Final Report EURAMET.AUV.A-S1

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Summary

The Supplementary Regional Comparison EURAMET.AUV.A-S1 has been carried out under the auspices of EURAMET's Technical Committee for Acoustics, Ultrasound and Vibration, and the Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV) of the International Bureau of Weights and Measures (BIPM). The participating NMI's are the Centro Nacional de Metrología (CENAM, Mexico), the Danish Fundamental Metrology (DFM, Denmark), and the Directorate of Measures and Precious Metals (DMDM, Serbia). The role of the Pilot laboratory was jointly undertaken by the DFM and CENAM. The time schedule was organised in a single star configuration. Two LS1P microphones and two LS2aP were circulated among participants. This report includes the measurement results from the participants, and the analysis leading to a proposal for the reference values for the comparison.

Danish Fundamental Metrology Ltd.
Matematiktorvet 307
DK-2800 Kgs Lyngby

Tel +45 4593 1144
Fax +45 4593 1137
www.dfm.dtu.dk

Prepared by
Salvador Barrera-Figueroa and Lars Nielsen
Danish Fundamental Metrology Ltd.
Matematiktorvet 307
DK-2800 Kgs Lyngby

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Content

1 Introduction

The EURAMET.AUV.A-S1 regional supplementary comparison carried out under the auspices of EURAMET's TCAUV. The standards circulated among the laboratories were two LS1P microphones of the type Brüel & Kjær 4160, and two LS2aP of the type Brüel & Kjær 4134S and 4180. The microphones had to be calibrated using the reciprocity technique under pressure conditions in the frequency range from 31.5 Hz to 31.5 kHz, and the open-circuit pressure sensitivity level had to be reported at the nominal preferred 1/3rd-octave centre frequency band. The participating NMI's were the Centro Nacional de Metrología (CENAM, Mexico), Danish Fundamental Metrology (DFM, Denmark), and the Directorate for Measures and Precious Metals (DMDM, Serbia). The National Metrology Institute (INM, Romania) was included in the original timetable; however INM declined participating during the course of the comparison. The time schedule was organised in a single star configuration. The role of the Pilot laboratory was undertaken by the DFM and CENAM. The measurements took place between July 2009 and February 2010.

This report includes the measurement results from the participants, information about their calibration methods, uncertainty budgets, and the analysis leading to the assignation of the degrees of equivalence, and a link to the Key Comparisons CCAUV.A-K1, and CCAUV.A-K3.

2 Comparison protocol

The final version of the protocol was circulated and approved on July 2009. The measurement round started immediately after. Originally, the National Institute of Metrology (INM), Romania, was included in the participants. However, due to institutional reasons, INM declined participating in the comparison.

The protocol is based on the CCAUV.A-K3 comparison protocol, with some changes. The most relevant is the requirement for using the exact 1/3rd-octave centre frequencies from 31.5 Hz to 12.5 kHz for LS1 microphones, and from 31.5 Hz to 31.5 kHz for LS2 microphones. The microphones were transported in all cases by means of a courier company selected by each participant. The container used under the courier transportation was provided by DFM. The participants are listed in Table 1:

Table 1. Participants in the comparison EURAMET.AUV.A-S1

Participant	Acronym	Country (country code)	Regional Metrology Organisation
Centro Nacional de Metrologia	CENAM	Mexico (MX)	SIM
Danish Fundamental Metrology A/S	DFM	Denmark (DK)	EURAMET
Directorate for Measures and Precious Metals	DMDM	Republic of Serbia (RS)	EURAMET

3 Travelling microphones

Two LS1 and two LS2 microphones were supplied by DFM. The microphones were circulated among the participants, and monitored by DFM during the duration of the comparison. Monitoring was based on routine pressure reciprocity calibrations in the same frequency range defined for the measurements of the comparison. Table 2 shows the details of the microphones.

Table 2. Details of the microphones used in the comparison.

Microphone type	Manufacturer	Model	Serial number
LS1	Brüel & Kjær	4160	1453798
LS1	Brüel & Kjær	4160	1453812
LS2	Brüel & Kjær	4134S	0982363
LS2	Brüel & Kjær	4180	1124049

Figure 1 shows DFM's results of the control calibrations on the LS1 microphones for some selected frequencies during the comparison span. Figure 1 also shows the difference of each individual measurement run compared with the average of all measurements made by the DFM for the two microphones over the whole frequency range. Figure 2 shows the same for LS2 microphones.

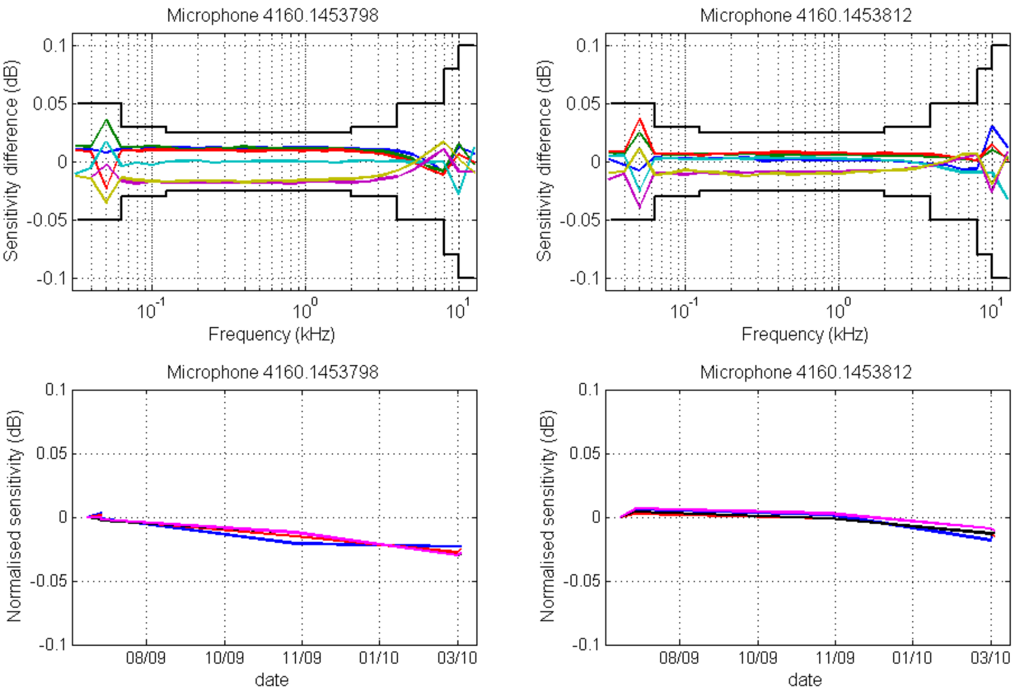

Figure 1 Upper charts: Difference of the sensitivity level of LS1 microphones obtained at each calibration at DFM with respect to their common average for each microphone as a function of frequency (DFM's uncertainty bounds are shown). Lower charts: Changes in the sensitivity level of the microphones as a function of time. The sensitivity level has been normalised to the level of the first measurement. Blue line: 125 Hz; red line 250 Hz; black line 500 Hz; and magenta line 1 kHz.

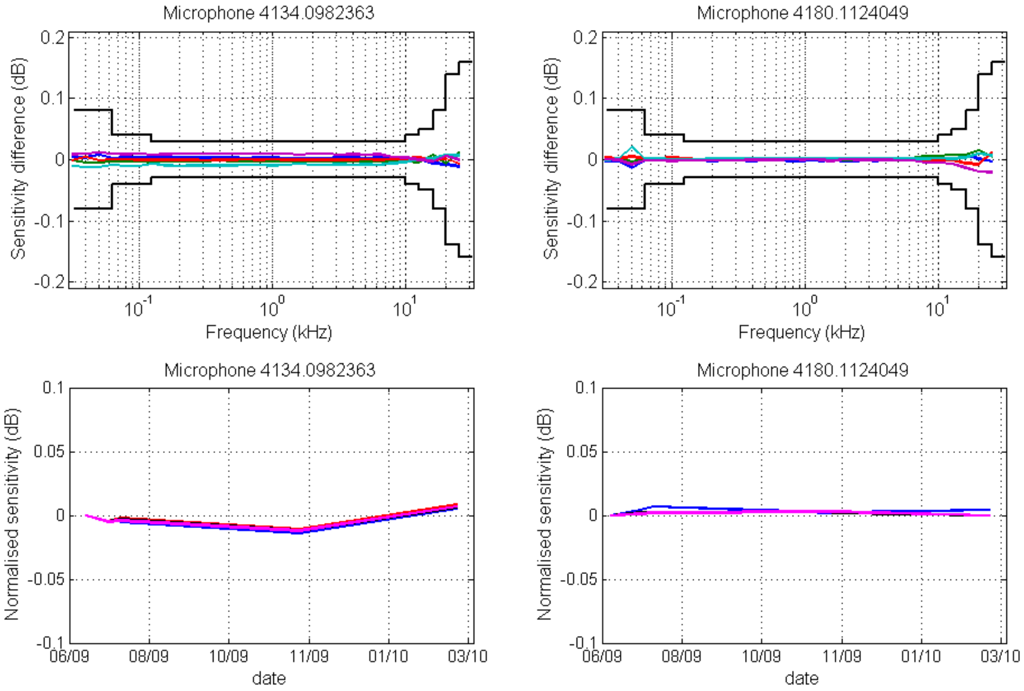

Figure 2 Upper charts: Difference of the sensitivity level of LS2 microphones obtained at each calibration at DFM with respect to their common average for each microphone as a function of frequency (DFM's uncertainty bounds are shown). Lower charts: Changes in the sensitivity level of the microphones as a function of time. The sensitivity level has been normalised to the level of the first measurement. Blue line: 125 Hz; red line 250 Hz; black line 500 Hz; and magenta line 1 kHz.

It can be seen that LS1 microphones were less stable than LS2 microphones, however always within DFM's uncertainty bounds for each type of microphones. The drift observed in microphone M4160.1453798 was considered in the analysis.

4 Reported results

4.1 Microphone sensitivities: Uncertainties

Each laboratory reported their results after their own measurement round as requested in the protocol. The open-circuit, pressure sensitivity level reported by each laboratory for each microphone is given in the Tables 3 and 4 below. The pressure sensitivity level is given in dB re 1 V/Pa. The uncertainties in dB declared by each laboratory are listed in Table 5. The DMDM did not report uncertainty for LS2 microphones at 31623 Hz, and therefore no analysis was performed at that frequency.

Table 3 Pressure sensitivity level of the LS1 microphones in dB re 1 V/Pa

Frequency (Hz)	M4160.1453798					M4160.1453812		
	DFM 2009 07 08	DMDM 2009 09 08	DFM 2009 11 17	CENAM 2010 01 20	DFM 2010 03 05	DFM	DMDM	CENAM
31.623	-26.855	-26.914	-26.876	-26.930	-26.878	-27.073	-27.117	-27.112
39.811	-26.876	-26.927	-26.892	-26.945	-26.901	-27.095	-27.131	-27.128
50.119	-26.898	-26.94	-26.889	-26.959	-26.941	-27.113	-27.146	-27.143
63.096	-26.912	-26.953	-26.927	-26.971	-26.937	-27.123	-27.157	-27.157
79.433	-26.928	-26.966	-26.941	-26.984	-26.956	-27.138	-27.170	-27.170
100.00	-26.945	-26.978	-26.959	-26.997	-26.973	-27.152	-27.180	-27.182
125.89	-26.959	-26.989	-26.971	-27.010	-26.988	-27.164	-27.191	-27.193
158.49	-26.971	-26.999	-26.983	-27.020	-27.000	-27.175	-27.200	-27.202
199.53	-26.982	-27.007	-26.993	-27.028	-27.010	-27.185	-27.207	-27.211
251.19	-26.990	-27.013	-27.003	-27.035	-27.019	-27.192	-27.213	-27.218
316.23	-26.997	-27.018	-27.009	-27.040	-27.025	-27.202	-27.217	-27.223
398.11	-27.001	-27.021	-27.013	-27.043	-27.031	-27.206	-27.221	-27.226
501.19	-27.002	-27.021	-27.014	-27.044	-27.031	-27.207	-27.219	-27.227
630.96	-27.000	-27.018	-27.011	-27.041	-27.028	-27.206	-27.217	-27.224
794.33	-26.992	-27.009	-27.004	-27.032	-27.021	-27.200	-27.211	-27.217
1000.0	-26.977	-26.991	-26.989	-27.015	-27.005	-27.186	-27.194	-27.203
1258.9	-26.950	-26.963	-26.962	-26.987	-26.978	-27.163	-27.168	-27.178
1584.9	-26.906	-26.916	-26.918	-26.940	-26.932	-27.122	-27.126	-27.137
1995.3	-26.835	-26.843	-26.846	-26.867	-26.861	-27.060	-27.061	-27.072
2511.9	-26.728	-26.733	-26.738	-26.755	-26.752	-26.966	-26.961	-26.972
3162.3	-26.574	-26.573	-26.584	-26.594	-26.596	-26.829	-26.817	-26.830
3981.1	-26.381	-26.371	-26.390	-26.391	-26.398	-26.657	-26.634	-26.649
5011.9	-26.226	-26.204	-26.233	-26.222	-26.234	-26.510	-26.475	-26.492
6309.6	-26.422	-26.389	-26.423	-26.395	-26.415	-26.653	-26.606	-26.617
7943.3	-27.732	-27.677	-27.723	-27.683	-27.706	-27.754	-27.692	-27.713
10000	-30.942	-30.884	-30.982	-30.959	-30.952	-30.638	-30.618	-30.725
12589	-35.828	-35.590	-35.822	-35.802	-35.844	-35.337	-35.123	-35.404

Table 4 Pressure sensitivity level of the LS2 microphones in dB re 1 V/Pa

	M4134.0982363			M4180.1124049		
Frequency (Hz)	DFM	DMDM	CENAM	DFM	DMDM	CENAM
31.623	-40.127	-40.191	-40.150	-37.889	-37.938	-37.884
39.811	-40.135	-40.192	-40.156	-37.899	-37.945	-37.894
50.119	-40.139	-40.195	-40.162	-37.927	-37.952	-37.903
63.096	-40.147	-40.198	-40.166	-37.917	-37.957	-37.911
79.433	-40.149	-40.199	-40.170	-37.925	-37.962	-37.918
100.00	-40.155	-40.202	-40.175	-37.937	-37.969	-37.925
125.89	-40.158	-40.202	-40.178	-37.940	-37.972	-37.931
158.49	-40.163	-40.204	-40.181	-37.946	-37.976	-37.936
199.53	-40.165	-40.204	-40.183	-37.953	-37.979	-37.941
251.19	-40.168	-40.206	-40.186	-37.957	-37.982	-37.945
316.23	-40.171	-40.206	-40.188	-37.960	-37.985	-37.948
398.11	-40.173	-40.206	-40.189	-37.965	-37.987	-37.951
501.19	-40.174	-40.206	-40.191	-37.967	-37.988	-37.953
630.96	-40.176	-40.206	-40.191	-37.969	-37.989	-37.955
794.33	-40.175	-40.204	-40.191	-37.970	-37.989	-37.955
1000.0	-40.174	-40.202	-40.190	-37.969	-37.986	-37.954
1258.9	-40.171	-40.197	-40.185	-37.965	-37.980	-37.949
1584.9	-40.163	-40.189	-40.179	-37.955	-37.971	-37.941
1995.3	-40.151	-40.175	-40.166	-37.942	-37.954	-37.926
2511.9	-40.132	-40.155	-40.145	-37.918	-37.929	-37.901
3162.3	-40.100	-40.120	-40.112	-37.879	-37.888	-37.861
3981.1	-40.050	-40.069	-40.062	-37.817	-37.824	-37.801
5011.9	-39.974	-39.988	-39.982	-37.722	-37.725	-37.704
6309.6	-39.856	-39.868	-39.862	-37.580	-37.577	-37.560
7943.3	-39.694	-39.694	-39.689	-37.384	-37.370	-37.360
10000	-39.479	-39.465	-39.464	-37.146	-37.117	-37.120
12589	-39.273	-39.249	-39.259	-36.994	-36.953	-36.970
15849	-39.359	-39.292	-39.316	-37.358	-37.317	-37.331
19953	-40.310	-40.242	-40.271	-38.953	-38.962	-38.913
25119	-42.578	-42.419	-42.521	-41.760	-41.835	-41.706
31623	-45.744	-47.220	-45.511	-44.726	-45.743	-44.516

Table 5 Expanded uncertainties for LS1 and LS2 microphones in dB using a coverage factor of *k*=2, as declared by the participant laboratories.

Frequency (Hz)	LS1			LS2		
	DFM	DMDM	CENAM	DFM	DMDM	CENAM
31.623	0.050	0.090	0.040	0.080	0.100	0.070
39.811	0.050	0.090	0.040	0.080	0.100	0.070
50.119	0.050	0.090	0.040	0.080	0.100	0.070
63.096	0.030	0.080	0.040	0.040	0.085	0.050
79.433	0.030	0.080	0.040	0.040	0.085	0.050
100.00	0.030	0.080	0.040	0.040	0.085	0.050
125.89	0.025	0.080	0.030	0.030	0.085	0.050
158.49	0.025	0.080	0.030	0.030	0.085	0.050
199.53	0.025	0.080	0.030	0.030	0.085	0.050
251.19	0.025	0.080	0.030	0.030	0.085	0.050
316.23	0.025	0.080	0.030	0.030	0.085	0.050
398.11	0.025	0.080	0.030	0.030	0.085	0.050
501.19	0.025	0.080	0.030	0.030	0.085	0.050
630.96	0.025	0.080	0.030	0.030	0.085	0.050
794.33	0.025	0.080	0.030	0.030	0.085	0.050
1000.0	0.025	0.080	0.030	0.030	0.085	0.050
1258.9	0.025	0.080	0.030	0.030	0.085	0.050
1584.9	0.025	0.080	0.030	0.030	0.085	0.050
1995.3	0.025	0.080	0.030	0.030	0.085	0.050
2511.9	0.030	0.080	0.030	0.030	0.085	0.050
3162.3	0.030	0.080	0.030	0.030	0.085	0.050
3981.1	0.030	0.085	0.040	0.030	0.085	0.060
5011.9	0.050	0.091	0.050	0.030	0.085	0.060
6309.6	0.050	0.110	0.060	0.030	0.085	0.060
7943.3	0.050	0.140	0.080	0.030	0.090	0.060
10000	0.080	0.200	0.130	0.030	0.100	0.090
12589	0.100	0.430	0.180	0.040	0.120	0.100
15849				0.050	0.150	0.130
19953				0.080	0.220	0.190
25119				0.140	0.460	0.280
31623				0.160	-	0.400

4.2 Microphone parameters

Tables 6a and 6b contain a list of the values of the parameters of the microphones reported by the laboratories; each laboratory has determined the value of these parameters using their own internal procedures. These values are reported here as additional information, and no further action is intended on them. Furthermore, the values are reproduced here using the same number of significant digits reported by the participants.

Table 6a Microphone parameters reported by the participant laboratories (LS1 microphones).

	M4160.1453798			M4160.1453812		
	DFM	DMDM	CENAM	DFM	DMDM	CENAM
Equivalent volume (mm^3)	123	137	128.64	130	137	124.64
Front volume (mm^3)	548	536	543.00	541	536	545.53
Cavity depth (mm)	1.954	1.95	1.943	1.964	1.95	1.962
Resonance Frequency (Hz)	8.15	8.2	8.139	8.5	8.2	8.43
Loss factor	1.07	1.05	1.03	1.09	1.05	1.07
Pressure coeff. at 250 Hz (dB/Pa)	-0.0160	-0.016	-0.0165	-0.0152	-0.016	-0.0165
Temperature coef. at 250 Hz (dB/K)	-0.003	-0.002	-0.002	-0.0015	-0.002	-0.002

Table 6b Microphone parameters reported by the participant laboratories (LS2 microphones).

	M4134.0982363			M4180.1124049		
	DFM	DMDM	CENAM	DFM	DMDM	CENAM
Equivalent volume (mm^3)	7.2	7.8	6.65	9.9	9.0	11.5
Front volume (mm^3)	31.8	31.8	31.25	32.0	33.7	30.88
Cavity depth (mm)	0.470	0.5	0.498	0.466	0.5	0.495
Resonance Frequency (Hz)	23.3	22	22.876	21.1	22	20.845
Loss factor	1.1	1.15	1.055	1.1	1.05	1.12
Pressure coeff. at 250 Hz (dB/Pa)	-0.0040	-0.0055	-0.0052	-0.0059	-0.0055	-0.0052
Temperature coef. at 250 Hz (dB/K)	0.0019	-0.002	-0.0012	-0.0022	-0.002	-0.0012

5 Analysis of results

5.1 Degrees of equivalence, reference values, and linking to CCAUV Comparisons

The methodology used in this report is similar to the one used in the Key Comparisons CCAUV.A-K3 and CCAUV.A-K4 [1, 2]. Two ways can be followed to determine the reference values of the comparison and the equivalence degrees for the participants: as a stand-alone comparison, or linked to the existing CCAUV.A-K1, and CCAUV.A-K3 Comparisons. The former case will not be further developed in this report. The procedure that includes linking to the CCAUV Comparisons can be carried out considering that two laboratories, DFM (as DPLA) and CENAM participated in both comparisons and can be used as linking laboratories. It has to be added that the comparisons CCAUV.A-K1 and CCAUV.A-K3 to which EURAMET.AUV.A-S1 will be linked, were based on the 1992 edition of IEC 61094-2, whereas the results reported by DFM and CENAM follow the 2009 edition and the results from DMDM follow the 1992 edition. While expected differences have not been analysed, it has been assumed that for the purpose of this linking exercise these differences can be considered to have little effect on the analysis in the frequency range covered by EURAMET.AUV.A-S1.

Linking the comparisons requires that the data reported by the participants in these are included in the analysis [1,4]. This results in larger matrixes in which the results, and standards used in each comparison are included. Furthermore, the linking is also restricted to the frequencies analysed in the corresponding CCAUV comparisons. Additionally, the drift pattern shown by microphone 4160.1453798 suggested that the results from the control measurements performed by DFM should be included in order to evaluate a linear drift of the reference value of that microphone. An outline of the procedure is described below.

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, $\mathbf{a}$ is a vector of parameters of the model, $\mathbf{E}(\mathbf{y})$ is the expectation of the measurements and $\mathbf{X}$ is the design matrix; the elements of $\mathbf{E}(\mathbf{y})$ are the values that should have been measured in absence of uncertainty. The elements of the vector $\mathbf{y}$ are 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 [3].

In the analysis presented in this report it has been assumed that the correlation between two results y_i and y_j provided by different participants is equal to 0. In the case of two results y_i and y_j provided by the same participant, a common correlation coefficient for all participants has been assumed. The value of the common correlation coefficient ρ was chosen to be the same used in the analysis of comparison CCAUV.A-K3 [1], i. e., a unique value of 0.7. The results from the CCAUV Key Comparisons and the current comparison are considered independent due to the long time span between exercises. It has been assumed that that $\Sigma_{object} = 0$.

The covariance matrix and the matrix of the results of the participants are constructed using the data supplied by the participants. Note that the results reported in the CCAUV comparisons correspond to *nominal* 1/3-octave centre frequencies, while the results reported in the current comparison are reported at the *exact* centre frequencies. It is assumed in this analysis that the statistical behaviour at nominal and exact frequencies is the same since these are close to each other for the same 1/3-octave band.

The design matrix for LS1 microphones has the following form.

$$\begin{bmatrix} E(y_{1,1}) \\ \vdots \\ E(y_{1,12}) \\ E(y_{2,1}) \\ \vdots \\ E(y_{2,12}) \\ E(y_{3,1}) \\ \vdots \\ E(y_{3,5}) \\ E(y_{4,1}) \\ \vdots \\ E(y_{4,3}) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & t_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 1 & 0 & t_5 \\ 0 & 0 & 0 & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{bmatrix}, \qquad (1.a)$$

where the elements $y_{1,j}$ and $y_{2,j}$ correspond to the values of the sensitivity for the standards 1, and 2 reported by the *j*-th participant in the comparison CCAUV.A-K1 (a total of 12 participants, including DFM and CENAM). The elements $y_{3,j}$ correspond to the results reported by the *j*-th laboratory for the microphone 4160.1453798 including the three control measurements performed at DFM (see Table 3). The remaining elements $y_{4,j}$ correspond to the results of the microphone 4160.1453812 reported by the *j*-th laboratory in the current comparison. The elements t_i represent the dates of measurement of the microphone 4160.1453798, whereas a_5 describes the drift rate of the microphone.

Similarly, the design matrix for the LS2 microphones contains the elements $y_{1,j}$, $y_{2,j}$, $y_{3,j}$, and $y_{4,j}$ corresponding to the values of the sensitivity for the standards 1 to 4 reported by the *j*-th participant in the comparison CCAUV.A-K3. Standards 1 and 2 were measured by 9 participants, including DFM and CENAM while standards 3 and 4 were measured by 8 participants, also including DFM and CENAM. The elements $y_{5,j}$ and $y_{6,j}$ correspond to the results reported by the *j*-th laboratory for the LS2 microphones used in the current comparison. The matrix is shown below.

$$
\begin{bmatrix} E(y_{1,1}) \\ \vdots \\ E(y_{1,9}) \\ E(y_{2,1}) \\ \vdots \\ E(y_{2,9}) \\ E(y_{3,1}) \\ \vdots \\ E(y_{3,8}) \\ E(y_{4,1}) \\ \vdots \\ E(y_{4,8}) \\ E(y_{5,1}) \\ \vdots \\ E(y_{5,3}) \\ E(y_{6,1}) \\ \vdots \\ E(y_{6,3}) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \end{bmatrix}, \tag{1.b}
$$

Once these matrices are complete, the estimates of the unknown parameters of the model can be calculated using:

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

where y_r and 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 y_r

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

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

Results are presented in Tables 7 and 8. The degrees of equivalence are obtained using:

$$\mathbf{D} = \mathbf{A}(\mathbf{y} - \hat{\mathbf{y}}),$$
$$V(\mathbf{D}) = \mathbf{A}V(\mathbf{y} - \hat{\mathbf{y}})\mathbf{A}^T, \tag{4}$$

where **D** is a vector containing the degrees of equivalences D_i per laboratory, **A** is an arithmetic averaging matrix. Results are presented in Tables 9 and 10.

Finally, the inter-laboratory degrees of equivalence D_{ij} can be estimated using [3]:

$$D_{ij} = D_i - D_j$$
$$V(D_{ij}) = V(\mathbf{D})_{ii} + V(\mathbf{D})_{jj} - V(\mathbf{D})_{ij} - V(\mathbf{D})_{ji}, \tag{5}$$

where D_i is the i'th element of **D,** and $V(\mathbf{D})_{ij}$ is the element (i, j) of the covariance matrix $V(\mathbf{D})$. Results are shown in Tables 12 to 15.

5.2 Equivalence and consistency of results

Because of the fact that the participating laboratories are measuring the same items, it can be assumed that the reported results are drawn from a multivariate normal distribution $N(\mathbf{X}_a,\Sigma)$. This hypothesis is tested by means of an observed χ^2-distributed estimator, as described in reference [3]. The degrees of freedom of the χ^2 distribution are $\nu = n\text{-}k$, where n is the number of measurements, and k the number of standards. To accept the hypothesis with a significance of 5%, the probability $P\{\chi^2(\nu) > \chi^2\}$ has to be larger than 5%.

During the course of the comparison, any anomalous results need to be identified by the pilot laboratory. Any laboratory whose results show deviations judged to be irregular must be contacted in order to have an opportunity to revise their results. Details of this process are given below.

5.2.1 Identifying discrepant measurements

Once all data was collected, and the participants reported any problem with their measurement, the analysis method in reference [2] was implemented. This method uses the normalized deviations that were calculated for every frequency and measurement. The method assumes that 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 discrepant with a significance of 5%.

5.2.2 Handling of discrepant measurements

If a measurement has been judged to be discrepant, it should be excluded from the least squares calculation of the reference values. Otherwise the calculated reference values cannot be considered to be proper estimates of the SI values of the quantities represented by the circulated objects. If there is a discrepant measurement y_{ij} in a key comparison and the uncertainty assigned to this measurement is very small, the key comparison reference value will be attracted to this discrepant result. As a consequence the remaining results might appear to be discrepant as well even if they are mutually consistent. Since one discrepant measurement will always have a value $|d_{ij}|$ larger than the values $|d_{kj}|$, $i \neq k$ of two or more mutually consistent values, the value y_{ij} with the larger value $|d_{ij}|$ should be excluded first. A repeated least squares adjustment of the reference values will then show if there are further discrepant results.

The procedure of excluding discrepant results one by one can be summarized as follows:

1. Identify the result y_{ij} with the largest value $|d_{ij}|>2$ in the (reduced) set of results.

2. Exclude the result y_{ij} from the reduced set of results.

3. Repeat the least squares adjustment of reference values for the reduced set of results.

4. If the results in the reduced set are not mutually consistent, continue at point 1.

It has to be emphasized, that the discrepant results are excluded only from the calculation of the reference values and not from key comparison as such. It is therefore still necessary to calculate the deviations of the discrepant results from the reference values and the uncertainties of these deviations. Reference [3] gives a detailed explanation of the procedure.

6 Proposed reference values

6.1 Reference values

The analysis described in Section 5 results in a set of Reference Values, one per frequency associated with each one of the standards circulated. The reference values are listed below in Table 7 for LS1 microphones, and in Table 8 for LS2 microphones.

Table 7 Reference values for the comparison for LS1 microphones. Pressure sensitivity Levels in dB re 1V/Pa and expanded uncertainty *U* (*k* = 2) in dB.

Frequency (Hz)	Sensitivity (dB re 1 V/Pa)				Uncertainty, *k*=2			
	M1453798			M1453812	M1453798			M1453812
	2009 07 08	2009 09 08	2010 01 20		2009 07 08	2009 09 08	2010 01 20	
63.096	-26.924	-26.930	-26.945	-27.135	0.026	0.023	0.023	0.024
125.89	-26.968	-26.975	-26.992	-27.176	0.021	0.019	0.018	0.019
251.19	-26.997	-27.005	-27.021	-27.203	0.021	0.019	0.018	0.019
501.19	-27.008	-27.015	-27.032	-27.215	0.021	0.019	0.018	0.019
1000	-26.982	-26.989	-27.005	-27.193	0.021	0.019	0.018	0.019
1258.9	-26.954	-26.962	-26.977	-27.169	0.021	0.019	0.018	0.019
1584.9	-26.910	-26.917	-26.932	-27.128	0.021	0.019	0.018	0.019
1995.3	-26.838	-26.845	-26.860	-27.065	0.021	0.019	0.018	0.019
2511.9	-26.730	-26.737	-26.751	-26.969	0.024	0.022	0.020	0.021
3162.3	-26.574	-26.580	-26.592	-26.830	0.024	0.022	0.020	0.021
3981.1	-26.379	-26.384	-26.393	-26.654	0.026	0.023	0.023	0.024
5011.9	-26.221	-26.223	-26.228	-26.501	0.041	0.036	0.034	0.035
6309.6	-26.414	-26.412	-26.409	-26.638	0.042	0.038	0.036	0.038
7943.3	-27.726	-27.719	-27.704	-27.743	0.045	0.041	0.040	0.042

Table 8 Reference values for the comparison for LS2 microphones. Pressure sensitivity Levels in dB re 1V/Pa and expanded uncertainty *U* (*k* = 2) in dB.

Frequency (Hz)	Sensitivity (dB re 1 V/Pa)		Uncertainty, *k*=2	
	M0982363	**M1124049**	**M0982363**	**M1124049**
31.623	-40.140	-37.886	0.053	0.053
63.096	-40.154	-37.915	0.031	0.031
125.89	-40.163	-37.937	0.026	0.026
251.19	-40.173	-37.954	0.026	0.026
501.19	-40.179	-37.963	0.026	0.026
1000.0	-40.178	-37.965	0.026	0.026
1995.3	-40.155	-37.938	0.026	0.026
3981.1	-40.053	-37.814	0.027	0.027
6309.6	-39.857	-37.576	0.027	0.027
7943.3	-39.693	-37.379	0.027	0.027
10000	-39.478	-37.144	0.028	0.028
12589	-39.271	-36.991	0.037	0.037
15849	-39.353	-37.354	0.047	0.047
19953	-40.304	-38.947	0.074	0.074
25119	-42.566	-41.749	0.125	0.125

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 4 below shows average deviation in dB per laboratory as a function of frequency for LS1 and LS2 microphones, respectively.

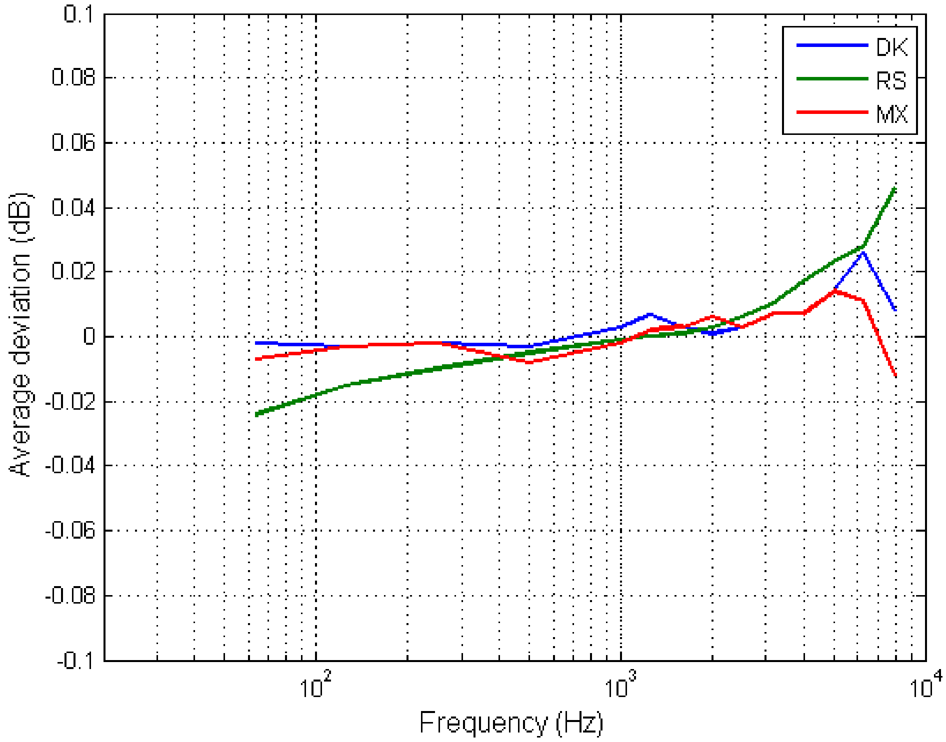

Figure 3 Average deviation in dB per laboratory and frequency for LS1 microphones.

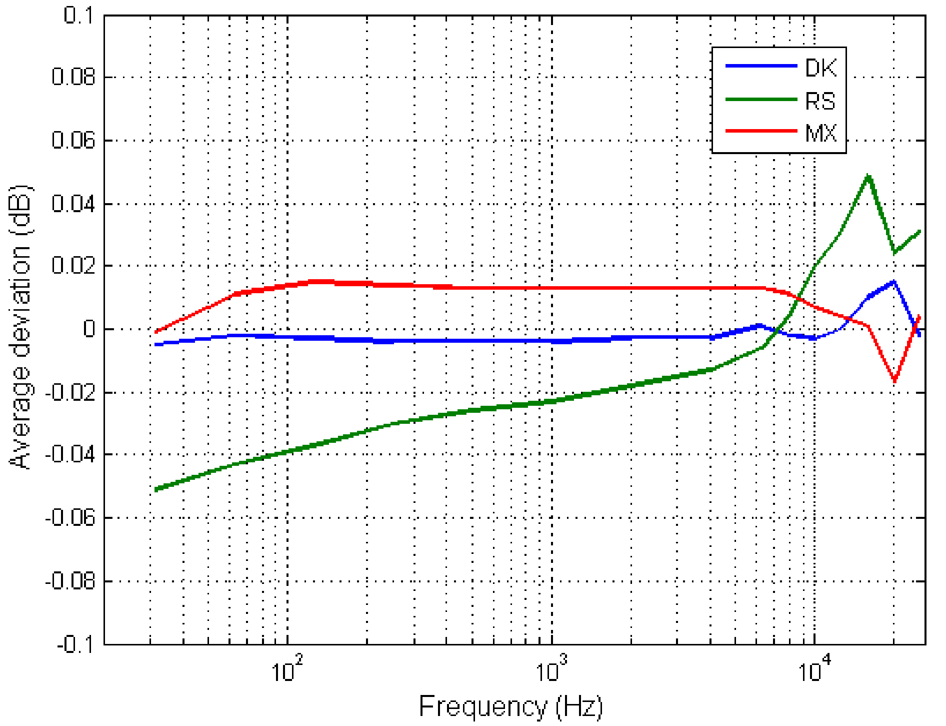

Figure 4. Average deviation in dB per laboratory and frequency for LS2 microphones.

Tables 9 and 10 present the degrees of equivalence and their uncertainties in tabular form for LS1 and LS2 microphones.

Table 9 Degrees of equivalence per laboratory as function of frequency: deviations (dB) and uncertainties *k* =2 (dB) for LS1 microphones.

	Deviations (dB)			Uncertainty *k*=2 (dB)		
Frequency (Hz)	**DFM**	**DMDM**	**CENAM**	**DFM**	**DMDM**	**CENAM**
63	-0.002	-0.022	-0.007	0.035	0.077	0.035
125	-0.003	-0.014	-0.003	0.026	0.076	0.036
250	-0.002	-0.009	-0.002	0.026	0.076	0.036
500	-0.003	-0.005	-0.008	0.026	0.076	0.026
1000	0.003	-0.001	-0.002	0.026	0.076	0.026
1250	0.007	0.000	0.002	0.026	0.076	0.026
1600	0.003	0.001	0.003	0.026	0.076	0.026
2000	0.001	0.003	0.006	0.026	0.076	0.026
2500	0.003	0.006	0.003	0.026	0.076	0.026
3150	0.007	0.010	0.007	0.026	0.076	0.052
4000	0.007	0.016	0.007	0.026	0.081	0.045
5000	0.014	0.023	0.014	0.069	0.090	0.044
6300	0.026	0.028	0.011	0.044	0.107	0.054
8000	0.008	0.046	-0.012	0.053	0.135	0.091

Table 10. Degrees of equivalence per laboratory as function of frequency: deviations (dB) and uncertainties *k* =2 (dB) for LS2 microphones.

	Deviations (dB)			Uncertainty *k*=2 (dB)		
Frequency (Hz)	**DFM**	**DMDM**	**CENAM**	**DFM**	**DMDM**	**CENAM**
31.5	-0.005	-0.051	-0.001	0.069	0.104	0.041
63	-0.002	-0.043	0.011	0.033	0.083	0.043
125	-0.003	-0.037	0.015	0.024	0.082	0.052
250	-0.004	-0.030	0.014	0.025	0.082	0.052
500	-0.004	-0.026	0.013	0.025	0.082	0.052
1000	-0.004	-0.023	0.013	0.025	0.082	0.052
2000	-0.003	-0.018	0.013	0.025	0.082	0.052
4000	-0.003	-0.013	0.013	0.025	0.082	0.052
6300	0.001	-0.006	0.013	0.024	0.082	0.052
8000	-0.002	0.004	0.011	0.024	0.087	0.043
10000	-0.003	0.020	0.007	0.023	0.096	0.042
12500	0.000	0.030	0.004	0.031	0.116	0.041
16000	0.010	0.049	0.001	0.040	0.145	0.059
20000	0.015	0.024	-0.017	0.065	0.214	0.147
25000	-0.002	0.031	0.004	0.116	0.440	0.180

The degrees of equivalence calculated for the frequencies, 250 Hz, and 1.0 kHz are shown in Figures 5 and 6 for LS1 and LS2 microphones, respectively.

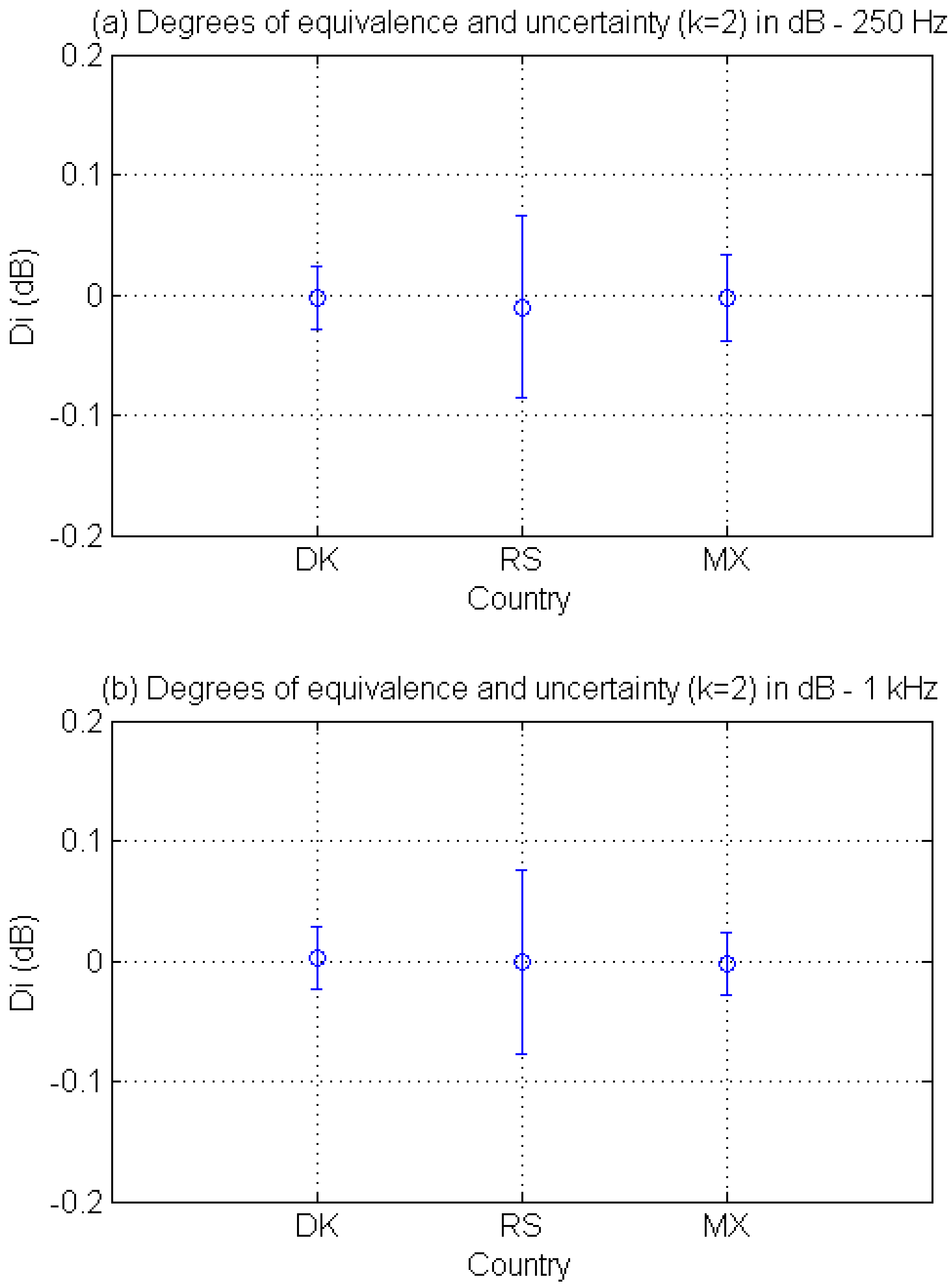

Figure 5 Degrees of equivalence, deviation and uncertainty at 250 Hz and 1.0 kHz for LS1 microphones.

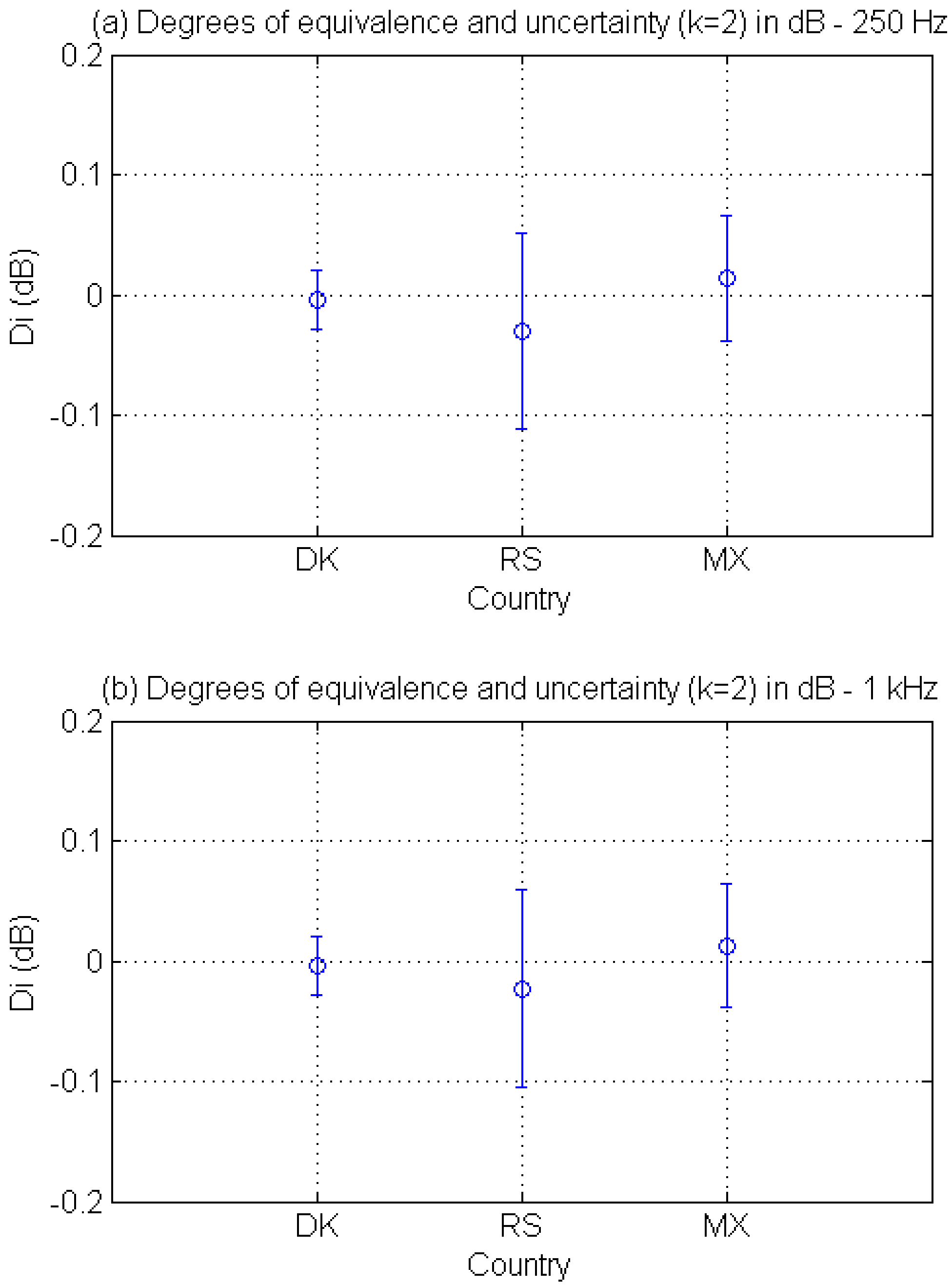

Figure 6 Degrees of equivalence, deviation and uncertainty at 250 Hz and 1.0 kHz for LS2 microphones.

Finally Tables 11a and 11b contain the results of the χ^2 test applied to the comparison results for specified values of the correlation coefficient between results provided by the same laboratory. The combination of correlation coefficient and reported uncertainties yields relatively high χ^2 test results compared to the 5% significance value. This has been suggested to be the result of either a low correlation coefficient or uncertainties which are too conservative. The analysis carried out for the Comparison CCAUV.A-K3 indicated that correlation coefficients higher than 0.7 cause the χ^2 test to fail for most frequencies [1]. Hence, a correlation coefficient having a value of 0.7 was used in that comparison. This same value of the correlation coefficient has been adopted in the analysis of the current comparison. It is more likely that the uncertainties are too conservative because one of the participants in the current comparison has declared uncertainties that are about twice as large as the other two participants.

Table 11a Results of the χ^2 test as described in reference [3] for LS1 microphones.

Frequency (Hz)	P{ χ^2 (ν)>χ^2 obs}
63	87.1
125	96.4
250	87.1
500	98.1
1000	96.3
1250	90.6
1600	91.4
2000	85.4
2500	71.5
3150	79.5
4000	59.6
5000	70.1
6300	67.7
8000	61.0

Table 16b Results of the χ^2 test as described in reference [3] for LS2 microphones.

Frequency (Hz)	P{ χ^2 (ν)>χ^2 obs}
31.5	100.0
63	100.0
125	100.0
250	100.0
500	100.0
1000	100.0
2000	100.0
4000	100.0
6300	100.0
8000	100.0
10000	100.0
12500	100.0
16000	99.9
20000	100.0
25000	78.7

6.3 Degrees of equivalence between laboratories

Tables 12, 13, 14 and 15 contain the inter-laboratory degrees of equivalence of this comparison. DMDM equivalences are emphasized.

Table 12 Inter-laboratory degrees of equivalence at 250 Hz for LS1 microphones. Upper triangle: differences (dB); lower triangle: uncertainties *k* =2 (dB)

250 Hz	NPL	DPLA	NIST	ETL	PTB	KRISS	CSIR	CSIRO	NRC	CENAM	GUM	VNIIFTRI	DMDM
NPL	-	0.010	0.010	0.015	0.000	0.010	-0.010	-0.010	0.045	0.010	-0.005	0.005	0.017
DPLA	0.039	-	0.000	0.005	-0.010	0.000	-0.020	-0.020	0.035	0.000	-0.015	-0.005	0.007
NIST	0.046	0.046	-	0.005	-0.010	0.000	-0.020	-0.020	0.035	0.000	-0.015	-0.005	0.007
ETL	0.046	0.046	0.052	-	-0.015	-0.005	-0.025	-0.025	0.030	-0.005	-0.020	-0.010	0.002
PTB	0.039	0.039	0.046	0.046	-	0.010	-0.010	-0.010	0.045	0.010	-0.005	0.005	0.017
KRISS	0.039	0.039	0.046	0.046	0.039	-	-0.020	-0.020	0.035	0.000	-0.015	-0.005	0.007
CSIR	0.054	0.054	0.059	0.059	0.054	0.054	-	0.000	0.055	0.020	0.005	0.015	0.027
CSIRO	0.046	0.046	0.052	0.052	0.046	0.046	0.059	-	0.055	0.020	0.005	0.015	0.027
NRC	0.039	0.039	0.046	0.046	0.039	0.039	0.054	0.046	-	-0.035	-0.050	-0.040	-0.028
CENAM	0.046	0.046	0.052	0.052	0.046	0.046	0.059	0.052	0.046	-	-0.015	-0.005	0.007
GUM	0.039	0.039	0.046	0.046	0.039	0.039	0.054	0.046	0.039	0.046	-	0.010	0.022
VNIIFTRI	0.054	0.054	0.059	0.059	0.054	0.054	0.065	0.059	0.054	0.059	0.054	-	0.012
DMDM	0.080	0.080	0.084	0.084	0.080	0.080	0.088	0.084	0.080	0.084	0.080	0.088	-

Table 13 Inter-laboratory degrees of equivalence at 1000 Hz for LS1 microphones. Upper triangle: differences (dB); lower triangle: uncertainties *k* =2 (dB)

1000 Hz	NPL	DPLA	NIST	ETL	PTB	KRISS	CSIR	CSIRO	NRC	CENAM	GUM	VNIIFTRI	DMDM
NPL	-	0.005	0.030	0.020	-0.005	0.005	-0.010	-0.005	0.045	0.010	0.005	0.010	0.009
DPLA	0.039	-	0.025	0.015	-0.010	0.000	-0.015	-0.010	0.040	0.005	0.000	0.005	0.004
NIST	0.046	0.046	-	-0.010	-0.035	-0.025	-0.040	-0.035	0.015	-0.020	-0.025	-0.020	-0.021
ETL	0.046	0.046	0.052	-	-0.025	-0.015	-0.030	-0.025	0.025	-0.010	-0.015	-0.010	-0.011
PTB	0.039	0.039	0.046	0.046	-	0.010	-0.005	0.000	0.050	0.015	0.010	0.015	0.014
KRISS	0.039	0.039	0.046	0.046	0.039	-	-0.015	-0.010	0.040	0.005	0.000	0.005	0.004
CSIR	0.054	0.054	0.059	0.059	0.054	0.054	-	0.005	0.055	0.020	0.015	0.020	0.019
CSIRO	0.046	0.046	0.052	0.052	0.046	0.046	0.059	-	0.050	0.015	0.010	0.015	0.014
NRC	0.046	0.046	0.052	0.052	0.046	0.046	0.059	0.052	-	-0.035	-0.040	-0.035	-0.036
CENAM	0.039	0.039	0.046	0.046	0.039	0.039	0.054	0.046	0.046	-	-0.005	0.000	-0.001
GUM	0.039	0.039	0.046	0.046	0.039	0.039	0.054	0.046	0.046	0.039	-	0.005	0.004
VNIIFTRI	0.054	0.054	0.059	0.059	0.054	0.054	0.065	0.059	0.059	0.054	0.054	-	-0.001
DMDM	0.080	0.080	0.084	0.084	0.080	0.080	0.088	0.084	0.084	0.080	0.080	0.088	-

Table 14 Inter-laboratory degrees of equivalence at 250 Hz for LS2 microphones. Upper triangle: differences (dB); lower triangle: uncertainties *k* =2 (dB)

250 Hz	CENAM	DPLA	GUM	KRISS	LNE	NIST	NMIJ	NPL	PTB	CSIRO	INMETRO	NIM	NRC	UME	VNIIFTRI	DMDM
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	0.044
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	0.026
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	0.014
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	0.039
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	0.046
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	0.030
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	0.014
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	0.024
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	0.034
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	0.035
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	0.031
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	0.022
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	0.025
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	0.037
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	-	0.015
DMDM	0.097	0.086	0.093	0.086	0.086	0.089	0.116	0.086	0.089	0.089	0.091	0.093	0.089	0.110	0.089	-

Table 15 Inter-laboratory degrees of equivalence at 1000 Hz for LS2 microphones. Upper triangle: differences (dB); lower triangle: uncertainties *k* =2 (dB)

1000 Hz	CENAM	DPLA	GUM	KRISS	LNE	NIST	NMIJ	NPL	PTB	CSIRO	INMET-RO	NIM	NRC	UME	VNI-IFTRI	DMDM
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	0.036
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	0.019
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	0.006
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	0.031
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	0.036
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	0.018
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	-0.004
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	0.026
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	0.026
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	0.024
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	0.023
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	0.012
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	0.015
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	0.028
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
DMDM	0.097	0.085	0.093	0.086	0.086	0.089	0.116	0.086	0.089	0.089	0.091	0.093	0.089	0.110	0.089	-

7 Conclusion

The results of comparison EURAMET.AUV.A-S1 Comparison have been analysed using a least-squares technique used in previous Key Comparisons.

The analysis includes a linking to the comparisons CCAUV.A-K1 and CCAUV.A-K3 considering:

+ The results from the two comparisons are analysed as one large comparison.

+ Results from the DMDM are excluded from the calculations of the reference values; DFM and CE-NAM serve as linking laboratories.

The results of the comparison are consistent and satisfactory.

8 References

[1] 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.

[2] S. Barrera-Figueroa, *Final Report on the Key Comparison CCAUV.A-K4*,

[3] L. Nielsen, *Identification and Handling of Discrepant Measurements in Key Comparisons,* Measurement Techniques , **46** (5), 2003.

[4] R. Barham, *Final Report on the Key Comparison CCAUV.A-K1*,

9 Appendix A: Calibration methods used by the participants

A description of the calibration method and the reporting of results, are given below as submitted by each participating laboratory. No editing of the contents but a small amount of reformatting has been performed. Numbering of tables, equation and figure numbers do not follow the numbering of this report.

DFM

Measurement principle

The calibration is performed as a full reciprocity calibration according to the standard IEC 61094-2 (2009) using three microphones pair-wise coupled using air filled Plane Wave couplers of four different lengths: nominal lengths (4, 6, 7.5, and 9) mm for LS1, and (3, 4, 5 and 6) mm for LS2 microphones. The resulting sensitivity is calculated using a modified version of MP.EXE software. The modification applies the new standard IEC 61094-2 (2009) and includes the additional heat conduction caused by the inner thread in the front cavity of type 4160 microphones. When calculating the heat conduction, the front cavity depth of the said microphones is increased by 1.4 mm. 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 a reference impedance in series with the microphone. This measurement impedance (nominal 10 nF || 0.7 MΩ) is calibrated in the frequency range 60 Hz to 40 kHz and the results extrapolated down to 20 Hz. An external polarization voltage is supplied by a Fluke DC Voltage Calibrator type 343A. The static pressure is measured by a barometer, Druck DPI 140 and the temperature and humidity are measured by a Vaisala temperature and humidity probe located close to the coupler. All measurements are conducted in a temperature controlled room at 23.0 ºC ± 1.0 ºC. Humidity is kept within the range 40% - 60% RH.

The transfer function is measured using a B&K Pulse analyser in connection with SSR software (Steady State Response). 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 3 sweeps with a detector band of 0.01 dB.

The microphone front cavity depth has been measured using an infrared triangulation device. The microphone parameters (equivalent volume, front volume, loss factor, and resonance frequency) are determined by fitting the sensitivity obtained using the above-mentioned 4 couplers. Once determined, the microphone parameters remain unchanged during all calibrations. Due to longitudinal modes in the couplers the high-frequency limits for the couplers are (35, 32, 24 and 21) kHz for LS2 microphones, and (24, 22, 14, and 12) kHz for LS1 microphones, respectively. Thus, at the highest frequencies the results are the average of a calibration in only two couplers.

DMDM

Calibration Method

According to International Standard IEC 61094-2 (1992): Measurement Microphones – Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique. The condenser microphones were calibrated by Reciprocity Calibration System (B&K type 9699) at the exact 1/3rd-octave frequencies from 31.5 Hz to 12.5 kHz for LS1 microphones and exact 1/3rd-octave frequencies from 31.5 Hz to 31.5 kHz for LS2 microphones. The each microphone under test was reciprocally acoustically coupled in pairs with two different combination of three national reference standards of DMDM. The each microphone under test was only used as receiver. Two different air filled plane-wave sapphire couplers were used in each measurement (5cm3 and 3cm3 for LS1, 0.4cm3 and 0.7cm3 for LS2). The coupled microphones were placed inside a pressurized chamber. The measurement data were analyzed using software MP.EXE Microphone pressure sensitivity calibration calculation program version 3.00 (September, 1999), E. Sandermann Olsen and K. Rasmussen from Technical University of Denmark. Ambient conditions in the laboratory were monitored using Vaisala PTU 303 unit. The temperature and pressure correction coefficients used to obtain sensitivity at standard conditions were nominal values (–0.002 dB/0C and –0.016 dB/kPa for LS1 microphones; –0.002 dB/0C and –0.0055 dB/kPa for LS2 microphones). Polarization voltage was checked by voltmeter HP 3456A.

Microphone parameter estimation

Front cavity depth

The front cavity depths were taken as nominal values (1.95mm for LS1 and 0.5 mm for LS2) from International Standard IEC 61094-1 Specification for Laboratory Standard Microphones-Part 1 (second edition, 2000-07).

Front cavity volume

Front cavity volumes were determined from front cavity depths and nominal areas calculated from the nominal diameters of the microphones diaphragms (18.6mm for LS1 and 9.3 mm for LS2), IEC 61094-1 Specification for Laboratory Standard Microphones-Part 1 (second edition, 2000-07), using the mathematical equations. The front cavity volumes were later corrected together with equivalent volumes using the data fitting method.

Equivalent volume

Equivalent volumes were taken from the manufacturer data for the LS1 and LS2 microphones (136 mm3 and 9.2 mm3, respectively) and determined with front cavity volumes by data fitting method. Fixing the front cavity volumes, the equivalent volumes were adjusted in a way that total volume gave minimal deviations between the sensitivities obtained using two different couplers at low to medium frequencies, for each microphone under test.

Resonance frequency, loss factor

Resonance frequencies and loss factors were taken as nominal values (8200Hz and 1.05 for LS1 and 22000 Hz and 1.05 for LS2) from the manufacturer data.

Coupler parameters

Coupler parameters such as diameter and length were measured, but for calculation were used nominal values (diameter 18.6mm, lengths 15mm and 7.5mm for LS1; diameter 9.3mm, lengths 4.7mm and 9.4mm for LS2) supplied by the manufacturer.

CENAM

Procedure

510-AC-P.005 "*Calibración primaria de micrófonos mediante la técnica de reciprocidad*" (Primary calibration of microphones by the reciprocity technique).

Standards and instrumentation

Instrument	Manufacturer	Type/Model	Serial number
LS1P - Standard microphones	Brüel & Kjær	4160	1734004/1734011
LS2P - Standard microphone	Brüel & Kjær	4180	1627796/1893458
Reciprocity apparatus	Brüel & Kjær	5998	2040462
Polarization voltage meter	Brüel & Kjær	5991	1468333
Signal analyzer	Brüel & Kjær	3560D	2415164
Barometer	MKS	Baratron	95111246A
Humidity and temperature processor.	Vaisala	HMI38	V3030005

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

Static pressure and temperature corrections are applied, to the measurement results, to get the pressure sensitivity product at environmental reference conditions (101.325 kPa, 23 ºC, 50% HR). Pressure sensitivity is calculated according to IEC 61094-2:2009. (*No additional area or front cavity depth as a result of the microphone front cavity inner thread was taken into account in the calculations.)*

Microphone acoustic parameters are calculated as
Front cavity and equivalent volumes, and loss factor were adjusted by a curve fitting process using the sensitivity levels obtained from a set of four plane wave couplers.
Front cavity depth is measured by means of an optic parallel and microscope.
Resonance frequency is calculated from the phase of pressure sensitivity.
Static pressure and temperature coefficients are used as given from the manufacturer's typical value.

Results
(N. B.: presented in the body of the report)

Uncertainty
The expanded measurement uncertainty is obtained multiplying the standard combined uncertainty by a coverage factor, k = 2, which gives a confidence level of al least 95%, under the assumption that the probability distribution function for the measurand is approximately normal.
The measurement uncertainty is estimated according to the Mexican National Standard NMX-CH-140-IMNC-2002 : "Guía para la Expresión de la Incertidumbre en las Mediciones", which is equivalent to the "Guide for the Expression of Uncertainties in Measurement: BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML (1995)".
The uncertainty value given in this certificate, does not take into account the contributions due to long-term stability, drift and transportation effects for the calibrated instrument.

Traceability
Calibration results are traceable to the kilogram (kg), Kelvin (K), second (s), metre (m) and ampere (A), base units of the SI, through the Mexican National Standards for Barometric Pressure (CNM-PNM-24), Temperature (CNM-PNE-2), Time (CNM-PNE-1), Length (CNM-PNM-2) and Intensity of Alternating Current (CNM-PNE-10), maintained by CENAM.

References:
[1] IEC International Standard 61094-2. Measurement microphones – Part 2: "Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique".

10 Appendix B: Uncertainty budgets

Uncertainty budgets were requested of all participants. The budgets are reproduced here as they were received from the participants. No editing of the contents but a small amount of reformatting has been performed. Table, equation and figure numbers are not following the numbering of the report.

DFM

Contributors to the uncertainty of the calibration.

The condensed uncertainty budget for a pressure reciprocity calibration of B&K Type 4160 and 4180 microphones are given in the tables below. The background for the budget is as follows:

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

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

Item 6: This figure represents the uncertainty on the applied radial wave-motion correction.

Item 7: The figure represents the uncertainty on the applied viscosity corrections.

Item 8: The figures represent the uncertainty on the increased heat conduction caused by the thread in the microphone front cavity.

Item 9: The figure 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 10: The figures represent the contribution of the rounding of the sensitivity.

Item 11: This figure represents the allowable repeatability of the calibration. This means that the calibration is repeated to verify the repeatability.

Item 12: The figure represents the uncertainty on applying a correction for dependence of static pressure and temperature on the microphone sensitivity.

Uncertainties for LS1 microphones

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	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000	12500
1	Coupler dimensions	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.1	2.1	2.1	2.2	2.5	3.8	5
2	Microphone parameters	9	9	9	7.8	7.9	8	8	7.9	7.9	7.8	7.8	7.9	8.3	9.2	9.9	7.5	3	15	20
3	Electrical transfer impedance	20	15	8	3.9	3.6	3.2	3.2	3.2	3.2	3.3	3.4	3.5	3.6	3.7	3.7	3.8	3.9	5.5	8
4	Environmental parameters	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.7	1.7	1.8	2.1	2.7	3.7	5.6	8.8	14.7	17
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	2.1	2.1
6	Radial wave-motion correction	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.3	0.5	1	3	6	6
7	Viscosity losses	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.5	1	3	5	10	10
8	Equations of environmental parameters	1.6	1.6	1.6	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
9	Excess surface (thread)	18	16	14	12	8	6	4.5	3.5	3.1	2.8	2.6	2.4	2.2	2	1.9	1.8	1.7	1.5	1
10	Rounding of results	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	$\sigma_B = \left(\sum u^2 / 3\right)^{1/2}$	*16.8*	*14.2*	*11.3*	*9.3*	*7.7*	*7.1*	*6.7*	*6.4*	*6.4*	*6.3*	*6.3*	*6.3*	*6.5*	*7.0*	*7.4*	*7.1*	*7.7*	*14.8*	*17.8*
	Components of type A uncertainties in dB*1000																			
11	Allowed reproducibility σ_A	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	15	20	30	45
	Overall uncertainty in dB*10000 at measurement conditions (*k*= 2)																			
	$\sigma = 2\left(\sigma_A^2 + \sigma_B^2\right)^{1/2}$	*39.1*	*34.7*	*30.1*	*27.3*	*25.3*	*24.5*	*24.1*	*23.8*	*23.7*	*23.6*	*23.6*	*23.7*	*23.9*	*24.4*	*24.9*	*33.2*	*42.8*	*66.9*	*96.8*
	Uncertainty on corrections to reference environmental conditions in dB*1000 (*k*= 2)																			
12	Correction to reference conditions	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.4	4.4	4.4	4.5	4.7	4.8	4.7	8.1	12.8	15
	Overall uncertainty in dB*1000 at reference conditions (*k*= 2)																			
		39	***35***	***30***	***28***	***26***	***25***	***24***	***24***	***24***	***24***	***24***	***24***	***24***	***25***	***25***	***34***	***44***	***68***	***98***
	Resulting uncertainty in dB																			
		0.04	***0.03***	***0.03***	***0.03***	***0.026***	***0.025***	***0.024***	***0.024***	***0.024***	***0.024***	***0.024***	***0.02***	***0.02***	***0.02***	***0.03***	***0.03***	***0.04***	***0.07***	***0.10***
	Uncertainty stated in the CMC in dB																			
	CMC values	**0.06**	**0.05**	**0.05**	**0.03**	**0.025**	**0.025**	**0.025**	**0.025**	**0.025**	**0.025**	**0.025**	**0.03**	**0.03**	**0.03**	**0.05**	**0.05**	**0.05**	**0.08**	**N.R.**

Uncertainties for LS2 microphones

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	Excess surface (thread)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	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																		
11	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)																		
12	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**	**N.R.**

DMDM:

DMDM: Uncertainty budget for LS1P

Input parameter	Sym.	Unit	Unce.	31.5Hz	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	3.15 kHz	4kHz	5kHz	6.3kHz	8kHz	10kHz
Voltage ratio correction	$Cor_{R,n}$	dB	A: $\sigma(R_{sr})$ B: 0.0017	0.0021	0.0021	0.0021	0.0017	0.0017	0.0017	0.0017	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020
Polarisation voltage	U_{POL}	V	0.0008 V norm.	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
Coupler volume correction	$Cor_{CV,n}$	mm^3	2.89 mm^3 rect.	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
Static pressure correction	Cor_{Ps}	kPa	0.035 kPa norm.	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
Capacitance correction	Cor_C	nF	0.0012 nF 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
Microphone front volume correct.	$Cor_{FV,n}$	mm^3	5.78 mm^3 rect.	0.0374	0.0374	0.0374	0.0374	0.0374	0.0374	0.0374	0.0374	0.0374	0.0374	0.0374	0.0374	0.0374
Static pressure correction	C_P	kPa	0.035 kPa norm.	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000
Temperature correction	C_T	K	1.169 K norm.	0.0002	0.0001	0.0001	0.0001	0.0001	0.0002	0.0006	0.0016	0.0023	0.0039	0.0061	0.0097	0.0167
Humidity correction	C_{RH}	%	3.424 % norm.	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0004	0.0005	0.0007	0.001	0.0015
Mic. front cavity length correct.	C_L	mm	0.058 mm rect.	0.0006	0.0004	0.0003	0.0002	0.0004	0.0009	0.0030	0.0076	0.0122	0.0196	0.0311	0.0495	0.0864
Reproducibility	M_p	dB	σ_A	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.015	0.015	0.015	0.02	0.025
Result rounding	M_p	dB	0.001 rect.	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				0.0427	0.039	0.039	0.039	0.039	0.039	0.0391	0.0398	0.0425	0.0452	0.0515	0.0661	0.099
Expanded uncertainty (k=2)				0.0854	0.078	0.078	0.078	0.078	0.078	0.0782	0.0795	0.0849	0.0904	0.103	0.1321	0.1979
Rounded uncertainty				0.085	0.078	0.078	0.078	0.078	0.078	0.078	0.08	0.085	0.090	0.1	0.13	0.2
Stated uncertainty (k=2)				0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.085	0.091	0.11	0.14	0.2

Stated uncertainty (k=2):
31.5Hz – 50Hz: 0.09 dB
63Hz – 3.15kHz: 0.08 dB
4kHz: 0.085 dB
5kHz: 0.091 dB
6.3kHz: 0.11 dB
8kHz: 0.14 dB
10kHz: 0.2 dB

DMDM: Uncertainty budget for LS2P

Input parameter	Sym.	Unit	Unce.	31.5Hz	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	3.15 kHz	4kHz	5kHz	6.3kHz	8kHz	10kHz	12.5 kHz	16kHz	20kHz	25kHz
Voltage ratio correc.	$Cor_{R,n}$	dB	A B	0.0021	0.0021	0.0021	0.0017	0.0017	0.0017	0.0017	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	0.0023	0.0023	0.0023	0.0023
Polarisation voltage	U_{POL}	V	0.0008 norm.	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
Coupler volume corr.	$Cor_{CV,n}$	mm^3	0.8 rect.	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086
Static pressure cor.	Cor_{Ps}	kPa	0.035 norm.	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	0.0015	0.0015
Capacitance correction	Cor_C	nF	0.0012 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	0.0011	0.0011	0.0011
Micr. front volume corr.	$Cor_{FV,n}$	mm^3	0.38 rect.	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378	0.0378
Static pressure cor.	C_P	kPa	0.035 norm.	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001
Temperature correction	C_T	K	1.169 norm.	0.0005	0.0004	0.0002	0.0002	0.0001	0.0001	0.0002	0.0004	0.0006	0.0009	0.0014	0.0022	0.0036	0.0061	0.0103	0.0185	0.0421
Humidity correction	C_{RH}	%	3.424 norm.	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0004	0.0005	0.0007	0.001	0.0016	0.0035
Micr. front cavity len. c.	C_L	mm	0.029 rect.	0.0012	0.0008	0.0006	0.0004	0.0003	0.0004	0.0008	0.0018	0.0029	0.0045	0.0072	0.0115	0.0187	0.0309	0.0526	0.0949	0.2163
Reproducibi lity	M_p	dB	σ_A	0.025	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.02	0.02	0.02	0.025	0.04
Result rounding	M_p	dB	0.001 rect.	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	0.0006	0.0006	0.0006
Combined standard uncertainty				0.0462	0.0407	0.0407	0.0407	0.0407	0.0407	0.0407	0.0407	0.0408	0.0409	0.0413	0.0423	0.0477	0.0539	0.0692	0.1072	0.2273
Expanded uncertainty (k=2)				0.0924	0.0814	0.0814	0.0814	0.0814	0.0814	0.0814	0.0814	0.0816	0.0819	0.0827	0.0847	0.0954	0.1078	0.1384	0.2143	0.4547
Rounded uncertainty				0.092	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.082	0.082	0.083	0.085	0.095	0.11	0.14	0.21	0.45
Stated uncertainty (k=2)				0.1	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.09	0.1	0.12	0.15	0.22	0.46

Stated uncertinty (k=2):

31.5Hz – 50Hz: 0.1 dB
63Hz – 6.3kHz: 0.085 dB
8kHz: 0.09 dB

10kHz: 0.1 dB
12.5Hz: 0.12dB
16 kHz: 0.15 dB

20kHz: 0.22 dB
25kHz: 0.46 dB

CENAM:

CENAM – Uncertainty budget for LS1P microphones.

	Measurement quantities							Microphone quantities							Coupler quantities					Others	Overall results			
Frequency, [Hz]	Voltage ratios, R_{ij}	Ref. capacitor, C	Ref. resistor, R	Static 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}	Radial wave motion	Polarization voltage, V_{pol}	Combined std uncertainty Type B	Std uncertainty Type A	Expanded uncertainty, $U_{95.45\%}$, k=2	CMC - Claimed Expanaded Uncertainty
31.623	7.8	9.5	0.1	3.0	11.0	2.8	1.0	78.8	1.2	80.8	0.0	0.0	0.7	1.2	3.8	2.7	0.2	0.1	0.0	9.2	0.011	0.013	0.03	0.04
39.811	7.8	9.5	0.0	2.9	10.9	2.8	1.0	79.8	1.0	81.3	0.1	0.0	0.6	1.2	3.8	2.7	0.1	0.1	0.0	9.2	0.012	0.013	0.03	0.04
50.119	7.8	9.5	0.1	2.9	11.0	2.8	1.0	79.4	1.1	81.1	0.0	0.0	0.6	1.2	3.8	2.7	0.1	0.1	0.0	9.2	0.012	0.013	0.03	0.04
63.096	7.8	9.5	0.0	2.9	10.8	2.8	1.0	80.1	0.9	81.5	0.1	0.0	0.6	1.2	3.8	2.7	0.1	0.1	0.0	9.2	0.012	0.013	0.03	0.04
79.433	7.8	9.5	0.0	2.9	10.7	2.8	1.0	80.7	0.7	81.8	0.1	0.1	0.5	1.2	3.8	2.7	0.1	0.1	0.0	9.2	0.012	0.011	0.03	0.04
100.00	7.8	9.5	0.0	2.9	10.8	2.8	1.0	80.5	0.8	81.7	0.1	0.0	0.5	1.2	3.8	2.7	0.1	0.1	0.0	9.2	0.012	0.011	0.03	0.04
125.89	7.8	9.5	0.0	2.9	10.7	2.8	1.0	81.0	0.6	81.9	0.1	0.1	0.4	1.2	3.8	2.7	0.1	0.1	0.0	9.2	0.012	0.008	0.03	0.03
158.49	7.8	9.5	0.0	2.9	10.7	2.8	1.0	81.4	0.5	82.2	0.1	0.3	0.4	1.2	3.8	2.7	0.1	0.0	0.0	9.2	0.012	0.008	0.03	0.03
199.53	7.8	9.5	0.0	2.9	10.7	2.8	1.0	81.2	0.5	82.1	0.1	0.2	0.4	1.2	3.8	2.7	0.1	0.0	0.0	9.2	0.012	0.008	0.03	0.03
251.19	7.8	9.5	0.0	2.9	10.7	2.8	1.0	81.6	0.4	82.2	0.1	0.4	0.4	1.2	3.8	2.7	0.1	0.0	0.0	9.2	0.012	0.008	0.03	0.03
316.23	7.8	9.5	0.0	2.9	10.9	2.8	1.0	81.8	0.3	82.3	0.2	1.6	0.3	1.2	3.8	2.7	0.0	0.0	0.0	9.2	0.012	0.008	0.03	0.03
398.11	7.8	9.5	0.0	2.9	10.8	2.8	1.0	81.7	0.4	82.3	0.1	1.1	0.4	1.2	3.8	2.7	0.0	0.0	0.0	9.2	0.012	0.008	0.03	0.03
501.19	7.8	9.5	0.0	2.9	11.0	2.8	1.0	81.8	0.3	82.3	0.3	2.0	0.3	1.2	3.8	2.7	0.0	0.0	0.0	9.2	0.012	0.008	0.03	0.03
630.96	7.8	9.5	0.0	2.9	12.4	2.9	1.1	81.5	0.2	81.9	1.2	6.7	0.2	1.2	3.7	2.7	0.0	0.0	0.0	9.2	0.012	0.008	0.03	0.03
794.33	7.8	9.5	0.0	2.9	11.7	2.9	1.1	81.7	0.2	82.1	0.7	4.6	0.3	1.2	3.8	2.7	0.0	0.0	0.0	9.2	0.012	0.008	0.03	0.03
1 000.0	7.8	9.5	0.0	3.0	12.9	2.9	1.2	81.4	0.1	81.7	1.5	8.4	0.2	1.2	3.7	2.7	0.0	0.0	0.0	9.2	0.012	0.008	0.03	0.03
1 258.9	7.8	9.5	0.0	3.0	14.0	3.0	1.2	80.9	0.1	81.2	2.6	13.2	0.1	1.2	3.7	2.7	0.0	0.0	0.0	9.2	0.012	0.008	0.03	0.03
1 584.9	7.8	9.5	0.0	3.1	15.8	3.2	1.3	80.0	0.0	80.1	4.8	21.5	0.0	1.2	3.6	2.7	0.0	0.0	0.0	9.2	0.012	0.008	0.03	0.03
1 995.3	7.8	9.5	0.0	3.2	18.3	3.4	1.5	78.6	0.1	78.5	9.0	33.4	0.0	1.2	3.6	2.8	0.0	0.0	0.0	9.2	0.012	0.008	0.03	0.03
2 511.9	7.8	9.5	0.0	3.3	22.2	3.8	1.7	76.4	0.3	75.8	17.3	51.3	0.1	1.2	3.4	2.9	0.0	0.0	0.0	9.2	0.012	0.008	0.03	0.03
3 162.3	7.8	9.5	0.0	3.6	29.3	4.4	2.1	68.0	0.6	65.0	35.7	60.6	0.2	1.2	3.2	3.0	0.0	0.0	1.0	9.2	0.012	0.008	0.03	0.03
3 981.1	7.8	9.5	0.0	4.0	42.0	5.4	2.8	65.7	1.0	61.9	75.4	111.5	0.3	1.2	2.8	3.2	0.0	0.0	3.0	9.2	0.017	0.009	0.04	0.04
5 011.9	7.8	9.5	0.0	4.7	59.7	7.0	3.7	55.0	1.4	47.4	141	132.1	0.3	1.2	2.3	3.5	0.0	0.0	5.0	9.2	0.022	0.010	0.05	0.05
6 309.6	7.8	9.5	0.0	5.1	75.4	8.0	5.1	49.2	2.0	32.9	150	130.9	0.1	2.0	2.0	3.8	0.0	0.0	10.0	9.2	0.022	0.012	0.05	0.06
7 943.3	7.8	9.5	0.0	5.5	79.0	11.1	7.5	30.0	2.0	45.0	200	33.2	2.0	3.0	0.7	4.5	0.0	0.0	30.0	9.2	0.023	0.021	0.06	0.08
10 000	7.8	9.5	0.0	6.0	105.0	16.4	11.4	40.1	2.1	55.0	350	33.0	5.0	5.0	1.8	5.7	1.0	0.0	60.0	9.2	0.038	0.028	0.09	0.13
12 589	7.8	9.5	0.0	8.0	120.0	25.0	25.0	50.0	5.0	75.0	500	33.0	10.0	8.0	2.0	8.0	2.0	0.1	150.0	9.2	0.055	0.040	0.135	0.18‡
	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	dB

‡ This frequency is not currently included in the CMC declared by CENAM.

CENAM – Uncertainty budget for LS2P microphones.

	Measurement quantities							Microphone quantities							Coupler quantities					Capillary tubes		Others	Overall results			
Frequency, [Hz]	Voltage ratios, R_{ij}	Ref. capacitor, C	Ref. resistor, R	Static 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}	Radial wave motion	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	CMC - Claimed Expanaded Uncertainty
31.623	8.9	9.5	1.2	3.1	1.1	1.1	1.3	130.6	6.1	130.6	1.1	1.2	1.3	8.6	10.6	13.0	1.9	2.0	0.0	2.2	104.6	13.0	**0.021**	**0.023**	**0.06**	**0.07**
39.811	8.9	9.5	1.1	3.4	1.0	1.0	1.1	121.9	4.9	121.9	1.1	1.1	1.2	8.6	10.8	13.3	1.7	1.8	0.0	1.5	39.3	13.0	**0.018**	**0.018**	**0.05**	**0.07**
50.119	8.9	9.5	1.1	3.3	1.1	1.1	1.2	125.6	5.4	125.6	1.1	1.1	1.2	8.6	10.7	13.2	1.8	1.9	0.0	1.8	67.7	13.0	**0.019**	**0.012**	**0.05**	**0.07**
63.096	8.8	9.5	1.0	3.5	1.0	1.0	1.1	118.6	4.4	118.6	1.0	1.1	1.2	8.5	11.0	13.4	1.6	1.7	0.0	1.2	15.1	13.0	**0.017**	**0.010**	**0.04**	**0.05**
79.433	8.8	9.5	1.0	3.6	1.0	1.0	1.0	120.9	3.6	120.9	1.0	1.0	1.1	8.5	11.0	13.4	1.4	1.5	0.0	1.3	12.2	13.0	**0.017**	**0.010**	**0.04**	**0.05**
100.00	8.8	9.5	1.0	3.6	1.0	1.0	1.0	119.9	4.0	119.9	1.0	1.1	1.2	8.5	11.0	13.4	1.5	1.5	0.0	1.2	13.5	13.0	**0.017**	**0.010**	**0.04**	**0.05**
125.89	8.8	9.5	0.9	3.6	0.9	0.9	1.0	121.8	3.3	121.8	1.0	1.0	1.1	8.5	11.0	13.4	1.3	1.4	0.0	1.3	11.0	13.0	**0.017**	**0.010**	**0.04**	**0.05**
158.49	8.6	9.5	0.8	3.7	2.4	1.4	0.8	115.5	2.8	115.5	0.8	0.9	1.0	8.1	11.5	13.2	1.1	1.2	0.0	1.4	15.0	13.0	**0.017**	**0.010**	**0.04**	**0.05**
199.53	8.7	9.5	0.9	3.7	1.7	1.2	0.9	118.3	3.0	118.3	0.9	0.9	1.1	8.3	11.3	13.3	1.2	1.3	0.0	1.3	13.2	13.0	**0.017**	**0.010**	**0.04**	**0.05**
251.19	8.6	9.5	0.8	3.8	3.0	1.5	0.8	113.1	2.6	113.1	0.8	0.8	1.0	8.0	11.6	13.0	1.1	1.1	0.0	1.4	16.5	13.0	**0.016**	**0.010**	**0.04**	**0.05**
316.23	8.5	9.5	0.7	3.8	2.8	1.5	0.7	113.4	2.1	113.4	0.7	0.7	0.9	8.0	11.6	13.0	0.9	1.0	0.0	1.3	12.1	13.0	**0.016**	**0.010**	**0.04**	**0.05**
398.11	8.5	9.5	0.7	3.8	2.9	1.5	0.7	113.2	2.4	113.2	0.7	0.8	1.0	8.0	11.6	13.0	1.0	1.0	0.0	1.3	14.1	13.0	**0.016**	**0.010**	**0.04**	**0.05**
501.19	8.5	9.5	0.7	3.8	2.8	1.4	0.7	113.5	2.0	113.5	0.7	0.7	0.9	7.9	11.5	13.0	0.9	0.9	0.0	1.2	10.6	13.0	**0.016**	**0.010**	**0.04**	**0.05**
630.96	8.5	9.5	0.7	3.8	2.7	1.4	0.7	113.3	1.7	113.3	0.7	0.8	0.9	8.0	11.5	12.9	0.9	0.9	0.0	1.1	4.3	13.0	**0.016**	**0.010**	**0.04**	**0.05**
794.33	8.5	9.5	0.7	3.8	2.7	1.4	0.7	113.4	1.8	113.4	0.7	0.8	0.9	8.0	11.5	12.9	0.9	0.9	0.0	1.2	7.2	13.0	**0.016**	**0.010**	**0.04**	**0.05**
1 000.0	8.5	9.5	0.7	3.7	2.7	1.4	0.7	113.3	1.6	113.3	0.8	0.9	0.9	8.0	11.5	12.9	0.9	0.9	0.0	1.1	2.1	13.0	**0.016**	**0.010**	**0.04**	**0.05**
1 258.9	8.5	9.5	0.6	3.8	2.7	1.3	0.6	113.0	1.4	113.0	1.0	1.0	0.9	7.9	11.4	12.9	0.8	0.8	0.0	1.0	1.0	13.0	**0.016**	**0.010**	**0.04**	**0.05**
1 584.9	8.5	9.5	0.6	3.8	2.9	1.3	0.6	112.6	1.3	112.6	1.1	1.2	0.9	7.9	11.4	12.9	0.8	0.8	0.0	0.9	1.1	13.0	**0.016**	**0.010**	**0.04**	**0.05**
1 995.3	8.4	9.5	0.6	3.9	3.0	1.3	0.6	112.1	1.1	112.1	1.2	2.1	0.8	7.8	11.3	12.8	0.7	0.7	0.0	0.8	2.2	13.0	**0.016**	**0.010**	**0.04**	**0.05**
2 511.9	8.3	9.5	0.5	4.0	3.3	1.3	0.5	111.3	0.9	111.3	1.5	3.7	0.7	7.8	11.1	12.8	0.6	0.6	0.0	0.6	3.4	13.0	**0.016**	**0.010**	**0.04**	**0.05**
3 162.3	8.3	9.5	0.5	4.0	3.7	1.3	0.6	110.4	0.8	110.4	2.0	6.2	0.7	7.8	11.1	12.8	0.6	0.6	0.0	0.6	0.8	13.0	**0.016**	**0.010**	**0.04**	**0.05**
3 981.1	8.3	9.5	0.5	4.2	4.5	1.2	0.6	148.2	0.6	148.2	4.7	10.4	0.7	7.7	10.8	12.8	0.6	0.6	0.0	0.7	0.7	13.0	**0.021**	**0.010**	**0.05**	**0.06**
5 011.9	8.3	9.5	0.4	4.3	5.4	1.3	0.6	144.7	0.5	144.7	32.0	16.1	0.7	7.7	10.5	12.9	0.5	0.5	5.0	0.6	0.8	13.0	**0.021**	**0.010**	**0.05**	**0.06**
6 309.6	8.2	9.5	0.4	4.5	6.0	1.3	0.6	139.1	0.5	139.1	47.3	24.7	0.6	7.7	10.0	13.0	0.4	0.4	10.0	0.5	0.4	13.0	**0.021**	**0.010**	**0.05**	**0.06**
7 943.3	8.2	9.5	0.4	4.9	8.2	1.4	0.8	129.3	0.7	129.3	52.7	36.3	0.6	7.7	9.3	13.2	0.4	0.4	20.0	0.5	0.5	13.0	**0.020**	**0.010**	**0.04**	**0.06**
10 000	8.2	9.5	0.4	5.8	42.0	1.7	2.5	114.1	1.4	114.1	81.1	46.5	0.6	7.6	8.1	13.6	0.4	0.4	30.0	0.4	0.4	13.0	**0.020**	**0.012**	**0.05**	**0.09**
12 589	8.1	9.5	0.3	5.8	45.0	1.8	2.7	172.8	2.4	89.9	90.7	45.0	0.6	7.6	6.1	14.2	0.4	0.4	50.0	0.4	0.5	13.0	**0.023**	**0.015**	**0.06**	**0.10**
15 849	8.1	9.5	0.3	10.0	50.0	2.3	5.1	123.9	3.7	53.6	74.6	20.0	0.5	7.6	4.1	15.3	0.3	0.3	100	0.4	0.3	13.0	**0.019**	**0.020**	**0.06**	**0.13**
19 953	12.0	9.5	0.3	15.0	46.0	3.0	9.8	316.0	4.2	52.6	282.4	42.9	0.5	7.5	12.8	17.4	0.3	0.3	150	0.3	0.4	13.0	**0.046**	**0.040**	**0.12**	**0.19**
25 119	15.0	9.5	0.2	20.0	35.0	5.6	15	635.5	6.5	132.2	300.0	150.7	0.4	7.2	24.5	19.8	0.2	0.2	200	0.2	0.3	13.0	**0.076**	**0.094**	**0.24**	**0.28**
31 623	30.0	9.5	0.3	30.0	44.0	14.4	25	1343	28.8	274.4	350.0	385.2	0.6	7.2	52.5	26.8	0.4	0.4	300	0.3	0.4	13.0	**0.150**	**0.120**	**0.38**	**0.40**
	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}	dBx10^{-4}	dB	dB	dB	dB