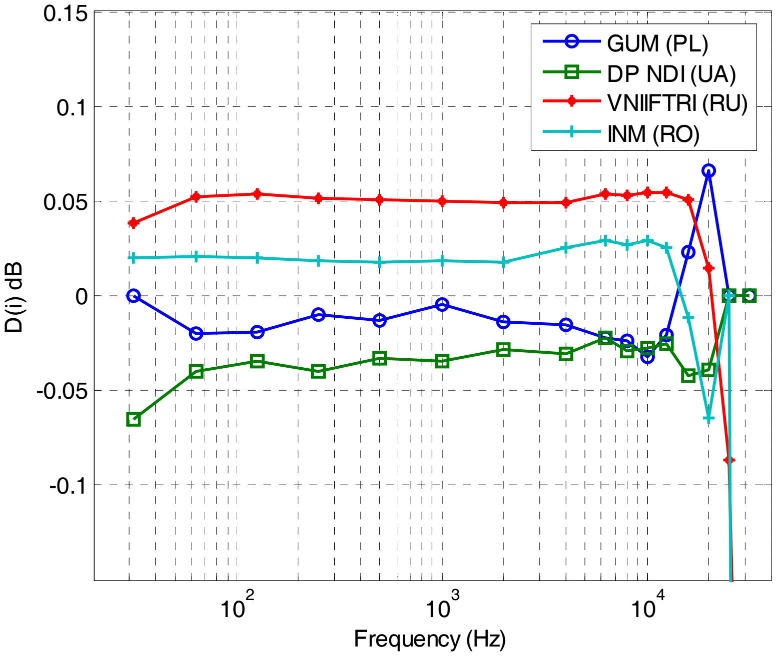


Figure 3. Deviations in dB per laboratory and frequency

Table 11 - Degrees of equivalence per laboratory as function of frequency: deviations (dB)

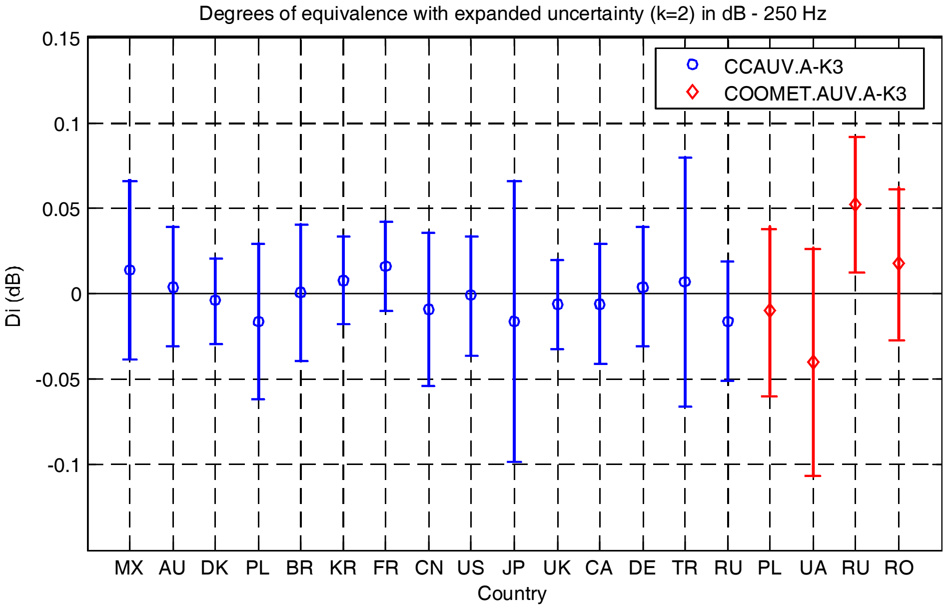
Frequency (Hz)	DPLA	GUM	DP NDI	VNIIFTRI	INM
31.5	-0.005		-0.065	0.038	0.020
63	-0.002	-0.020	-0.040	0.052	0.021
125	-0.003	-0.019	-0.034	0.054	0.020
250	-0.004	-0.010	-0.040	0.052	0.018
500	-0.004	-0.013	-0.033	0.051	0.017
1000	-0.004	-0.004	-0.034	0.050	0.018
2000	-0.003	-0.014	-0.029	0.049	0.018
4000	-0.003	-0.016	-0.031	0.049	0.025
6300	0.001	-0.022	-0.022	0.053	0.029
8000	-0.002	-0.024	-0.029	0.053	0.027
10000	-0.003	-0.033	-0.028	0.055	0.029
12500	0.000	-0.020	-0.025	0.055	0.025
16000	0.010	0.023	-0.042	0.050	-0.011
20000	0.015	0.066	-0.039	0.015	-0.064
25000	-0.002	---	---	-0.087	---
31500	0.172	---	---	-0.498	-1.259

Table 12 - Degrees of equivalence per laboratory as function of frequency: uncertainties *k*=2 (dB)

Frequency (Hz)	DPLA	GUM	DP NDI	VNIIFTRI	INM
31.5	0.069		0.092	0.130	0.061
63	0.033	0.051	0.077	0.065	0.053
125	0.024	0.049	0.067	0.039	0.044
250	0.025	0.049	0.067	0.039	0.044
500	0.025	0.049	0.058	0.039	0.044
1000	0.025	0.049	0.058	0.039	0.044
2000	0.025	0.049	0.058	0.039	0.044
4000	0.025	0.049	0.058	0.039	0.044
6300	0.024	0.049	0.058	0.039	0.044
8000	0.024	0.058	0.067	0.047	0.044
10000	0.023	0.067	0.076	0.056	0.045
12500	0.031	0.077	0.086	0.083	0.047
16000	0.040	0.088	0.132	0.119	0.081
20000	0.065	0.163	0.190	0.166	0.120
25000	0.116	---	---	0.286	---
31500	0.132	---	---	0.869	0.236

6.3 Degrees of equivalence and link to CCAUV.A-K3

Figure 4 and tables 13 and 14 contain the inter-laboratory degrees of equivalence of this comparison linked to the CCAUV.A-K3 Key Comparison. Although the degrees of equivalence are presented for two frequencies, 250 Hz and 1000 Hz, the degrees of equivalence at 1 kHz are selected as reference for this comparison.



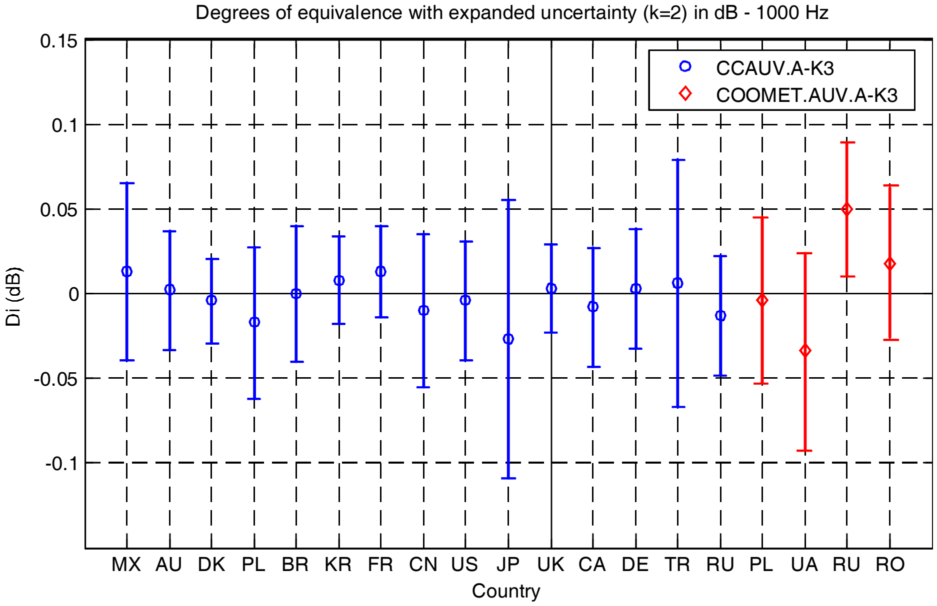


Figure 4 – Inter-laboratory degrees of equivalence at 250 Hz and 1000 Hz linked to the CCAUV.A-K3 key comparison

Table 13 - Inter-laboratory degrees of equivalence at 250 Hz.
The upper triangle contains the differences (dB); the lower triangle contains the uncertainties *k* =2 (dB)

250 Hz	CENAM	DPLA	GUM	KRISS	LNE	NIST	NMIJ	NPL	PTB	CSIRO	INMETRO	NIM	NRC	UME	VNIIFTRI	GUM	DP NDI	VNIIFTRI	INM
CENAM	-	0.018	0.030	0.006	-0.002	0.015	0.030	0.020	0.010	0.010	0.013	0.023	0.020	0.007	0.030	0.024	0.054	-0.038	-0.004
DPLA	0.059	-	0.012	-0.012	-0.020	-0.003	0.012	0.002	-0.008	-0.008	-0.005	0.005	0.002	-0.011	0.012	0.006	0.036	-0.056	-0.022
GUM	0.070	0.053	-	-0.024	-0.032	-0.015	0.000	-0.010	-0.020	-0.020	-0.017	-0.007	-0.010	-0.023	0.000	-0.007	0.023	-0.068	-0.034
KRISS	0.059	0.038	0.054	-	-0.008	0.009	0.024	0.015	0.005	0.004	0.008	0.017	0.014	0.002	0.024	0.018	0.048	-0.043	-0.010
LNE	0.059	0.038	0.054	0.039	-	0.017	0.032	0.022	0.012	0.012	0.015	0.025	0.022	0.009	0.032	0.025	0.055	-0.036	-0.002
NIST	0.064	0.045	0.059	0.046	0.046	-	0.015	0.006	-0.005	-0.005	-0.001	0.008	0.005	-0.007	0.015	0.009	0.039	-0.052	-0.019
NMIJ	0.098	0.087	0.095	0.087	0.087	0.091	-	-0.010	-0.020	-0.020	-0.017	-0.007	-0.010	-0.023	0.000	-0.007	0.023	-0.068	-0.034
NPL	0.059	0.038	0.054	0.039	0.039	0.046	0.087	-	-0.010	-0.010	-0.007	0.003	0.000	-0.013	0.010	0.003	0.033	-0.058	-0.024
PTB	0.064	0.045	0.059	0.046	0.046	0.052	0.091	0.046	-	0.000	0.003	0.013	0.010	-0.003	0.020	0.013	0.043	-0.048	-0.014
CSIRO	0.064	0.045	0.058	0.044	0.044	0.051	0.090	0.044	0.051	-	0.004	0.013	0.010	-0.003	0.020	0.014	0.044	-0.048	-0.014
INMETRO	0.067	0.049	0.061	0.048	0.048	0.054	0.092	0.048	0.054	0.056	-	0.009	0.006	-0.006	0.016	0.010	0.040	-0.051	-0.018
NIM	0.070	0.053	0.064	0.052	0.052	0.058	0.094	0.052	0.058	0.059	0.062	-	-0.003	-0.016	0.007	0.001	0.031	-0.061	-0.027
NRC	0.064	0.045	0.058	0.044	0.044	0.051	0.090	0.044	0.051	0.052	0.056	0.059	-	-0.013	0.010	0.004	0.034	-0.058	-0.024
UME	0.091	0.078	0.086	0.078	0.078	0.082	0.110	0.078	0.082	0.082	0.085	0.087	0.082	-	0.023	0.016	0.046	-0.045	-0.012
VNIIFTRI	0.064	0.045	0.058	0.044	0.044	0.051	0.090	0.044	0.051	0.052	0.056	0.059	0.052	0.082	-	-0.006	0.024	-0.068	-0.034
GUM	0.071	0.055	0.066	0.055	0.055	0.060	0.096	0.055	0.060	0.060	0.063	0.066	0.060	0.088	0.060	-	0.030	-0.061	-0.028
DP NDI	0.084	0.071	0.080	0.071	0.071	0.075	0.106	0.071	0.075	0.075	0.078	0.080	0.075	0.099	0.075	0.079	-	-0.091	-0.058
VNIIFTRI	0.065	0.046	0.059	0.046	0.046	0.052	0.091	0.046	0.052	0.052	0.056	0.059	0.052	0.082	0.052	0.059	0.075	-	0.033
INM	0.068	0.050	0.063	0.051	0.051	0.056	0.093	0.051	0.056	0.056	0.059	0.062	0.056	0.085	0.056	0.063	0.077	0.055	-

Table 14 - Inter-laboratory degrees of equivalence at 1 kHz
The upper triangle contains the differences (dB); the lower triangle contains the uncertainties $k = 2$ (dB)

1000 Hz	CENAM	DPLA	GUM	KRISS	LNE	NIST	NMIJ	NPL	PTB	CSIRO	INMETRO	NIM	NRC	UME	VNIIFTRI	GUM	DP NDI	VNIIFTRI	INM
CENAM	-	0.017	0.030	0.005	0.000	0.017	0.040	0.010	0.010	0.012	0.013	0.024	0.021	0.008	0.027	0.018	0.048	-0.037	-0.005
DPLA	0.059	-	0.013	-0.012	-0.017	0.000	0.023	-0.007	-0.007	-0.005	-0.004	0.007	0.004	-0.009	0.010	0.001	0.031	-0.054	-0.022
GUM	0.070	0.053	-	-0.025	-0.030	-0.012	0.010	-0.020	-0.020	-0.018	-0.017	-0.006	-0.009	-0.022	-0.003	-0.012	0.018	-0.067	-0.035
KRISS	0.059	0.038	0.054	-	-0.005	0.013	0.035	0.005	0.005	0.007	0.008	0.019	0.016	0.003	0.022	0.013	0.043	-0.042	-0.010
LNE	0.060	0.038	0.054	0.040	-	0.017	0.040	0.010	0.010	0.012	0.013	0.024	0.021	0.008	0.027	0.018	0.048	-0.037	-0.005
NIST	0.064	0.045	0.059	0.046	0.047	-	0.022	-0.008	-0.008	-0.006	-0.004	0.006	0.004	-0.010	0.009	0.000	0.030	-0.054	-0.022
NMIJ	0.098	0.087	0.095	0.087	0.088	0.091	-	-0.030	-0.030	-0.028	-0.027	-0.016	-0.019	-0.032	-0.013	-0.022	0.008	-0.077	-0.045
NPL	0.059	0.038	0.054	0.039	0.040	0.046	0.087	-	0.000	0.002	0.003	0.014	0.011	-0.002	0.017	0.008	0.038	-0.047	-0.015
PTB	0.064	0.045	0.059	0.046	0.047	0.052	0.091	0.046	-	0.002	0.003	0.014	0.011	-0.002	0.017	0.008	0.038	-0.047	-0.015
CSIRO	0.064	0.045	0.058	0.044	0.045	0.051	0.090	0.044	0.051	-	0.002	0.012	0.010	-0.004	0.015	0.006	0.036	-0.048	-0.016
INMETRO	0.067	0.049	0.061	0.048	0.049	0.054	0.092	0.048	0.054	0.056	-	0.011	0.008	-0.005	0.014	0.005	0.035	-0.050	-0.018
NIM	0.070	0.053	0.064	0.052	0.053	0.058	0.094	0.052	0.058	0.059	0.062	-	-0.003	-0.016	0.003	-0.006	0.024	-0.060	-0.028
NRC	0.064	0.045	0.058	0.044	0.045	0.051	0.090	0.044	0.051	0.052	0.056	0.059	-	-0.014	0.005	-0.003	0.027	-0.058	-0.026
UME	0.091	0.078	0.086	0.078	0.078	0.082	0.110	0.078	0.082	0.082	0.085	0.087	0.082	-	0.019	0.010	0.040	-0.044	-0.012
VNIIFTRI	0.064	0.045	0.058	0.044	0.045	0.051	0.090	0.044	0.051	0.052	0.056	0.059	0.052	0.082	-	-0.009	0.021	-0.063	-0.031
GUM	0.071	0.055	0.066	0.055	0.056	0.060	0.096	0.055	0.060	0.060	0.063	0.066	0.060	0.088	0.060	-	0.030	-0.054	-0.023
DP NDI	0.078	0.063	0.073	0.063	0.064	0.068	0.101	0.063	0.068	0.067	0.070	0.073	0.067	0.093	0.067	0.072	-	-0.084	-0.053
VNIIFTRI	0.065	0.046	0.059	0.046	0.047	0.052	0.091	0.046	0.052	0.052	0.056	0.059	0.052	0.082	0.052	0.059	0.067	-	0.032
INM	0.068	0.050	0.063	0.051	0.051	0.056	0.093	0.051	0.056	0.056	0.059	0.062	0.056	0.085	0.056	0.063	0.070	0.055	-

7 Conclusions

The results of COOMET.AUV.A-K3 Comparison have been analysed using a least-squares technique. The analysis differs from that performed on the CCAUV.A-K3 Key Comparison in the sense that:

- All the results from the two comparisons are analysed as one large comparison.
- All results from the participants from the Regional Comparison are excluded from the calculations of the reference values, except DPLA that serves as link.

The results of the comparison are satisfactory. In cases where the linking laboratories are consistent, as here, the present linking procedure seems to be robust enough to link any two similar comparisons.

8 References

[CCAUV.A-K3] V. Cutanda-Henríquez, and K. Rasmussen, *Final Report on the Key Comparison CCAUV.A-K3*, Centro Nacional de Metrología, México, Danish Primary Laboratory for Acoustics, Denmark, May 2006.

[NIELSEN 2002] L. Nielsen, *Identification and handling of discrepant measurements in key comparisons*, Danish Institute of Fundamental Metrology, DFM-01-R28, 2002.

Appendix – Uncertainty budgets

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

Responce $u_k(y)$ and contribution ζ_k for microphones type 4180

Responce $u_k(y)$ in dB·10^{-4}

Ordinal No	Input quantity		Sign	On frequencies											
				63 Hz		1 kHz		6,3 kHz		10 kHz		16 kHz		20 kHz	
				$u_k(y)$	ζ_k, %	$u_k(y)$	ζ_k, %	$u_k(y)$	ζ_k, %	$u_k(y)$	ζ_k, %	$u_k(y)$	ζ_k, %	$u_k(y)$	ζ_k, %
1	Voltage ratio	systematic uncertainty	$U_{12}^{1)}$	83	9	62	5	62	5	62	4	83	2	83	1
2			$U_{13}^{1)}$	28	1	21	1	21	1	21	0	28	0	28	0
3			$U_{23}^{1)}$	28	1	21	1	21	1	21	0	28	0	28	0
4		rendom uncertainty	u_{Aij}	39	2	49	3	49	3	49	3	52	1	70	1
5	Temperature		T	12	0	11	0	38	2	81	8	149	7	153	2
6	Static pressure		p_s	59	4	57	4	64	6	75	6	72	2	40	0
7	Relative humidity		H	3	0	3	0	4	0	6	0	13	0	20	0
8	Condenser capacity		C_s	25	1	25	1	25	1	25	1	25	0	25	0
9	Frequency		f	1	0	0	0	4	0	10	0	31	0	53	0
10	Coupler length		l_c	0	0	0	0	2	0	5	0	16	0	28	0
11	Coupler diameter		d_c	0	0	0	0	0	0	0	0	0	0	0	0
12	Coupler volume (passport's)		V_{cp}	36	2	37	2	37	2	38	2	39	0	39	0
13	Front cavity depth		l_F	10	0	1	0	68	7	182	38	527	83	937	94
14	Front cavity diameter		d_F	3	0	1	0	0	0	0	0	0	0	0	0
15	Front cavity volume		V_F	64	5	66	5	67	6	67	5	69	1	70	1
16	Total volume		V_Σ	241	73	248	77	211	62	144	24	8	0	17	0
17	Polarizing voltage		U_p	13	0	13	0	13	0	13	0	13	0	13	0
18	Resonance frequency		f_0	0	0	0	0	16	0	33	1	52	1	45	0
19	Loss factor		D	0	0	1	0	16	0	29	1	9	0	26	0
20	Static pressure corrections		δ_p	24	1	24	1	24	1	24	1	24	0	24	0
21	Temperature corrections		δ_t	36	2	36	2	36	2	36	1	36	0	36	0
22	Speed of sound uncertainty		c_0	0	0	0	0	16	0	33	1	52	1	45	0
23	Ratio of specific heat uncertainty		k	0	0	0	0	16	0	33	1	52	1	45	0
	Combined uncertainty		$u_c(y)$	282		283		267		294		579		967	
					100		100		100		100		100		100

$u_k(y)$ - is the part of standard uncertainty of output estimate y,

resulting from the standard uncertainty u(xk) each input estimate xk

$\zeta_k = u_k^2(y)/u_c^2(y)$

$u_c(y)$ - combined uncertainty

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Condensed uncertainty budget for type 4160 microphones

The condensed uncertainty budget for a pressure reciprocity calibration of B&K Type 4160 microphones are given in the table below. The background for the budget is given in the following remarks:

Item 1: The figures represents the combined effects of the uncertainty on the coupler length (5 μm) and diameter (5 μm) including the resulting changes in heat conduction corrections.

Item 2: The figures represents the combined effects of the uncertainty on the microphone resonance frequency (200 Hz), loss factor (0.05), cavity depth (10 μm), front cavity (3 mm^3) and equivalent volume (1 mm^3).

Item 3: The figures represents 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 represents the combined effects of the measurement uncertainties on static pressure (40 Pa), temperature (1 K) and relative humidity (5 %).

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

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

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

Item 8: The figures represents the estimated error committed by not taking the increased heat conduction caused by the thread in the microphone front cavity into account.

Item 9: The figures represents 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 12: The figures represents the uncertainty on applying a correction for dependence of static pressure and temperature on the microphone sensitivity. (Uncertainty on resonance frequency 200 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
	$\sigma_{\mathrm{B}} = \left(\sum u^2/3\right)^{1/2}$	21.4	16.1	13.5	9.1	8.1	7.6	7.4	7.4	7.4	7.5	7.6	8.8	11.0	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)																	
	$\sigma = 2\left(\sigma_{\mathrm{A}}^2 + \sigma_{\mathrm{B}}^2\right)^{1/2}$	82.0	59.4	45.0	35.1	29.0	25.1	24.9	24.9	24.9	24.9	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	0.1	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)
Warsaw, Poland

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	5	5	5	5	5	5	5	5	5	6	7	8	9	17

COOMET.A– K3 LS2 Standard Microphone reciprocity calibration

Acoustics Laboratory - National Institute of Metrology, Bucharest, Romania

UNCERTAINTY BUDGET - SHORT EXPLANATIONS

In the technical documentation for "Reciprocity Calibration System Type 9699" the microphone pressure sensitivity is calculated be the equation below:

$$M_{P,n} = Cor_{R,n} + Cor_{CV} + Cor_{Ps} + Cor_{FV,n} + Cor_{C} + S_{ref} \quad \text{in dB re. 1V/Pa}$$

and

$$M_{P,n} = Cor_{R,n} + Cor_{CV} + Cor_{Ps} + Cor_{FV,n} + Cor_{C} + S_{list} + C_P + C_T + C_{RH} + C_L$$

the terms having the known signification.

Calculated uncertainty $\Delta M_P(f)$ from Technical Review no1/1998:

$$\Delta M_P(f)[dB] \cong \sqrt{\sum_{i=1}^{N}\left[\Delta Q_i \cdot \frac{dM_P(f)}{dQ_i}[dB]\right]^2}$$

where ΔQ_i are the uncertainty of input quantity *(i)* influencing the microphone pressure sensitivity.

$$\Delta M_P(f)\left[dB\right] \cong \sqrt{\underset{(1)}{u^2\left(Cor_{R,n}\right)} + \underset{(2)}{u^2\left(Cor_{CV}\right)} + \underset{(3)}{u^2\left(Cor_{Ps}\right)} + \underset{(4)}{u^2\left(Cor_{FV,n}\right)} + \underset{(5)}{u^2\left(Cor_{C}\right)} + \underset{(6)}{u^2\left(C_P\right)} + \underset{(7)}{u^2\left(C_T\right)} + \underset{(8)}{u^2\left(C_{RH}\right)} + \underset{(9)}{u^2\left(C_L\right)} + \underset{(10)}{u^2\left(C_{UPOL}\right)}}$$

(1) Uncertainty for Voltage Ratio Correction, $u(Cor_{R,n})$

The Voltage Ratio Correction for one microphone:

$Cor_{R,1}[dB] = \left(R_{12}[dB] + R_{13}[dB] - R_{23}[dB]\right)/2$ equation (4.10) from technical documentation.

$$u\left(Cor_{R,1}\right) = \sqrt{\left[\frac{\partial Cor_{R,1}}{\partial R_{12}} u\left(R_{12}\right)\right]^2 + \left[\frac{\partial Cor_{R,1}}{\partial R_{13}} u\left(R_{13}\right)\right]^2 + \left[\frac{\partial Cor_{R,1}}{\partial R_{23}} u\left(R_{23}\right)\right]^2}$$

$$\frac{\partial Cor_{R,1}}{\partial R_{12}} u\left(R_{12}\right) = \frac{1}{2} u\left(R_{12}\right) \quad ; \quad \frac{\partial Cor_{R,1}}{\partial R_{23}} u\left(R_{23}\right) = -\frac{1}{2} u\left(R_{23}\right) \; ; \quad \frac{\partial Cor_{R,1}}{\partial R_{13}} u\left(R_{13}\right) = \frac{1}{2} u\left(R_{13}\right)$$

$$u\left(Cor_{R,1}\right) = \sqrt{\frac{u^2\left(R_{12}\right) + u^2\left(R_{13}\right) + u^2\left(R_{23}\right)}{4}}$$

using the approximation $u\left(R_{12}\right) = u\left(R_{13}\right) = u\left(R_{23}\right) = u\left(R\right)$

$$u\left(Cor_{R,1}\right) = \frac{\sqrt{3}}{2} u\left(R\right)$$

$u(R)$ is evaluated as type A uncertainty and it is experimental standard deviation of the mean $\overline{R}$

$u(R) = S\left(\overline{R}\right)$ is obtained from the experimental data.

(2) Uncertainty for Coupler Volume Correction, $u(Cor_{CV})$

is given by:

$Cor_{CV} = 10 \log \left(\dfrac{2 \cdot V_{mic}[nom] + V_{coup}}{2 \cdot V_{mic}[nom] + V_{coup}[nom]}\right)$ equation (4.13) from technical documentation.

where:

$V_{mic}[nom]$: sum of nominal front cavity volume and nominal equivalent volume of diaphragm
$V_{coup}[nom]$: nominal cavity volume of the applied coupler
V_{coup}: cavity volume of the individually applied coupler

The coupler volume uncertainty is:

$u(Cor_{CV}) = \frac{\partial Cor_{CV}}{\partial V_{coup}} u(V_{coup})$ where $u(V_{coup})$ is the uncertainty of coupler volume.

$$u(Cor_{CV}) = 10 \left(\frac{\frac{1}{2\,V_{mic}[nom] + V_{coup}[nom]}}{\frac{2\,V_{mic}[nom] + V_{coup}}{2\,V_{mic}[nom] + V_{coup}[nom]} \ln 10} \right) u(V_{coup}) = \frac{10}{\ln 10} \left(\frac{1}{2\,V_{mic}[nom] + V_{coup}} \right) u(V_{coupler})$$

(3) Uncertainty for Static Pressure Correction, *$u(Cor_{Ps})$*

Static Pressure Correction se determină cu relaţia: $Cor_{Ps} = 10 \log \left(\frac{P_{s,nom}}{P_s} \right)$ [dB] ; $P_{s,nom}$ = 101.325 kPa

$u(Cor_{Ps}) = \frac{\partial Cor_{Ps}}{\partial Ps} u(Ps)$, where $u(Ps)$ is the measurement uncertainty of the static pressure

$$u(Cor_{Ps}) = \frac{10}{\ln 10} \cdot \frac{u(Ps)}{Ps}$$

The static pressure is measured with a barometer with the permissible error of 0.1 kPa specified in technical documentation; rectangular distribution:

$$u(Cor_{Ps}) = \frac{10}{\ln 10} \cdot \frac{0.1}{\sqrt{3} \cdot 101.325} = 0.0025 \text{ dB}$$

(4) Uncertainty for Front Volume Correction for microphone, *$u(Cor_{FV,n})$*

$$u(Cor_{FV,n}) = \frac{\partial Cor_{FV,n}}{\partial V_F} u(V_F)$$
$$u(Cor_{FV,n}) \cong u(V_F)$$

From the informations purchased by the producer for LS2P Microphone type 4180, is estimated as $u(V_F)$ = 0.1 mm^3.

$$u(Cor_{FV,n}) = \frac{10}{\ln 10} \cdot \frac{u(V_F)}{V_{total,micr}} = \frac{10}{\ln 10} \cdot \frac{0.1}{34 + 9.2} = 0.01 \text{ dB}$$

(5) Uncertainty Capacitance Correction, *$u(Cor_C)$*

The capacitance correction, expressed in dB, is given by

$Cor_C = 10 \log \left(\frac{C_{nom}}{C} \right)$ where C_{nom} = 4.7 nF and *C* is the capacitance of reference capacitor in Transmitter Unit; the value of this, given in calibration chart, is 4.635 nF.

The capacitance correction uncertainty is

$$u(Cor_C) = \frac{\partial Cor_C}{\partial C} u(C)$$

where $u(C)$ is the uncertainty of *C* which is given by the producer at 95% : *U* = 0.05%, k = 2

u(C) = 0.025% = 0.00115875 nF

$$u(Cor_C) = \frac{10}{\ln 10} \cdot \frac{u(C)}{C} = 0.0011 \text{ dB}$$

(6) Uncertainty with Static Pressure, *u(C_P)*

Reference sensitivity correction with static pressure is given by:

$C_P = \alpha_P (Ps - 101.325 kPa)$, where α_P is pressure coefficient in [dB/kPa]; given as a function of frequencies in tables 5.14-5.15 (coupler UA 1414+LS2P 4180) and the tables 5.16-5.17 (coupler UA 1430+LS2P 4180).

$$u\left[C_P(f)\right] = \frac{\partial C_P}{\partial Ps} u(Ps) = \alpha_P(f) \cdot u(Ps)$$

$u(Ps) = 0.1$ kPa same as (3) paragraph.

(7) Uncertainty with Temperature, *u(C_T)*

$C_T = \beta_T \left(t_{coupl} - 23^\circ C\right)$, where β_T is the microphone temperature coefficient [dB/ºC] taken from the same tables as α_P from (6) paragraph.

$u(C_T(f)) = \frac{\partial C_T}{\partial t_{coupl}} u(t) = \beta_T(f) \cdot u(t)$, where $u(t) = 0.5$ ºC

(8) Uncertainty with Relativ Humidity, *u(C_RH)*

$C_{RH} = \gamma_{RH} \left(H_{coupl} - 50\%\right)$, where γ_{RH} is humidity coefficient [dB/10%RH], taken from the same tables as α_P and β_T .

$$u(C_{RH}(f)) = \frac{\partial C_{RH}}{\partial H_{coupl}} u(H) = \gamma_{RH}(f) \cdot u(H)$$

$u(H) = 10\%$

(9) Uncertainty of Microphone Front Cavity Length, *u(C_L)*

$C_L(f) = \delta_L \cdot \left(L_F - L_{F,nom}\right) \cdot 10 \cdot u(L_F)$, where δ_L is Length coefficient [dB/0.1 mm] we can obtain, from the same tables, funtion of frequency.

$$u\left[C_L(f)\right] = \frac{\partial C_L(f)}{\partial L_F} u(L_F) = \delta_L \cdot 10 \cdot u(L_F)$$

$u(L_F) = 0.01$ mm

$$u\left[C_L(f)\right] = \delta_L \cdot 10 \cdot 0.01$$

(10) Uncertainty of Polarisation Voltage *u(C_UPOL)*

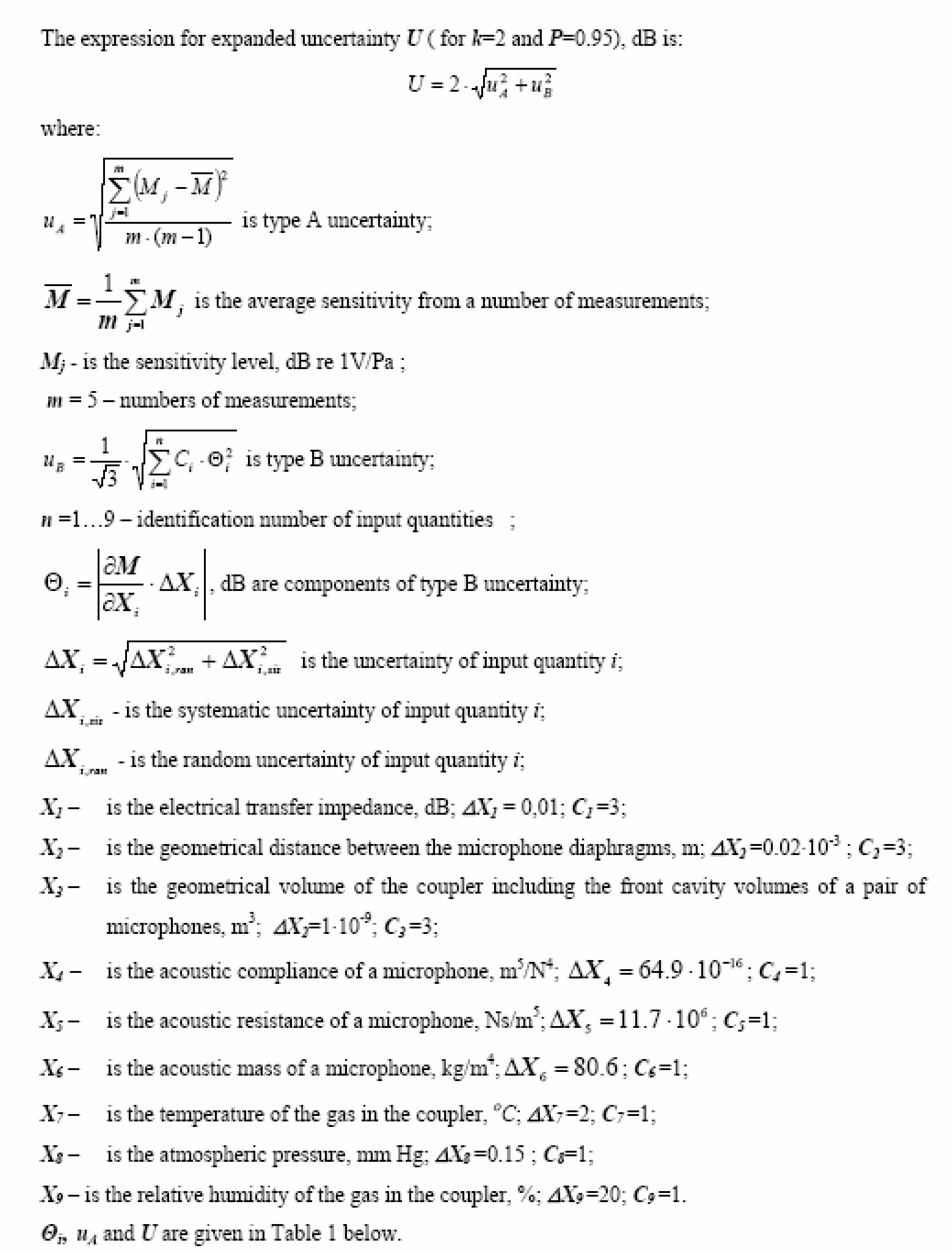
$u(C_{POL}) = u(U_{POL})$

$u(U_{POL})$ = 0.05 V → 0.025%

$u(C_{POL}) = 20 \log(1 + 0.025/100) = 0.0022$ dB; Normal distribution

Uncertainty components

Input Parameter; Symbol	Unit	Nomin. Val.	Uncertainty				Standard Uncertainty (dB) Frecvency (kHz)													
			Unit	Type A	Type B	Distr.	0.031	0.063	0.125	0.250	0.500	1 k	2 k	4 k	6,3 k	8 k	10 k	12,5 k	16 k	20 k
Voltage Ratio Correction, $Cor_{R,n}$	dB	exp. data	dB	$\bar{S}(R)$	0.0014	norm	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014	0.0012	0.0011	0.0011	0.0012	0.0012	0.0014	0.0016	0.0019
Pol. Voltage, C_{POL}	V	200	%		0.025	norm	0.0022	0.0022	0.0022	0.0022	0.0022	0.0022	0.0022	0.0022	0.0022	0.0022	0.0022	0.0022	0.0022	0.0022
Couplor Volume Correction, Cor_{CV}	mm^3	638.53	mm^3		0.2	norm	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
		319.27	mm^3		0.15	norm	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016							
Static Pressure Correction, Cor_{Ps}	kPa	101.325	kPa		0.1	norm	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
Front Volume Correction for microphone, $Cor_{FV,n}$	mm^3	34	mm^3		0.1	norm	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101	0.0101
Capacitance Correction, Cor_C	nF	4.635	%		0.025	norm	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011
Static pressure Correction, C_P	kPa	101.325	kPa		0.1	norm	0.0006	0.0010	0.0012	0.0014	0.0016	0.0017	0.0017	0.0017	0.0015	0.0013	0.0010	0.0004	0.0003	0.0004
Temperature Correction, C_T	ºC	23	ºC		0.5	norm	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0002	0.0005	0.0015	0.0019	0.0031	0.0052	0.0088	0.0158
Humidity Correction, C_{RH}	%	50	%		10	norm	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0007	0.0009	0.0010	0.0014	0.0012	0.0029	0.0048
Reproductibility, M_p	dB						0.0250	0.0250	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0200	0.0400	0.0600
Result Rounding, M_p	dB						0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006
Combined Standard Uncertainty							0.027	0.027	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.023	0.042	0.063
Expanded Standard Uncertainty (k=2)							0.055	0.055	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.047	0.085	0.126



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:

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

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

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

m = 5 – numbers of measurements;

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

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

$\Theta_i = \left| \dfrac{\partial M}{\partial X_i} \cdot \Delta X_i \right|$, 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; $\Delta X_3 = 1 \cdot 10^{-9}$; C_3=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, °C; 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 Table 1 below.

Table 1 – Uncertainty budget

Hz	**Θi×10^3, dB**									*u*a×10^3 dB	*u*b, dB	***U*, dB**
	Θ1	Θ2	Θ3	Θ4	Θ5	Θ6	Θ7	Θ8	Θ9			
31,5	10,0	0,0	10,7	18,6	0,0	0,0	1,9	0,8	1,2	70,0	0,018	0,14
40	10,0	0,0	10,7	18,7	0,0	0,0	1,7	0,8	1,2	50,0	0,018	0,11
50	10,0	0,0	10,7	18,8	0,0	0,0	1,6	0,8	1,2	37,0	0,018	0,08
63	10,0	0,0	10,7	18,9	0,0	0,0	1,4	0,8	1,2	27,0	0,018	0,07
80	10,0	0,0	10,7	19,0	0,0	0,0	1,3	0,8	1,2	20,0	0,018	0,05
100	10,0	0,0	10,7	19,0	0,0	0,0	1,2	0,8	1,2	15,0	0,018	0,05
125	10,0	0,0	10,7	19,1	0,0	0,0	1,1	0,8	1,2	10,0	0,018	0,04
160	10,0	0,0	10,7	19,2	0,0	0,0	1,0	0,8	1,2	5,0	0,018	0,04
200	10,0	0,0	10,7	19,2	0,0	0,0	1,0	0,8	1,2	5,0	0,018	0,04
250	10,0	0,0	10,7	19,3	0,0	0,0	0,9	0,8	1,2	5,0	0,018	0,04
315	10,0	0,0	10,7	19,3	0,0	0,0	0,8	0,8	1,2	5,0	0,018	0,04
400	10,0	0,0	10,7	19,4	0,0	0,0	0,8	0,8	1,2	5,0	0,018	0,04
500	10,0	0,0	10,7	19,4	0,0	0,0	0,7	0,8	1,2	5,0	0,018	0,04
630	10,0	0,0	10,7	19,4	0,0	0,0	0,7	0,8	1,2	5,0	0,018	0,04
800	10,0	0,0	10,7	19,4	0,1	0,0	0,7	0,8	1,2	5,0	0,018	0,04
1000	10,0	0,1	10,7	19,4	0,1	0,0	0,7	0,8	1,2	5,0	0,018	0,04
1250	10,0	0,1	10,7	19,3	0,1	0,1	0,7	0,8	1,2	5,0	0,018	0,04
1600	10,0	0,2	10,7	19,2	0,2	0,1	0,7	0,8	1,2	5,0	0,018	0,04
2000	10,0	0,2	10,7	19,1	0,3	0,2	0,8	0,8	1,2	7,0	0,018	0,04
2500	10,0	0,4	10,7	18,8	0,5	0,2	0,9	0,8	1,3	7,0	0,018	0,04
3150	10,0	0,6	10,7	18,4	0,9	0,4	1,1	0,8	1,3	7,0	0,018	0,04
4000	10,0	1,0	10,7	17,6	1,3	0,6	1,5	0,8	1,4	8,0	0,018	0,04
5000	10,0	1,5	10,8	16,5	2,1	0,9	2,1	0,8	1,6	10,0	0,018	0,04
6300	10,0	2,4	10,8	14,6	3,1	1,2	3,0	0,8	1,8	12,0	0,017	0,04
8000	10,0	4,0	10,8	11,5	4,5	1,5	4,6	0,8	2,2	15,0	0,017	0,05
10000	10,0	6,4	10,9	6,9	5,7	1,4	7,2	0,8	2,9	25,0	0,018	0,06
12500	10,0	10,7	11,1	1,7	4,7	0,6	11,6	0,8	4,0	40,0	0,020	0,09
16000	10,0	18,2	11,2	3,1	2,2	1,6	19,4	0,9	6,0	60,0	0,026	0,13
20000	10,0	32,9	11,2	24,6	5,3	20,2	34,6	0,9	9,8	80,0	0,046	0,18
25000	10,0	75,0	10,5	42,9	41,4	55,9	78,4	0,8	20,7	120,0	0,101	0,31
31500	10,0	338,5	10,7	151,8	142,2	313,6	352,0	0,8	86,9	150,0	0,454	0,96