SIM.AUV.A-K1 LS1P Microphone Inter-laboratory Comparison

Final Report

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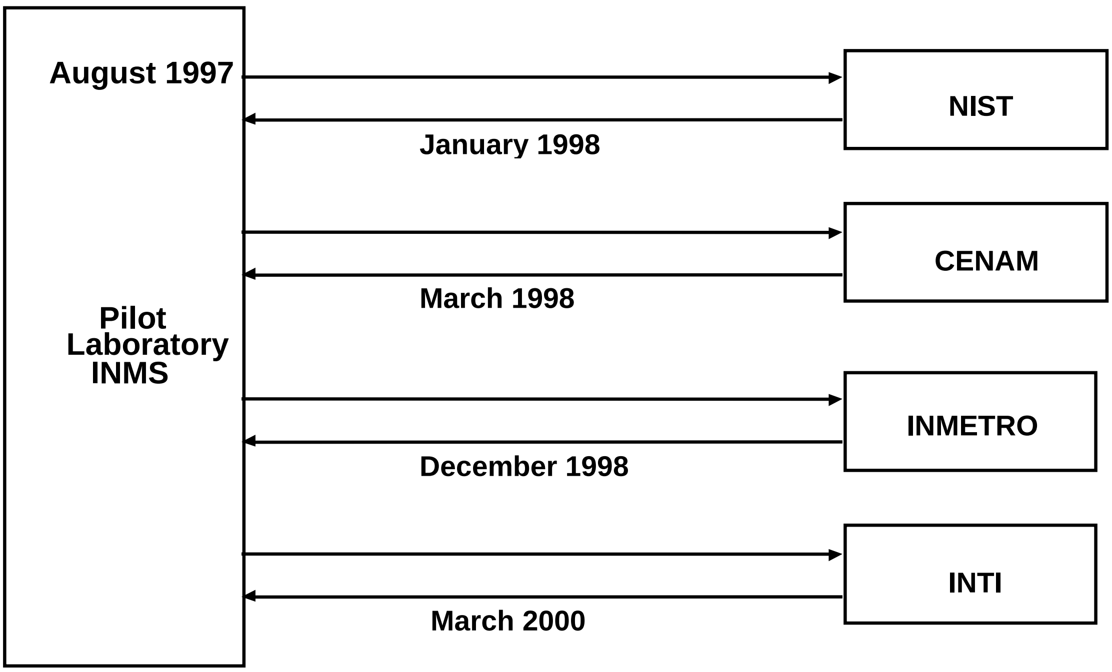
Abstract

The final results of Sistema Interamericano de Metrologia (SIM) inter-laboratory comparison on microphone calibration SIM.AUV.A-K1 in the frequency range from 125 Hz to 8000 Hz are presented. Initially the comparison involved NORAMET countries: U.S.A., Canada and Mexico. Later, the comparison was extended to include Argentina and Brazil resulting in a SIM.AUV.A-K1 microphone inter-laboratory comparison. The national metrology institutes (NMIs) of the five American countries that participated were the Institute for National Measurement Standards (INMS - Canada), National Institute of Standards and Technology (NIST - U.S.A.), Centro Nacional de Metrología (CENAM - Mexico), Instituto Nacional de Metrologia, Normalização e Qualidade Industrial (INMETRO - Brazil) and Instituto Nacional de Tecnología Industrial, (INTI - Argentina). The INMS, Canada was the pilot laboratory that provided the data for this report. The final results were presented, discussed and agreed upon by all participants during a meeting held in INMETRO in October 2000. The maximum RMS deviation for the two LS1P laboratory standard microphones measured by the above participants is 0.037 dB.

1. Introduction

The comparison was organized in a "Star" fashion, i.e., the LS1P condenser microphone transfer standards were calibrated by the pilot laboratory before delivery to and after the return from a participating laboratory. The main aim is to monitor the drift in sensitivity of the microphones at the time intervals between calibrations by each of the participants. The transfer dates of the microphones are shown in Fig. 1.

Fig. 1



2. Participants

The national metrology institutes (NMIs) of the five American countries that participated were:

- National Institute of Standards and Technology (NIST - U.S.A.),
- Centro Nacional de Metrología (CENAM - Mexico),
- Instituto Nacional de Metrologia, Normalização e Qualidade Industrial (INMETRO - Brazil) and
- Instituto Nacional de Tecnología Industrial, (INTI - Argentina)
- Institute for National Measurement Standards (INMS - Canada), pilot laboratory.

3. Transfer standards

The two transfer standards were laboratory type LS1P microphones:

(1) Brüel and Kjær 4160 microphone, s/n 907045 and
(2) Brüel and Kjær 4160 microphone, s/n 1734004;

The third microphone that stayed at the pilot laboratory was

(3) Brüel and Kjær 4160 microphone, s/n 907039.

4. Raw data collected

All the data submitted by the participants are shown in Annex A.

5. Calibration arrangements at the Pilot Laboratory

The laboratory standard microphones (Transfer standard microphones: Brüel and Kjær 4160 microphones, s/n 907045 and s/n 1734004; and an INMS standard microphone that did not travel s/n 907039) were calibrated with the reciprocity method [1, 2] inside an environmentally controlled chamber [3], at the IEC reference conditions of 23 ^{o}C, 101.325 kPa and 50 % RH. The expanded uncertainty (*k* = 2) of the temperature, pressure and humidity measurements were 0.05 ^{o}C, 20 Pa and 5 % RH, respectively. When the microphones were returned from the participants, they were allowed to stabilise under laboratory conditions for two days before measurements. The microphones were then immersed in the above reference environment for at least 12 hours with ISO standard air [4] before the commencement of data logging.

Based on the data collected over a 31 months period (see Annex A), the stabilities of the transfer standard microphones (s/n 907045 and s/n 1734004) including the repeatability of the pilot laboratory calibration system were assessed [5, 6, 7]. The deviations from the mean microphone open-circuit sensitivity levels (the average of the five sets of INMS measurements listed in the Annex A) shown in Fig. 2A and 2B are within approximately 0.011 dB. For the microphone (s/n 907039) which remained at the pilot laboratory without the need to endure air transportation to and from the participating laboratories, the corresponding deviations (Fig. 2C) were significantly smaller for frequencies below 8000 Hz and these deviations are within + 0.007 dB and − 0.006 dB.

It should be noted that the deviations shown for the three microphones (Figures 2A, 2B and 2C) are the combined contributions from the sensitivity level stability of the microphones and the stability of the primary calibration system of the pilot laboratory. Since the microphone manufacturer Brüel and Kjær indicated the stability of their LS1P microphones may have a stability coefficient of approximately 0.01 dB per year, one may conclude that the stability of the primary microphone calibration system of the pilot laboratory is excellent.

Fig. 2A
Deviation from the mean sensitivity level of transfer standard microphone s/n 907045

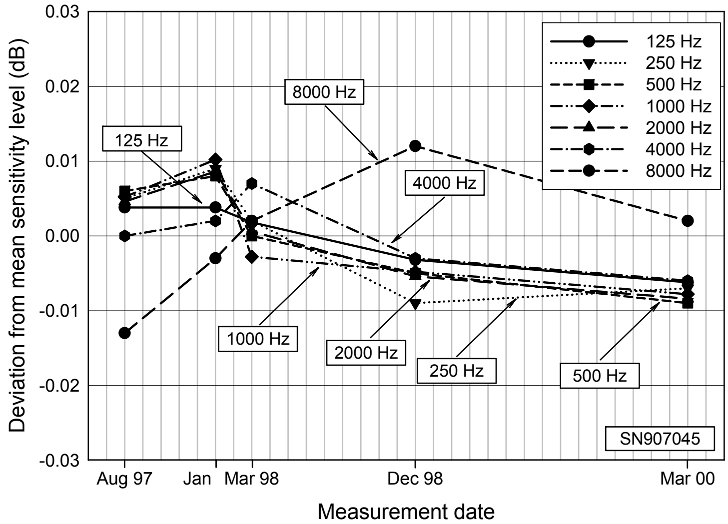
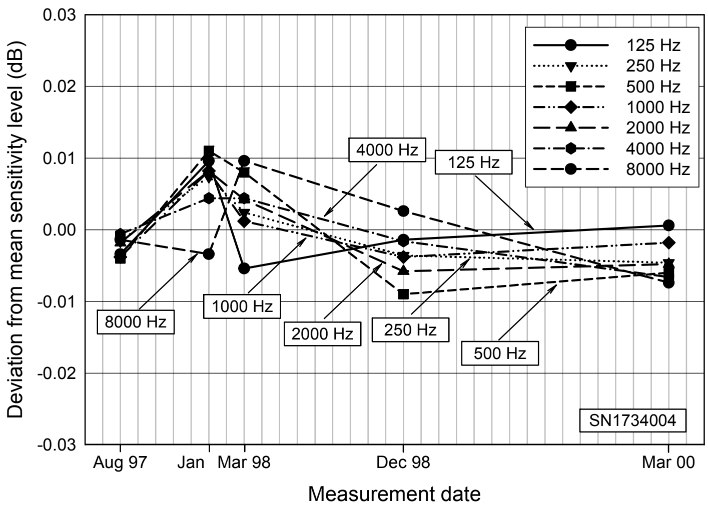


Fig. 2B
Deviation from the mean sensitivity level of transfer standard microphone s/n 1734004



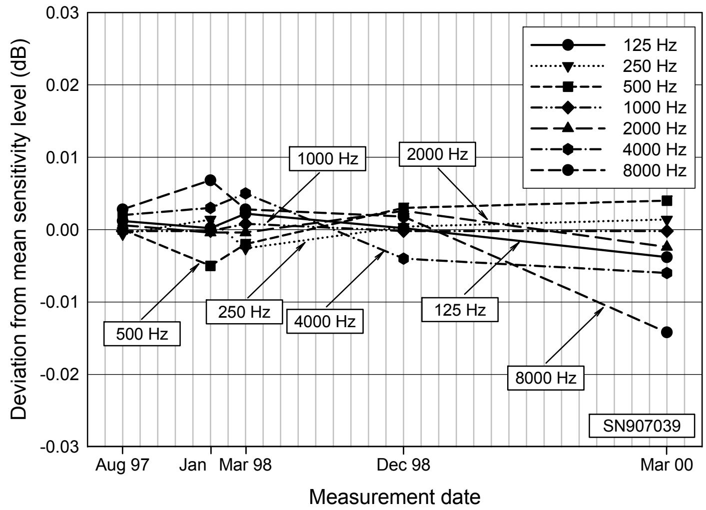


Fig. 2C
Deviation from the mean sensitivity level of laboratory standard microphone s/n 907039 (INMS microphone that did not travel)

6. Protocol

Since the comparison started in 1997 (before the formation of the CCAUV) the protocol adopted was relatively simple. The participants were requested to perform reciprocity calibration of the above two transfer standard microphones (Brüel and Kjær Model 4160, Serial numbers 907045 and 1734004) at the following seven frequencies:

(125, 250, 500, 1000, 2000, 4000 and 8000) Hz.

The participants were requested to include the open-circuit sensitivities of the microphones in their report, corrected to the reference environmental conditions if so desired, and with estimated expanded uncertainties (k = 2).

7. Laboratory methods

NIST USA

The calibration method and coupler used by the NIST satisfied the pertinent requirements of IEC 61094-2 (1992) and ANSI S1.10-1966 (R1997). A large-volume (20-cm^3) coupler was filled with air for measurements from 63 Hz to 500 Hz, and with hydrogen gas for the measurements at 1000 Hz and higher frequencies. The data submitted by the NIST were not converted to reference environmental conditions.

INTI, Argentina

The INTI used the Brüel and Kjær type 4143 Reciprocity Apparatus in conjunction with the Brüel and Kjær 1023 sine generator and 1618 band pass filter and a Fluke 45 voltmeter. The dimensions of the IEC plane wave coupler and front cavity depth were measured to within 10 μm. The measured open-circuit sensitivity levels of the microphones were corrected for temperature and barometric pressure.

CENAM, Mexico

The CENAM also used the Brüel and Kjær type 4143 Reciprocity Apparatus in conjunction with a Fluke 5700A signal generator and a HP 3458A voltmeter. The microphone front cavity dimensions were measured with a depth microscope. An IEC plane wave coupler was used. The measured open-circuit sensitivity levels of the microphones were corrected for temperature and barometric pressure.

INMETRO, Brazil

The INMETRO used the Brüel and Kjær type 4143 Reciprocity Apparatus in conjunction with the Hewlett Packard type 33120A sine generator and Brüel and Kjær type 1617 band pass filter and a Hewlett Packard type 3458A voltmeter. A large volume coupler (20 cm^3) was used for the measurements from 63 Hz to 800 Hz. A plane wave coupler (3 cm^3) was used for the measurements of the 1000 Hz and higher frequencies. The measured open-circuit sensitivity levels of the microphones were corrected for temperature and barometric pressure.

NRC, Canada

The NRC used the Brüel and Kjær type 4143 EH 4004 Reciprocity Apparatus in conjunction with the Brüel and Kjær 1049 sine generator and 1617 band pass filter and a Datron 1271 voltmeter. The dimensions of the IEC plane wave coupler front cavity depth were not measured. However, subsequent measurement showed that the nominal values used were very close to the measured values (between 13 μm to 23 μm). The measured open-circuit sensitivity levels of the microphones were corrected for temperature and barometric pressure.

8. Results of measurements

The estimated expanded uncertainties ($k = 2$) declared by the laboratories are summarized in Table 1. Figures 3 and 4 represent the measurement deviation of each laboratory from the mean of the measured values of the five laboratories at each frequency over the specified frequency range. Since the pilot laboratory measured before and after each of the participants, the mean value of the five runs (see Annex A) was taken as the value for the NRC. The maximum departure of the measured values shown in Figures 3 and 4 is within the estimated uncertainty of 0.05 dB for reciprocity calibration of LS1P laboratory standard microphones given in IEC 1094-2 (1992).

Freq. (Hz)	125	250	500	1000	2000	4000	8000
NRC	0.05	0.02	0.04	0.04	0.04	0.05	0.06
CENAM	0.04	0.04	0.04	0.05	0.05	0.05	0.1
INMETRO	0.05	0.05	0.05	0.05	0.05	0.07	0.11
NIST	0.04	0.04	0.04	0.04	0.04	0.04	0.12
INTI	0.05	0.05	0.05	0.05	0.05	0.1	0.1

Table 1 Measurement standard uncertainties in dB ($k = 2$) quoted by each laboratory.

The measurement deviations from the mean values for all laboratories shown in Figures 3 and 4 for the two microphones were used to obtain the standard deviation for each microphone at each frequency shown in Figure 5. It may be concluded that microphone s/n 1734004 exhibits relatively better stability characteristics.

To demonstrate the measurement capabilities of the participants, the measurement deviation from the mean of both microphones shown in Figures 3 and 4 were used to obtain the RMS deviation from the mean measurement for each laboratory at each frequency shown in Fig. 6. The maximum RMS deviation for the two microphones measured by the NMIs is 0.037 dB.

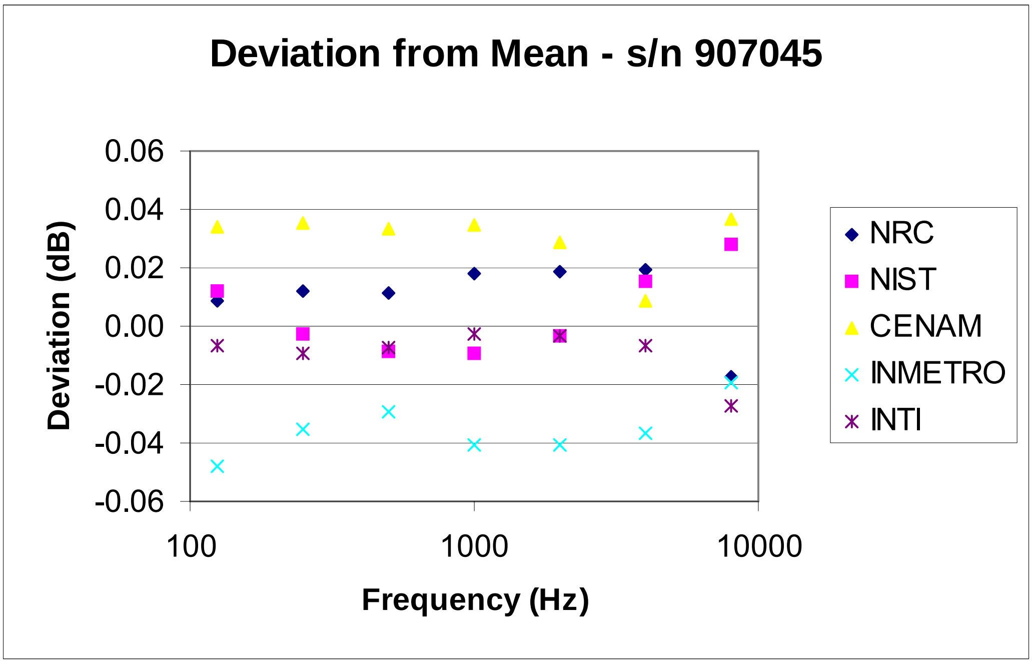


Fig. 3 Deviations of the measurement obtained by each laboratory from the mean of the measured values from all participants for microphone s/n 907045

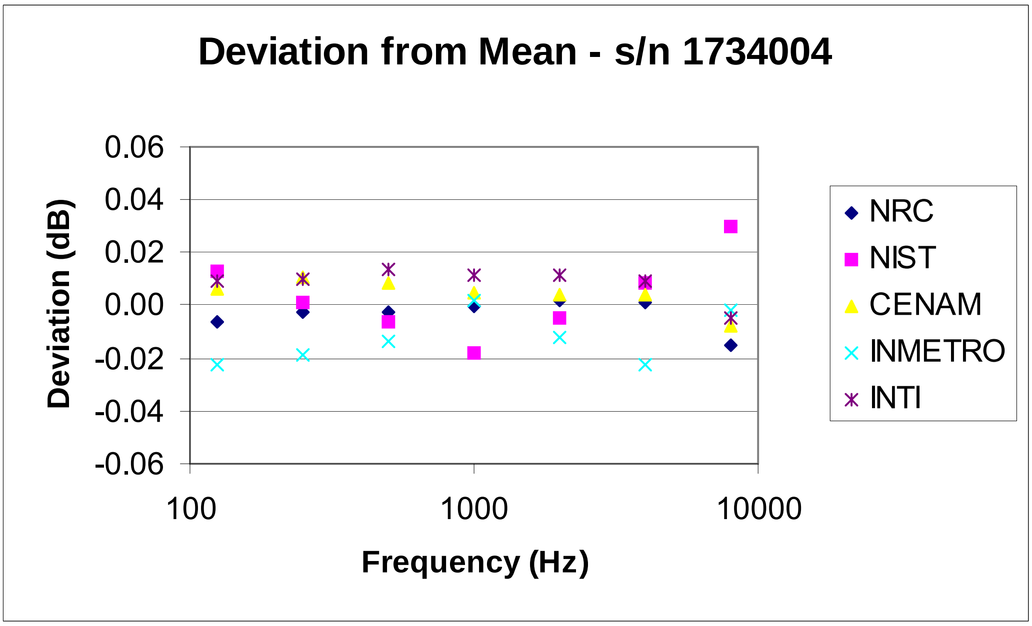


Fig. 4 Deviations of the measurement obtained by each laboratory from the mean of the measured values from all participants for microphone s/n 1734004

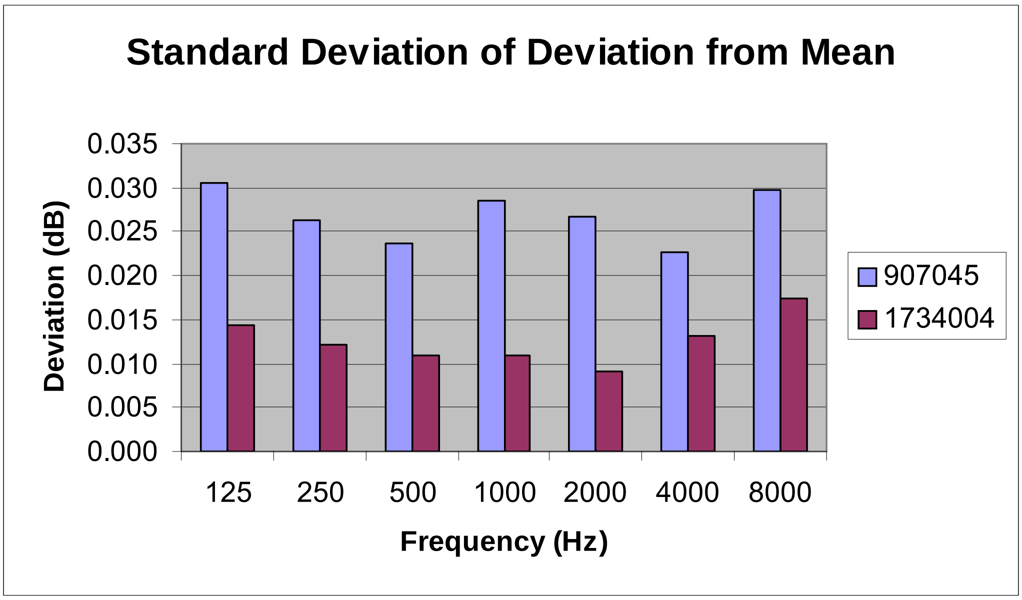


Fig. 5 For the two microphones, the deviations shown in Figures 3 and 4 were used to compute the standard deviation from the mean of the measured values by the participants. It may be concluded that microphone s/n 1734004 exhibits relatively better stability characteristics.

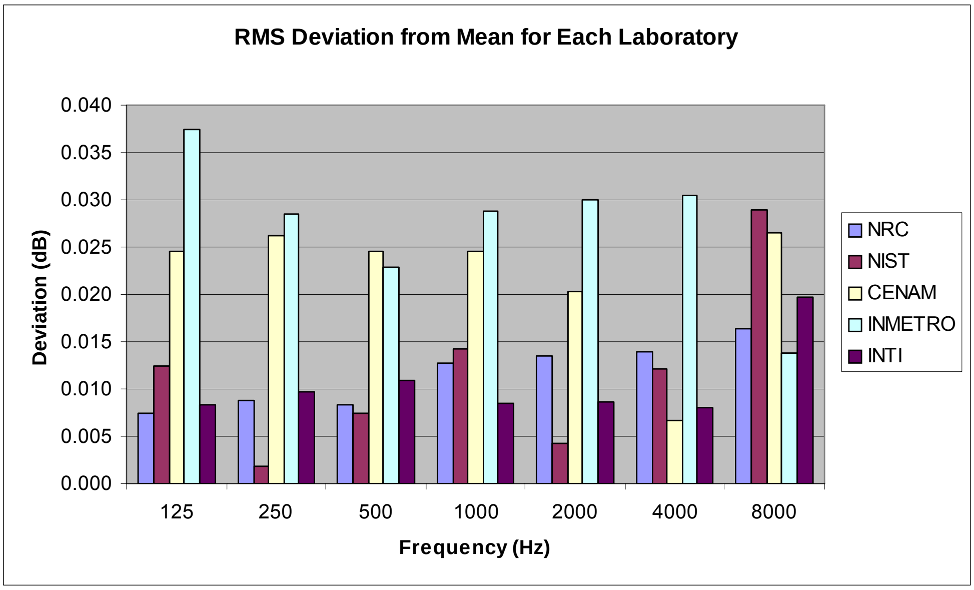


Fig. 6 The deviations of both microphones shown in Figures 3 and 4 were used to obtain the RMS deviation from the mean of the measured values for each laboratory.

In general, all the participants used the plane-wave coupler [1, 2] that has a volume of approximately 3 cc filled with air, except the NIST that used a large-volume coupler with a volume of approximately 20 cc filled with air for frequencies up to 500 Hz and filled with hydrogen at higher frequencies. The data summary for this comparison is shown in the Annex A, including the uncertainty budgets for the INMETRO and the INTI. The corresponding budgets for the other participants have already been published in the CCAUV.A-K1 comparison report [8].

9. Linking of SIM.AUV.A-K1 to CCAUV.A-K1

In view of the fact that two laboratories: INMETRO and INTI did not participate in the CIPM comparison: CCAUV.A-K1, an effort is made here to provide some insight to link the data of regional comparison: SIM.AUV.A-K1 of the two laboratories to the CIPM international comparison: CCAUV.A-K1. The method adopted here is based on methodology given by Sutton [9].

There may be other methods of linking. Since all the measured data are presented here (Annex A) future new linking methods can be implemented if so desired. It should be noted that for this SIM comparison (SIM.AUV.A-K1) the agreement of the microphone sensitivity levels measured by the participating NMIs were within a few hundredths of a decibel, further work to achieve marginal improvements will have no significant effect for most industrial applications.

In particular, it should be pointed out there are not many methodologies that can handle,
a) the use of different traveling standards (i.e., otherwise that would imply that the same artifacts used in a CIPM comparison should be used in RMO comparisons in order to establish a proper linkage),
b) measurement results from several transfer standards,
c) multiple loops or repeated measurements by a laboratory, and
d) correlation among measurements,
at the same time and still provide a single set of degrees of equivalence for each participating laboratory.

Microphone sensitivity levels, $s_j(L_i)$, reported by each laboratory L_i for the "j-th" traveling microphone in SIM.AUV.A-K1 are given in the following two tables.

Sensitivity levels reported by SIM labs, microphone serial number 907045 (From Annex A), dB							
SIM NMI	**125 Hz**	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**4 kHz**	**8 kHz**
NRC	-26.498	-26.518	-26.522	-26.486	-26.305	-25.703	-27.201
NIST	-26.500	-26.537	-26.549	-26.519	-26.333	-25.708	-27.143
NRC	-26.498	-26.514	-26.520	-26.481	-26.301	-25.701	-27.191
CENAM	-26.478	-26.499	-26.507	-26.475	-26.301	-25.715	-27.134
NRC	-26.500	-26.521	-26.528	-26.494	-26.309	-25.696	-27.186
INMETRO	-26.560	-26.570	-26.570	-26.550	-26.370	-25.760	-27.190
NRC	-26.505	-26.532	-26.533	-26.496	-26.315	-25.706	-27.176
INTI	-26.519	-26.544	-26.548	-26.512	-26.333	-25.730	-27.198
NRC	-26.508	-26.530	-26.537	-26.499	-26.318	-25.709	-27.186

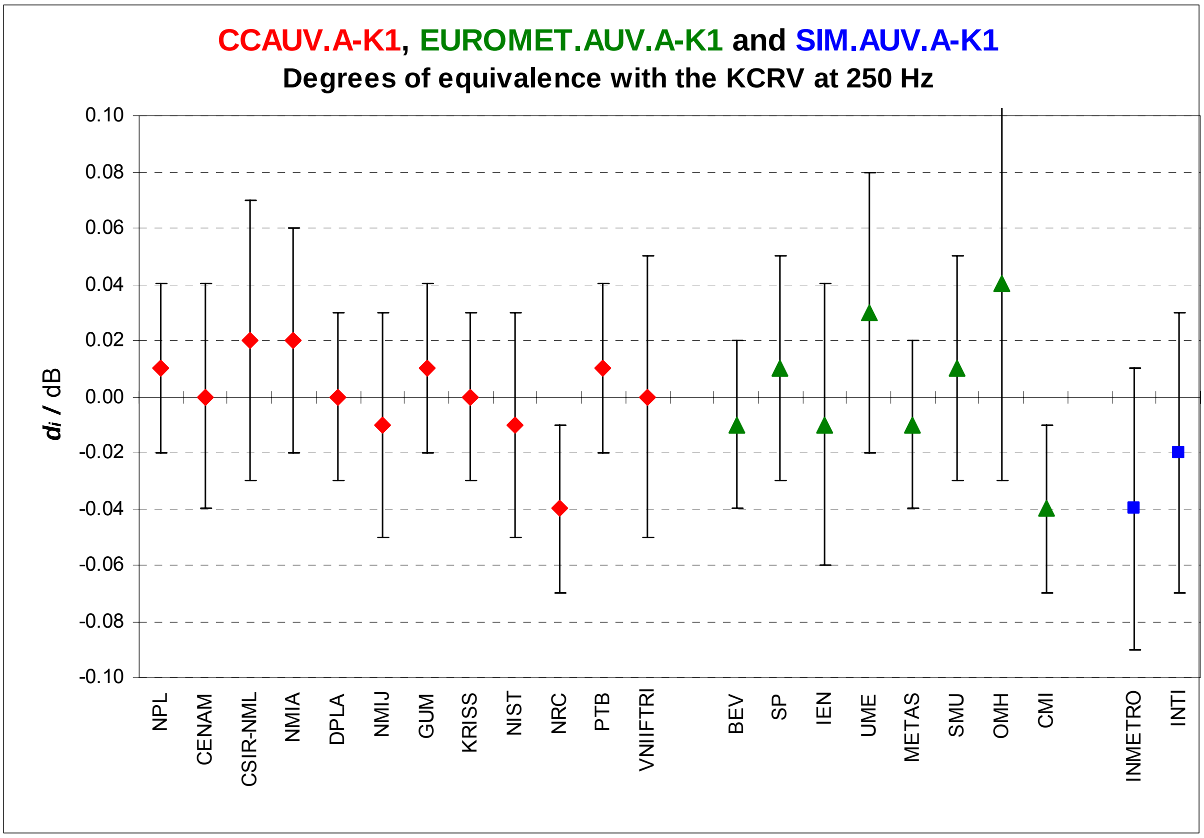
Sensitivity levels reported by SIM labs, microphone serial number 1734004 (From Annex A), dB							
SIM NMI	**125 Hz**	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**4 kHz**	**8 kHz**
NRC	-26.991	-27.011	-27.020	-26.993	-26.855	-26.403	-27.351
NIST	-26.975	-27.010	-27.023	-27.010	-26.863	-26.399	-27.308
NRC	-26.978	-27.002	-27.005	-26.981	-26.845	-26.398	-27.353
CENAM	-26.981	-27.000	-27.008	-26.987	-26.854	-26.403	-27.346
NRC	-26.993	-27.007	-27.008	-26.988	-26.849	-26.398	-27.340
INMETRO	-27.010	-27.030	-27.030	-26.990	-26.870	-26.430	-27.340
NRC	-26.989	-27.013	-27.025	-26.993	-26.859	-26.404	-27.347
INTI	-26.978	-27.001	-27.003	-26.980	-26.846	-26.398	-27.343
NRC	-26.987	-27.014	-27.022	-26.991	-26.858	-26.409	-27.357

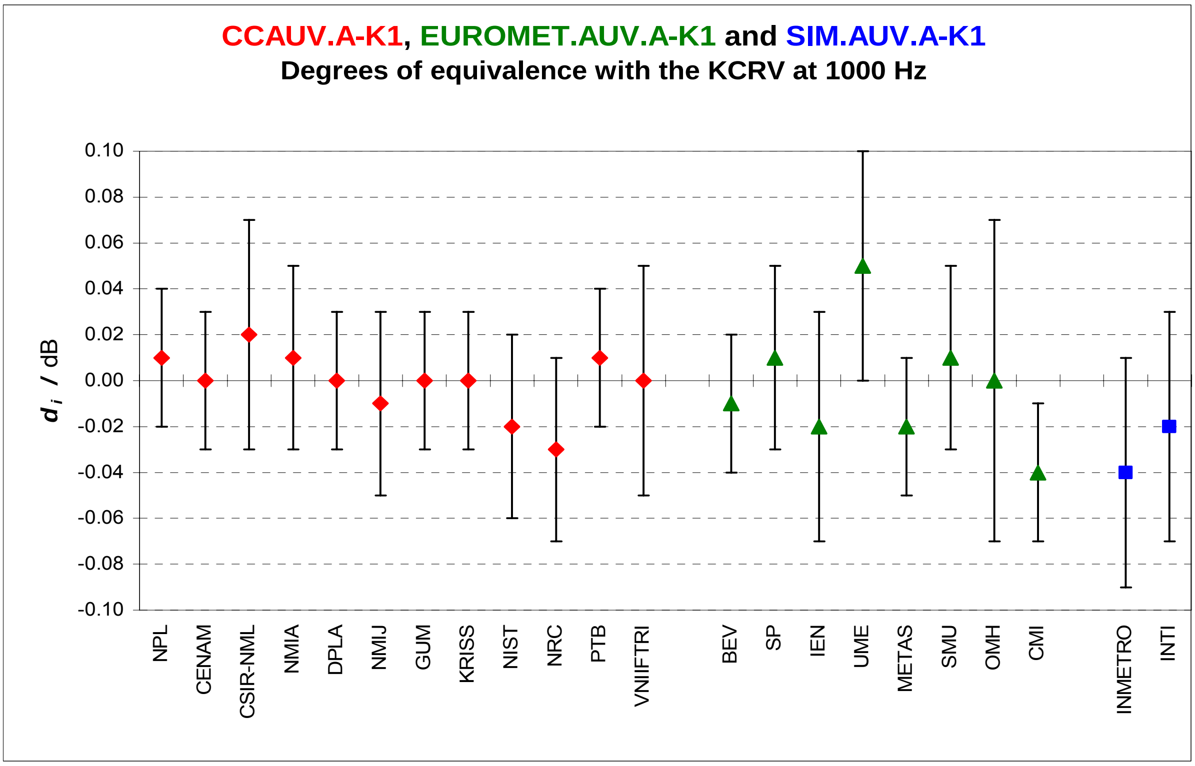
'Nominal' sensitivity levels (or SIM reference values), given in the following table, were obtained as the arithmetic mean of all measurements available for each microphone, $s_{0,j}$. The methodology, discussion and linked degrees of equivalence are presented in Annex B.

Nominal sensitivity levels* used as reference values in linking calculations for SIM.AUV.A-K1 LS1P microphone comparison, dB		
Frequency	Microphone serial number 907045	Microphone serial number 1734004
125 Hz	**-26.507**	**-26.987**
250 Hz	**-26.529**	**-27.010**
500 Hz	**-26.535**	**-27.016**
1 kHz	**-26.501**	**-26.990**
2 kHz	**-26.321**	**-26.855**
4 kHz	**-25.714**	**-26.405**
8 kHz	**-27.178**	**-27.343**

* rounded to three digits.

As a demonstration of the effect of applying this methodology, the linked degrees of equivalence with the KCRV at 250 Hz and at 1000 Hz from Annex B are presented graphically in the following figures. These are the two frequencies represented graphically in the KCDB and the IMETRO and INTI results have been added to these graphs, in which each participating laboratory has only one result.


CCAUV.A-K1, EUROMET.AUV.A-K1 and SIM.AUV.A-K1
Degrees of equivalence with the KCRV at 250 Hz
di / dB
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
NPL
CENAM
CSIR-NML
NMIA
DPLA
NMIJ
GUM
KRISS
NIST
NRC
PTB
VNIIFTRI
BEV
SP
IEN
UME
METAS
SMU
OMH
CMI
INMETRO
INTI


CCAUV.A-K1, EUROMET.AUV.A-K1 and SIM.AUV.A-K1
Degrees of equivalence with the KCRV at 1000 Hz
di / dB
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
NPL
CENAM
CSIR-NML
NMIA
DPLA
NMIJ
GUM
KRISS
NIST
NRC
PTB
VNIIFTRI
BEV
SP
IEN
UME
METAS
SMU
OMH
CMI
INMETRO
INTI

10. Conclusions

For this SIM.AUV.A-K1 comparison, there were five participating NMIs: the Institute for National Measurement Standards (INMS - Canada), National Institute of Standards and Technology (NIST - U.S.A.), Centro Nacional de Metrología (CENAM - Mexico), Instituto Nacional de Metrologia, Normalização e Qualidade Industrial (INMETRO - Brazil) and Instituto Nacional de Tecnología Industrial, (INTI - Argentina) who measured the sensitivity levels of two LS1P microphones at octave frequencies from 125 Hz to 8 kHz. Each of the laboratories used the apparatus of their choice, with no restriction on coupler sizes, and the inclusion of gas other than air where necessary. The measurements were made at various environmental conditions with the data corrected to the IEC reference environmental conditions of 23 ^{o}C, 101.325 kPa and 50 % relative humidity.

The maximum RMS deviation of microphone sensitivity levels from the mean value measured by the above NMIs for both microphones is 0.037 dB. The overall data confirmed that the above comparisons were in good agreement since IEC 1094-2 (1992) gives an estimated uncertainty of 0.05 dB for reciprocity calibration of LS1P laboratory standard microphones.

The linking method chosen [9] is well suited to link RMO to CIPM comparisons despite the number of transfer standards used. Otherwise, degrees of equivalence have to be computed for each transfer standard and later on reduced to a single set of DOEs, by averaging them or via some other algorithm. Sutton´s algorithm can handle all measurement data of each participating laboratory when several traveling standards are used, besides being able to incorporate the results of all linking labs in a well-known least-squares formulation whose solution is relatively straightforward.

This has enabled the results of the INMETRO and the INTI to be linked to the CCAUV.A-K1 comparison.

11. Acknowledgement

The authors would like to thank the participants: Salvador Barrera-Figueroa, José Noé Razo-Razo, Alfredo Elias-Juarez (CENAM); Walter Erico Hoffmann and Zemar M. D. Soares (INMETRO); Victor Nedzelnitsky (NIST); Lucia N. Taibo and Jorge M. Riganti (INTI), for their participation and suggestions during the comparison. Special thanks to Executive Secretary of CCAUV Dr. Allisy-Roberts and Dr. Claudine Thomas of BIPM for their advice and helpful comments.

References

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8. R. Barham, Report on key comparison CCAUV.A-K1, 2003 *Metrologia* **40** *Technical Supplement* 09002.

9. C.M. Sutton, "Analysis and linking of international measurement comparisons," *Metrologia*, 41, 272-277, 2004

Annex A

Data Summary

Columns with "Before" indicate data for microphones that were calibrated by the pilot laboratory before delivery to the participants, and columns with "After" indicate data for microphones that were calibrated by the pilot laboratory after the return from the participants.

		INMS Measurements					Data from participants (1)				
Mic. S/N	Freq. (Hz)	Before NIST	After NIST (Before CENAM)	After CENAM (Before INMETRO)	After INMETRO (Before INTI)	After INTI	NIST Original data	NIST data with pressure correction (2)	CENAM data	INMETRO data	INTI data
907045	125	-26.498	-26.498	-26.500	-26.505	-26.508	-26.483	-26.500	-26.478	-26.560	-26.519
	250	-26.518	-26.514	-26.521	-26.532	-26.530	-26.520	-26.537	-26.499	-26.570	-26.544
	500	-26.522	-26.520	-26.528	-26.533	-26.537	-26.532	-26.549	-26.507	-26.570	-26.548
	1000	-26.486	-26.481	-26.494	-26.496	-26.499	-26.502	-26.519	-26.475	-26.550	-26.512
	2000	-26.305	-26.301	-26.309	-26.315	-26.318	-26.318	-26.333	-26.301	-26.370	-26.333
	4000	-25.703	-25.701	-25.696	-25.706	-25.709	-25.701	-25.708	-25.715	-25.760	-25.730
	8000	-27.201	-27.191	-27.186	-27.176	-27.186	-27.134	-27.143	-27.134	-27.190	-27.198
1734004	125	-26.991	-26.978	-26.993	-26.989	-26.987	-26.958	-26.975	-26.981	-27.010	-26.978
	250	-27.011	-27.002	-27.007	-27.013	-27.014	-26.993	-27.010	-27.000	-27.030	-27.001
	500	-27.020	-27.005	-27.008	-27.025	-27.022	-27.006	-27.023	-27.008	-27.030	-27.003
	1000	-26.993	-26.981	-26.988	-26.993	-26.991	-26.993	-27.010	-26.987	-26.990	-26.980
	2000	-26.855	-26.845	-26.849	-26.859	-26.858	-26.848	-26.863	-26.854	-26.870	-26.846
	4000	-26.403	-26.398	-26.398	-26.404	-26.409	-26.392	-26.399	-26.403	-26.430	-26.398
	8000	-27.351	-27.353	-27.340	-27.347	-27.357	-27.299	-27.308	-27.346	-27.340	-27.343

Notes:

(1) All the participants, except NIST, provided data to which a correction had been applied to arrive at a microphone sensitivity referred to the reference environmental conditions.

(2) The NIST data with corrections [3] to the reference environmental conditions were used to prepare the data presented in Section 8 of this report.

INMETRO Uncertainty Budget - LS1P Microphone Calibration (Sound Pressure Level)

Type B uncertainty							
Source of uncertainty - Rectangular distribution as semi-ranges (10^{-4} dB)							
Frequency / Hz	125	250	500	1000	2000	4000	8000
Measurement							
Capacitor	48	48	48	48	48	48	48
Polarization Voltage	20	20	20	20	20	20	20
Microphone parameters							
Acoustic impedance (fit)	200	200	200	200	200	250	320
Couplers							
Diameter	40	40	40	40	40	40	40
Length	20	20	20	20	20	20	20
Correction of results to normal environmental conditions							
Static pressure	15	15	15	15	15	20	30
Temperature	20	20	20	20	20	20	20
Environmental conditions							
Static pressure	49	49	49	49	49	49	49
Temperature	8	8	8	8	8	8	8
Humidity	8	8	8	8	8	8	8
Rounding error	3	3	3	3	3	3	3
Estimate of type B uncertainty, k = 1	219	219	219	219	219	266	333

Type A uncertainty							
Type A uncertainty as Normal distribution (10^{-4} dB)							
Repeatibility	80	80	80	80	100	225	410
Estimate of type A uncertainty, k = 1	80	80	80	80	100	225	410

Overall uncertainty (10^{-4} dB)							
Overall uncertainty, k = 2	**466**	**466**	**466**	**466**	**481**	**696**	**1057**

Final expanded uncertainty	**500**	**500**	**500**	**500**	**500**	**700**	**1100**

INTI - Uncertainty budget

LS1P microphone pressure reciprocity calibration	Frequency range: 4 kHz to 8 kHz

Uncertainty Source	**Symbol**	**c_i** (1)	**Interval (±)**	**Distribution** (2)	**Factor**	ν_i (3)	**u_i**
Equivalent volume		1	0.03	R	1.7	10000	0.017
Voltage ratio		1	0.02	R	1.7	10000	0.012
Reference impedance		1	0.005	R	1.7	10000	0.003
Specific heat ratio		1	0.002	R	1.7	10000	0.001
Barometric pressure		1	0.002	R	1.7	10000	0.001
Heat-conduction correction		1	0.01	R	1.7	10000	0.006
Wave motion correction		1	0.08	R	1.7	10000	0.046
Insert voltage		1	0.005	R	1.7	10000	0.003
Polarizing voltage		1	0.01	R	1.7	10000	0.006
Pressure coefficient		1	0.008	R	1.7	10000	0.005
Temperature coefficient		1	0.001	R	1.7	10000	0.001
Humidity coefficient		1	0.001	R	1.7	10000	0.001
Combined Uncertainty	u_c			**N (1σ)**		14612.9	0.05
Expanded Uncertainty (k = 2)	U			**N (95%)**	2.0		**0.1**

(1) Sensitivity coefficients
(2) N: normal; R:rectangular
(3) Degrees of freedom

Annex B

Linking of SIM.AUV.A-K1 to CCAUV.A-K1

1. Introduction

National metrology institutes (NMIs) who did not take part in a CIPM key comparison can establish the comparability of their measurement capabilities via regional comparisons as if they had actually participated in such CIPM key comparison. For that purpose, there should be laboratories who take part in both comparisons and from whose results a linking to that CIPM key comparison can be achieved.

This Annex describes the linking of regional key comparison SIM.AUV.A-K1 to the CCAUV.A-K1 comparison of pressure reciprocity calibration of microphones. It is achieved as a generalized linear least-squares problem, following the work by C. Sutton [9].

Degrees of equivalence from the CCAUV.A-K1 final report [8] are taken to perform the link of SIM.AUV.A-K1, at octave frequencies from 125 Hz up to 8 kHz. The three linking laboratories are the NRC, NIST and the CENAM.

The participating laboratories in the SIM.AUV.A-K1 were the NRC, NIST, CENAM, INMETRO and the INTI. This comparison made use of two B&K 4160 microphones which were circulated in a star type comparison by the pilot laboratory, the NRC. The calibration results before and after each participant are available in Annex A.

2. Problem setup

The linking methodology given in [9] is suitable for the linking of two comparisons in which several traveling standards might have been used. In addition, it is able to incorporate multiple loops, multiple measurements and correlations between measurements, if available. These features make it feasible to attempt the linkage of the SIM.AUV.A-K1 to the CCAUV.A-K1, and because of its least squares formulation, the method gives, without further assumptions or calculations, the degrees of equivalence (DOE's) of the participating laboratories.

In outline, the linear least-squares problem consists in solving the following set of equations,

$$s_j(\mathrm{L}_i) \quad s_{0,j} = d_i \quad (s_{0,j} \quad s_j) + e_{j,i} \qquad \textbf{(1)}$$

$$s_c(\mathrm{L}_i) \quad s_{KCRV} = d_i \quad (s_{KCRV} \quad s_c) + e_{c,i} \qquad \textbf{(2)}$$

$$s_{KCRV} - s_c = 0 \qquad \textbf{(3)}$$

where, in this case,
$s_j(\mathrm{L}_i)$ is the microphone sensitivity level reported by laboratory L_i for the "*j*-th" traveling microphone in the SIM.AUV.A-K1, $s_{0,j}$ is the 'nominal' sensitivity level of the "*j*-th" traveling microphone, s_j corresponds to the actual (or true) sensitivity level of microphone standard "*j*" in the SIM comparison, $e_{j,i}$ represents random errors associated with the "*j*-th" traveling

microphone standard on measurements performed by laboratory "*i*", $s_c(L_i)$ is the sensitivity level reported by the linking laboratory L_i in the CCAUV.A-K1 microphone comparison, s_{KCRV} is the microphone sensitivity level that was obtained as the key comparison reference value (KCRV), s_c is the actual microphone sensitivity level that corresponds to the reference value in the CCAUV.A-K1, and d_i is the deviation (or bias) of laboratory "*i*" in either the SIM or CCAUV comparisons; this deviation is assumed to remain constant in both comparisons.

So, equations 1 to 3 can be put together as an over-determined linear set of equations

$$y = Ax + \varepsilon \qquad \textbf{(5)}$$

where

- the vector y of known quantities is structured as

$$y = [s_j(\mathrm{L}_i)_p \quad s_{0,j}, s_c(\mathrm{L}_i)_p \quad s_{KCRV}, 0]^T \qquad \textbf{(6)}$$

where *p* indicates the *p*th comparison measurement

- the vector b of unknown quantities is given by

$$x = [d_i, s_{0,j} - s_j, s_{KCRV} - s_c]^T \qquad \textbf{(7)}$$

- the matrix A, commonly referred to as the design matrix, for the particular case with five participating labs in SIM.AUV.A-K1, for two traveling microphones and three SIM linking laboratories who took part in CCAUV.A-K1, has the following structure

$$\mathbf{A} = \left[\begin{array}{cccccccc}
1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\
\hline
1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & -1 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\
\hline
1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 \\
\hline
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{array}\right]$$

The first two parts of the matrix are for the two traveling microphones where the first column of A shows that the pilot laboratory performed measurements before and after each of the four other participants for each microphone of the regional comparison that is being linked.
The third part shows the three SIM linking laboratories in the CCAUV key comparison and the final line shows the KCRV.

The least squares problem is set to minimize a vector ε of random errors over x, such that the restriction $s_{KCRV} - s_c = 0$ is held. That is,

$$\min_{\underline{x}} \|\varepsilon\|_2^2 = \min_{\underline{x}} \|\underline{y} - \underline{A}\underline{x}\|_{2,\Phi^{-1/2}}^2 \qquad \textbf{(8)}$$

such that $\quad [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1]\ \underline{\mathbf{x}} = \underline{\mathbf{0}}$

whose solution is given by,

$$x = (A^T \Phi^{-1} A)^T A \Phi^{-1} y \qquad \textbf{(9)}$$

an estimate of the covariance matrix $\mathbf{\Phi}$ is needed to estimate x. In the absence of enough data measurements, different correlation factors among measurements may have to be tested. The covariance matrix **Φ** is symmetric; in practice, its diagonal elements correspond to the standard uncertainty squared associated with each data element in the vector y. That is,

$$\Phi(\underline{y}) = \begin{bmatrix} u(y_1, y_1) & \cdots & u(y_1, y_n) \\ \vdots & \ddots & \vdots \\ u(y_n, y_1) & \cdots & u(y_n, y_n) \end{bmatrix}$$

$$\Phi = \mathrm{cov}(\underline{y}) = [u(y_i, y_j)] = r_{ij} u(y_i) u(y_j) \qquad \textbf{(10)}$$

Consistency between measurements and the model used in the least squares formulation, is verified by comparing the measure of goodness given by,

$$\varepsilon^2 = (y - Ax)^T \Phi^{-1} (y - Ax) \qquad \textbf{(11)}$$

with the expected value of ε^2, considering it follows a chi-squared distribution with *v* degrees of freedom, i.e.,

$$E\left[\xi_\nu^2\right] = \nu \qquad \sigma\left[\xi_\nu^2\right] = \sqrt{2\nu} \qquad \textbf{(12)}$$

After which,

a) the DOEs respect to the KCRV are obtained by,

$$d_i = x_i, \quad for \quad i = 1,...,n$$
$$U_i = k\sqrt{C_{ii}}, \quad where \quad C = (A^T \Phi^{-1} A)^{-1} \qquad \textbf{(13)}$$

b) the DOEs between pairs of laboratories are given by,

$$d_{ij} = x_i - x_j, \quad for \quad i, j = 1,...,n, \quad i \neq j$$
$$U_{ij} = k\sqrt{C_{ii} + C_{jj} - 2C_{ij}} \qquad \textbf{(14)}$$

3. Measurement data to perform the link

This section uses the data in Appendix A to perform the least squares estimation described in Section 2.

3.1 Measurement results reported for SIM.AUV.A-K1 comparison

Sensitivity levels / dB reported by SIM labs, for microphone serial number 907045							
SIM NMI	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
NRC	**-26.498**	**-26.518**	**-26.522**	**-26.486**	**-26.305**	**-25.703**	**-27.201**
NIST	**-26.500**	**-26.537**	**-26.549**	**-26.519**	**-26.333**	**-25.708**	**-27.143**
NRC	**-26.498**	**-26.514**	**-26.520**	**-26.481**	**-26.301**	**-25.701**	**-27.191**
CENAM	**-26.478**	**-26.499**	**-26.507**	**-26.475**	**-26.301**	**-25.715**	**-27.134**
NRC	**-26.500**	**-26.521**	**-26.528**	**-26.494**	**-26.309**	**-25.696**	**-27.186**
INMETRO	**-26.560**	**-26.570**	**-26.570**	**-26.550**	**-26.370**	**-25.760**	**-27.190**
NRC	**-26.505**	**-26.532**	**-26.533**	**-26.496**	**-26.315**	**-25.706**	**-27.176**
INTI	**-26.519**	**-26.544**	**-26.548**	**-26.512**	**-26.333**	**-25.730**	**-27.198**
NRC	**-26.508**	**-26.530**	**-26.537**	**-26.499**	**-26.318**	**-25.709**	**-27.186**

Sensitivity levels / dB reported by SIM labs, for microphone serial number 1734004							
SIM NMI	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
NRC	**-26.991**	**-27.011**	**-27.020**	**-26.993**	**-26.855**	**-26.403**	**-27.351**
NIST	**-26.975**	**-27.010**	**-27.023**	**-27.010**	**-26.863**	**-26.399**	**-27.308**
NRC	**-26.978**	**-27.002**	**-27.005**	**-26.981**	**-26.845**	**-26.398**	**-27.353**
CENAM	**-26.981**	**-27.000**	**-27.008**	**-26.987**	**-26.854**	**-26.403**	**-27.346**
NRC	**-26.993**	**-27.007**	**-27.008**	**-26.988**	**-26.849**	**-26.398**	**-27.340**
INMETRO	**-27.010**	**-27.030**	**-27.030**	**-26.990**	**-26.870**	**-26.430**	**-27.340**
NRC	**-26.989**	**-27.013**	**-27.025**	**-26.993**	**-26.859**	**-26.404**	**-27.347**
INTI	**-26.978**	**-27.001**	**-27.003**	**-26.980**	**-26.846**	**-26.398**	**-27.343**
NRC	**-26.987**	**-27.014**	**-27.022**	**-26.991**	**-26.858**	**-26.409**	**-27.357**

Measurement uncertainties / dB (k = 1) given by the participants in the SIM.AUV.A-K1							
SIM NMI	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
NRC	**0.025**	**0.01**	**0.02**	**0.02**	**0.02**	**0.025**	**0.03**
NIST	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.06**
CENAM	**0.02**	**0.02**	**0.02**	**0.025**	**0.025**	**0.025**	**0.05**
INMETRO	**0.025**	**0.025**	**0.025**	**0.025**	**0.025**	**0.035**	**0.055**
INTI	**0.025**	**0.025**	**0.025**	**0.025**	**0.025**	**0.05**	**0.05**

3.2 Measurement results taken from CCAUV.A-K1

Deviations / dB of the SIM linking labs with respect to the KCRV given in the CCAUV.A-K1 final report [8]							
SIM links	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
NRC	**-0.04**	**-0.04**	**-0.04**	**-0.03**	**-0.03**	**-0.04**	**-0.05**
NIST	**0**	**-0.01**	**0**	**-0.02**	**-0.02**	**0**	**-0.01**
CENAM	**0**	**0**	**0**	**0**	**0.01**	**0.01**	**-0.01**

Measurement uncertainties / dB (k = 1) given by the SIM linking labs in the CCAUV.A-K1 comparison							
SIM links	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
NRC	**0.02**	**0.015**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**
NIST	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.06**
CENAM	**0.02**	**0.02**	**0.015**	**0.015**	**0.015**	**0.025**	**0.05**

Measurement uncertainty / dB (k = 1) of the KCRV given in the CCAUV.A-K1 final report [8]							
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
u_{kcrv}	**0.006**	**0.005**	**0.005**	**0.005**	**0.006**	**0.006**	**0.011**

3.3 Combined data

The data in the tables of 3.1 and 3.2 give the following set of known differences, according to equation (6).

Set of data vectors y / dB used for calculations at the indicated frequency						
125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
0.0093	**0.0114**	**0.0129**	**0.0153**	**0.0156**	**0.0112**	**-0.0227**
0.0073	**-0.0076**	**-0.0141**	**-0.0177**	**-0.0124**	**0.0062**	**0.0353**
0.0093	**0.0154**	**0.0149**	**0.0203**	**0.0196**	**0.0132**	**-0.0127**
0.0293	**0.0304**	**0.0279**	**0.0263**	**0.0196**	**-0.0008**	**0.0443**
0.0073	**0.0084**	**0.0069**	**0.0073**	**0.0116**	**0.0182**	**-0.0077**
-0.0527	**-0.0406**	**-0.0351**	**-0.0487**	**-0.0494**	**-0.0458**	**-0.0117**
0.0023	**-0.0026**	**0.0019**	**0.0053**	**0.0056**	**0.0082**	**0.0023**
-0.0117	**-0.0146**	**-0.0131**	**-0.0107**	**-0.0124**	**-0.0158**	**-0.0197**
-0.0007	**-0.0006**	**-0.0021**	**0.0023**	**0.0026**	**0.0052**	**-0.0077**
-0.0041	**-0.0012**	**-0.0040**	**-0.0027**	**0.0004**	**0.0017**	**-0.0082**
0.0119	**-0.0002**	**-0.0070**	**-0.0197**	**-0.0076**	**0.0057**	**0.0348**
0.0089	**0.0078**	**0.0110**	**0.0093**	**0.0104**	**0.0067**	**-0.0102**
0.0059	**0.0098**	**0.0080**	**0.0033**	**0.0014**	**0.0017**	**-0.0032**
-0.0061	**0.0028**	**0.0080**	**0.0023**	**0.0064**	**0.0067**	**0.0028**
-0.0231	**-0.0202**	**-0.0140**	**0.0003**	**-0.0146**	**-0.0253**	**0.0028**
-0.0021	**-0.0032**	**-0.0090**	**-0.0027**	**-0.0036**	**0.0007**	**-0.0042**
0.0089	**0.0088**	**0.0130**	**0.0103**	**0.0094**	**0.0067**	**-0.0002**
-0.0001	**-0.0042**	**-0.0060**	**-0.0007**	**-0.0026**	**-0.0043**	**-0.0142**
-0.0400	**-0.0400**	**-0.0400**	**-0.0300**	**-0.0300**	**-0.0400**	**-0.0500**
0.0000	**-0.0100**	**0.0000**	**-0.0200**	**-0.0200**	**0.0000**	**-0.0100**
0.0000	**0.0000**	**0.0000**	**0.0000**	**0.0100**	**0.0100**	**-0.0100**
0.0000	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**

4. Linking results

4.1 Degrees of equivalence with respect to the KCRV

DOEs for each participant in the SIM.AUV.A-K1 with respect to the KCRV from the CCAUV.A-K1								
Frequency	125 Hz		250 Hz		500 Hz		1 kHz	
NMI	d_i	$U_i (k = 2)$	d_i	$U_i (k = 2)$	d_i	$U_i (k = 2)$	d_i	$U_i (k = 2)$
	/ dB		/ dB		/ dB		/ dB	
NRC	**-0.03**	0.04	**-0.01**	0.03	**-0.02**	0.04	**-0.02**	0.04
NIST	**-0.01**	0.04	**-0.01**	0.04	**-0.02**	0.04	**-0.03**	0.04
CENAM	**0.00**	0.04	**0.00**	0.04	**0.00**	0.03	**0.00**	0.03
INMETRO	**-0.06**	0.05	**-0.04**	0.05	**-0.04**	0.05	**-0.04**	0.05
INTI	**-0.03**	0.05	**-0.02**	0.05	**-0.02**	0.05	**-0.02**	0.05

DOEs for each participant in SIM.AUV.A-K1 respect to CCAUV.A-K1's KCRV						
Frequency	2 kHz		4 kHz		8 kHz	
NMI	d_i	$U_i (k = 2)$	d_i	$U_i (k = 2)$	d_i	$U_i (k = 2)$
	/ dB		/ dB		/ dB	
NRC	**-0.01**	0.04	**-0.03**	0.04	**-0.04**	0.08
NIST	**-0.03**	0.04	**-0.01**	0.04	**0.00**	0.11
CENAM	**0.01**	0.03	**-0.01**	0.05	**-0.01**	0.10
INMETRO	**-0.05**	0.05	**-0.05**	0.07	**-0.04**	0.12
INTI	**-0.02**	0.05	**-0.02**	0.09	**-0.05**	0.11

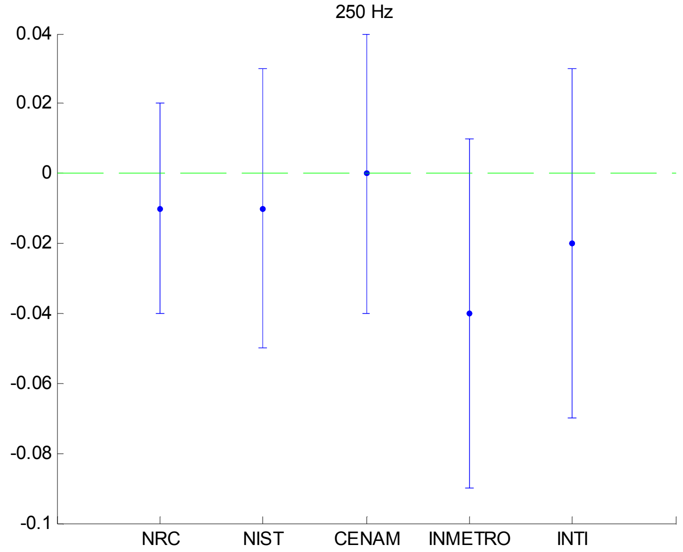

Figure 1. Degrees of equivalence at 250 Hz.

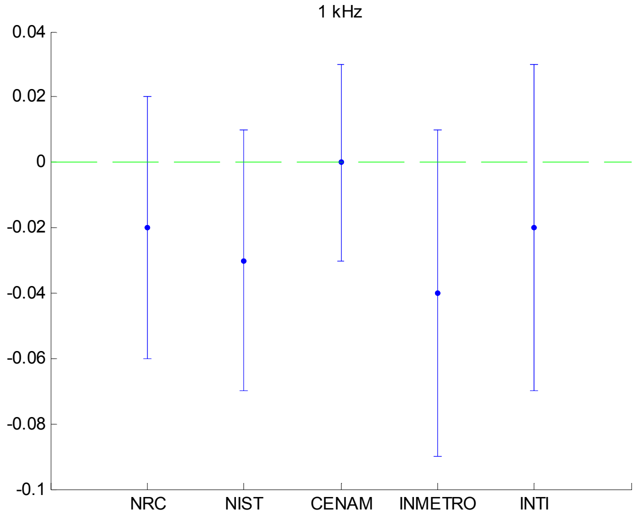

Figure 2. Degrees of equivalence at 1 kHz.

4.2 Degrees of equivalence between laboratories

DOEs between pairs of laboratories at 125 Hz										
j	NRC		NIST		CENAM		INMETRO		INTI	
i	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)
	/ dB		/ dB		/ dB		/ dB		/ dB	
NRC			-0.02	0.05	-0.03	0.05	0.03	0.06	-0.01	0.06
NIST	0.02	0.05			-0.01	0.05	0.05	0.06	0.02	0.06
CENAM	0.03	0.05	0.01	0.05			0.06	0.06	0.02	0.06
INMETRO	-0.03	0.06	-0.05	0.06	-0.06	0.06			-0.04	0.07
INTI	0.01	0.06	-0.02	0.06	-0.02	0.06	0.04	0.07		

DOEs between pairs of laboratories at 250 Hz										
j	NRC		NIST		CENAM		INMETRO		INTI	
i	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)
	/ dB		/ dB		/ dB		/ dB		/ dB	
NRC			0.00	0.04	-0.01	0.04	0.03	0.05	0.01	0.05
NIST	0.00	0.04			-0.02	0.05	0.03	0.06	0.00	0.06
CENAM	0.01	0.04	0.02	0.05			0.05	0.06	0.02	0.06
INMETRO	-0.03	0.05	-0.03	0.06	-0.05	0.06			-0.03	0.07
INTI	-0.01	0.05	0.00	0.06	-0.02	0.06	0.03	0.07		

DOEs between pairs of laboratories at 500 Hz										
j	NRC		NIST		CENAM		INMETRO		INTI	
i	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)
	/ dB		/ dB		/ dB		/ dB		/ dB	
NRC			0.00	0.05	-0.02	0.05	0.03	0.06	0.00	0.06
NIST	0.00	0.05			-0.02	0.05	0.02	0.06	0.00	0.06
CENAM	0.02	0.05	0.02	0.05			0.04	0.06	0.02	0.06
INMETRO	-0.03	0.06	-0.02	0.06	-0.04	0.06			-0.02	0.07
INTI	0.00	0.06	0.00	0.06	-0.02	0.06	0.02	0.07		

DOEs between pairs of laboratories at 1 kHz										
j	NRC		NIST		CENAM		INMETRO		INTI	
i	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)
	/ dB		/ dB		/ dB		/ dB		/ dB	
NRC			0.02	0.05	-0.02	0.05	0.03	0.06	0.00	0.06
NIST	-0.02	0.05			-0.03	0.05	0.01	0.06	-0.01	0.06
CENAM	0.02	0.05	0.03	0.05			0.04	0.06	0.02	0.06
INMETRO	-0.03	0.06	-0.01	0.06	-0.04	0.06			-0.02	0.07
INTI	0.00	0.06	0.01	0.06	-0.02	0.06	0.02	0.07		

DOEs between pairs of laboratories at 2 kHz										
j	NRC		NIST		CENAM		INMETRO		INTI	
i	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)
	/ dB		/ dB		/ dB		/ dB		/ dB	
NRC			0.01	0.05	-0.03	0.05	0.04	0.06	0.01	0.06
NIST	-0.01	0.05			-0.04	0.05	0.03	0.06	-0.01	0.06
CENAM	0.03	0.05	0.04	0.05			0.06	0.06	0.03	0.06
INMETRO	-0.04	0.06	-0.03	0.06	-0.06	0.06			-0.03	0.07
INTI	-0.01	0.06	0.01	0.06	-0.03	0.06	0.03	0.07		

DOEs between pairs of laboratories at 4 kHz										
j	NRC		NIST		CENAM		INMETRO		INTI	
i	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)
	/ dB		/ dB		/ dB		/ dB		/ dB	
NRC			-0.02	0.05	-0.02	0.06	0.02	0.08	-0.01	0.10
NIST	0.02	0.05			0.00	0.06	0.05	0.07	0.01	0.10
CENAM	0.02	0.06	0.00	0.06			0.05	0.08	0.01	0.10
INMETRO	-0.02	0.08	-0.05	0.07	-0.05	0.08			-0.03	0.11
INTI	0.01	0.10	-0.01	0.10	-0.01	0.10	0.03	0.11		

DOEs between pairs of laboratories at 8 kHz										
j	NRC		NIST		CENAM		INMETRO		INTI	
i	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)	D_{ij}	U_{ij} (k = 2)
	/ dB		/ dB		/ dB		/ dB		/ dB	
NRC			-0.04	0.12	-0.03	0.10	0.00	0.11	0.00	0.11
NIST	0.04	0.12			0.01	0.14	0.04	0.15	0.04	0.14
CENAM	0.03	0.10	-0.01	0.14			0.03	0.14	0.03	0.13
INMETRO	0.00	0.11	-0.04	0.15	-0.03	0.14			0.01	0.14
INTI	0.00	0.11	-0.04	0.14	-0.03	0.13	-0.01	0.14		

The above calculations were performed considering a correlation factor r = 0.7 between the repeated measurements of each participant in the SIM.AUV.A-K1, measurements among different participants were considered uncorrelated, it was also assumed that results of the linking labs in the CCAUV.A-K1 were uncorrelated, r = 0.

Different values for the correlation factors were tested and, after rounding to two decimal figures, in some cases there are differences of order 0.01 dB in the calculated deviations, x, with respect to the KCRV. A similar trend appears in the case of the associated measurement uncertainties in the DOEs; lower correlation factors result in higher uncertainty values.

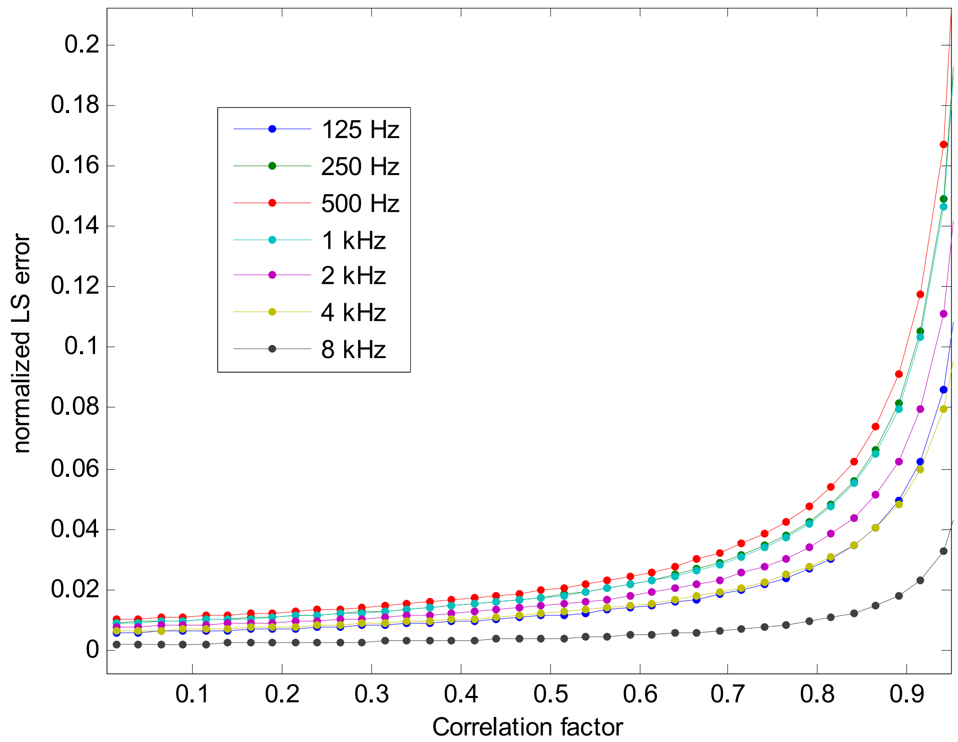

Figure 3. Normalized errors obtained in least squares approximations using different correlation factors, i.e., different covariance matrices.

5. Remarks

The linking calculations made use of the NRC, NIST and the CENAM results in the CCAUV.A-K1, except at 250 Hz and 8 kHz where the NRC results were not taken into consideration as the deviations were not constant in the two comparisons.