NPL REPORT CAIR 02

Report on key comparison CCAUV.A-K1

Richard Barham

August 2003

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Richard Barham
Centre for Acoustics and Ionising Radiation

ABSTRACT

This is the final report for key comparison CCAUV.A-K1 on the pressure calibration of laboratory standard microphones in the frequency range from 125 Hz to 8 kHz. Twelve national measurement laboratories took part in the key comparison and the National Physical Laboratory piloted the project. Two travelling standard microphones were circulated to the participants and results in the form of regular calibration certificates were collected throughout the project. The key comparison reference value (KCRV) has been calculated using the unweighted mean value of the results. Deviations from this value are below 0.05 dB at all frequencies. A frequency of 250 Hz has been chosen to illustrate the degrees of equivalence with the KCRV. In all but one case, the degree of equivalence is smaller than the associated uncertainty.

ISSN 1740-0953

National Physical Laboratory
Queens Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of the Managing Director, NPL
by Dr R C Preston, authorised by Head of Centre for Acoustics and Ionising Radiation

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2. INTRODUCTION

This is the final report for key comparison CCAUV.A-K1 on primary measurement standards for sound in air. This project was among the first group of key comparisons organized by the newly formed Consultative Committee for Acoustics, Ultrasound and Vibration, and builds upon earlier comparisons organized informally or under the auspices of the International Electrotechnical Commission (IEC). The basis of this key comparison was the calibration of laboratory standard microphones upon which primary measurement standards for sound in air are founded. Twelve national measurement institutes took part and the National Physical Laboratory in the UK, piloted the project. The participants are listed in Table 1.

Participant (in order of participation)	Acronym	Country	Country Code	Regional Metrology Organisation
National Physical Laboratory	NPL	United Kingdom	UK	EUROMET
Danish Primary Laboratory for Acoustics	DPLA	Denmark	DK	EUROMET
National Institute of Standards and Technology	NIST	United States	US	SIM
Electrotechnical Laboratory†	ETL	Japan	JP	APMP
Physikalisch-Technische Bundesanstalt	PTB	Germany	DE	EUROMET
Korea Research Institute of Science and Standards	KRISS	Korea	KR	APMP
National Metrology Laboratory of South Africa	CSIR-NML	South Africa	ZA	SADAMET
National Measurement Laboratory	CSIRO	Australia	AU	APMP
National Research Council	NRC	Canada	CA	SIM
Centro Nacional de Metrologia	CENAM	Mexico	MX	SIM
Central Office of Measures	GUM	Poland	PL	EUROMET
All Russian Scientific and Research Institute for Physical-Technical and Radiological Measurement	VNIIFTRI	Russian Federation	RU	COOMET

†Since taking part in the key comparison ETL has been re-organised and is now part of NMIJ

Table 1. List of participating institutes (in order of participation).

3. PROTOCOL

The protocol specified the determination of the pressure sensitivity of two IEC type LS1P microphones according to IEC 61094-2 (1992), at standard environmental conditions specified therein, and in the frequency range from 63 Hz to 8 kHz. The microphones were circulated as travelling standards to each participant in turn, who were asked to calibrate them by their normal method (as might be offered to a customer) and report the results in their usual calibration certificate format. In addition, information was requested on the microphone parameters used to determine the sensitivity, any variation from the requirements of IEC 61094-2 together with an estimate of its likely effect on the results, and a breakdown of the declared standard uncertainty showing the components considered.

The first participant received the microphones in April 1999 and the final participant completed their measurements in April 2001.

4. TRAVELLING STANDARDS

Two new Brüel and Kjær type 4160 microphones were purchased specifically for this project and calibrated regularly at NPL prior to circulation to establish their suitability for the key comparison. The results declared by NPL also derived from these pre-circulation measurements.

Stability of the microphones was monitored throughout the project by regular calibration at the pilot laboratory. A full calibration of each microphone was conducted, just before circulation to each participant and again on return of the microphones. The spread in these NPL results is shown in Figure 1. For each microphone, the absolute value of the difference in sensitivity level from the NPL mean value is no more than 0.02 dB at frequencies from 63 Hz to 5 kHz, and no more than 0.03 dB at 6.3 kHz and 8 kHz. The standard deviation of these NPL results is less than that allowed for in the NPL uncertainty analysis, thus confirming that both microphones had an acceptable level of stability during these measurements.

Figure 1 also shows the trend with time in these results at 250 Hz. For reference, the corresponding results declared by the participants are also included. From this data there appears to be a small number of instances of possible correlation between the stability of the microphone and the results from participants. However a degree of apparent correlation is to be expected even if the results from each participant varied randomly relative to the stability monitoring measurements. The variability in the microphone sensitivity measured by NPL and by participants is well within the declared expanded uncertainties of measurement, and of the order of typical repeatability, so the data is not conclusive. Consequently in this report, data from each participant are compared directly and no attempt was made to correct for variations in the travelling standards.

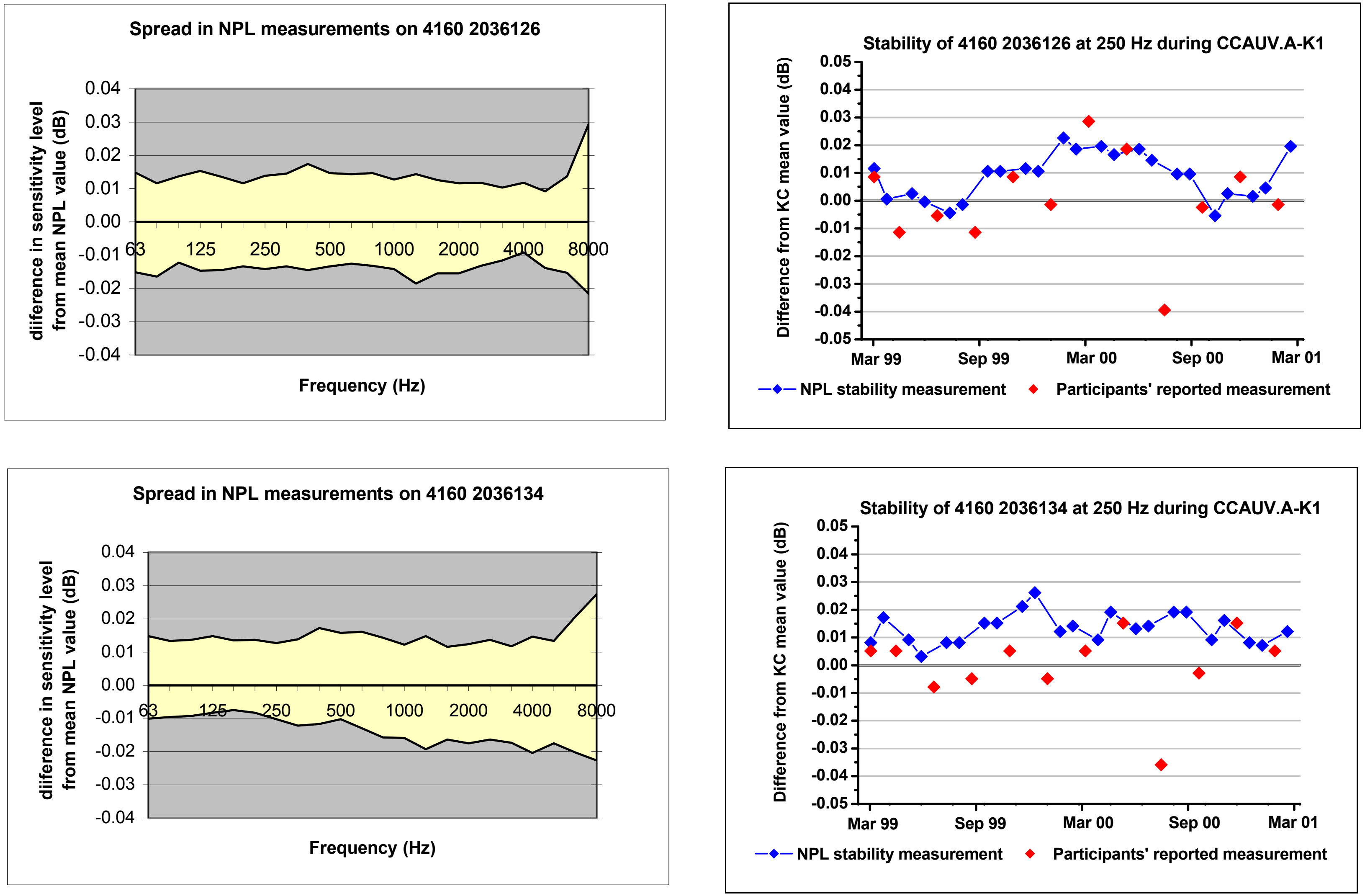

Figure 1. Stability of the travelling standard microphones in terms of the maximum positive and negative differences from the mean value of NPL measurements throughout the key comparison and the typical variation with time at a frequency of 250 Hz

5. METHODOLOGIES

The protocol required that the calibration method used be based on IEC 61094-2 (1992), but this Standard does not require any particular experimental implementation to be used. Great variation is methodology is therefore possible and a number of distinctively different facilities have been developed to implement the requirements of the Standard. The following short descriptions of each facility have been supplied by the participants and serve as a record of the configurations used at the time of the key comparison. Each participant is required to keep more detailed technical records as part of the quality requirements of the Mutual Recognition Agreement.

The protocol also required that any variation from the requirements of IEC 61094-2 (1992) be declared together with an estimate of the effect this variation would have on the determination of the microphone sensitivity. Where such declarations were made, they are summarised in the descriptions below.

NPL, UK – The NPL facility implements a three-microphone procedure where each is assumed to be reciprocal and is used as both transmitter and receiver at appropriate points in the procedure. The microphones are coupled in pairs using a plane-wave coupler of nominal length 7.5 mm, filled with air at all frequencies. The acoustical transfer impedance is calculated by software written by NPL to implement the transmission line analysis and associated models given in IEC 61094-2. The electrical transfer impedance of the coupled microphone pair is determined by comparison with a calibrated resistance (with appropriate allowance for an inevitable stray capacitance) placed in series with the transmitting microphone.

The equipment for this measurement has been developed by NPL, the main components being a combined resistance box and switching unit, a pair of lock-in amplifiers (EG&G model 5209) and purpose designed microphone power supplies. The receiver microphone is connected to a preamplifier B&K type 2645, and the transmitter microphone to a unit supplying the correct terminal and ground shield arrangements. Measurements are made at discrete frequencies by an automated procedure. Data for the effective volume of the microphone and cavity depth are measured separately. The volume is determined using an acoustical method where the microphone is compared with a set of known volumes of similar geometry. The cavity depth is measured with a depth-focusing microscope. Nominal values are assumed for the acoustical impedance of the microphone, in terms of lumped parameters for acoustical mass, compliance and resistance. These nominal values derive from historical data collected at NPL. All of the measurements are conducted in a temperature controlled room at 23.0ºC ± 1.5ºC. Atmospheric pressure and humidity are not controlled but measurements are only conducted when they are in the range 99.0 kPa to 103.5 kPa and 30% to 60% respectively.

The calibration method used for the measurements reported followed the requirements of IEC 61094-2 (1992), except in the determination of the physical properties of air (density, speed of sound, ratio of specific heats etc.), where the methodology agreed within Euromet[1] (and proposed for a future revision of IEC 61094-2) was used. It was estimated that the systematic differences resulting from this approach amounted to less than 0.003 dB.

The measurement facility is accredited by the United Kingdom Accreditation Service (UKAS) and detailed records are maintained on the precise configuration of the hardware and software at any particular time.

DPLA, Denmark - The microphone calibration facilities at DPLA consist of two separate measurement facilities. One is located at Brüel & Kjær, Nærum and performs routine calibrations, accredited by DANAK. A second is located at DTU, Kgs. Lyngby and is used for research and development. Regular internal comparisons between the two facilities are performed to ensure mutual agreement on calibration results. For the present CCAUV-A.K1 key comparison the facilities at DTU were used.

The calibration is performed as a full reciprocity calibration according to IEC 61094-2, using three microphones pairwise coupled through four air-filled plane wave couplers of different length (nominal lengths 4 – 6 – 7.5 – 9 mm). The resulting sensitivity is calculated using software (MP.EXE) developed at DTU. The calculations are performed according to IEC 61094-2 extended with a correction for radial wave-motion effects using a Bessel function distribution of the diaphragm displacement.

The main component of the equipment is a two-channel controller system with switching facilities and a relay operated resistance chain (50 Ω - 700 kΩ). This equipment is developed and built at DTU. The receiver microphone is connected to a preamplifier B&K type 2673 with insert voltage facilities (driven ground shield) and the transmitter microphone is connected to a similar housing but with grounded shield. Polarising voltages are supplied by a Fluke DC Voltage Calibrator type 343A.

During the calibrations the coupler and microphones are located under a cylindrical bulb of volume of about 20 litre, which can be hermetically closed and wherein the static pressure can be changed by ±20%. The static pressure is measured by a Druck DPI 140 barometer and the temperature by a calibrated Pt 100 resistance located close to the coupler. All measurements are conducted in a temperature controlled room at 23.0°C ± 1.5°C. Humidity is kept within the range 40% - 60% RH.

Two different techniques are used to determine the complex electrical transfer impedance:

1. The electrical current through the transmitter is measured as the voltage across the above-mentioned resistance chain connected in series with the transmitter. The measuring instruments are: Function generator HP 3325A, Digital voltmeter HP 3458A, Phase meter Wavetek 740 and periodically a 1/3-octave filter, B&K 1617. The driving voltage and the resistance value are varied such that all voltage measurements are made within the upper 4 dB of a fixed range of the voltmeter. The measurements are made at discrete frequencies controlled via computer.

2. The electrical current through the transmitter is measured as the voltage across a 10 nF calibrated capacitor in parallel with the above-mentioned resistance chain set at its maximum value 700 kΩ. An Audio analyser B&K 2012 performs the measurements in 1/12-octave steps using a constant driving voltage of 5 V.

Deviations between results obtained using both measuring techniques are within 0.01 dB. Both methods have been used for the CCAUV-A.K1 key comparison. The actual results reported refer to the first method because an uncertainty budget has been established for this method only.

The front cavity depths of the microphones are measured by an optical distance sensor, ODS 30. The sum of front cavity volume and microphone equivalent volume is determined by fitting the final results for the four couplers in the frequency range up to about 2 kHz. The resonance frequency is determined by the 90 degree phase response of the microphones. Finally the ratio of equivalent volume to front cavity volume and the loss factor are determined by data fitting of the final results obtained above 2 kHz – 4 kHz for the four couplers used during the calibration.

NIST, USA - The calibration method used for the reported measurements (values of microphone pressure sensitivity level) is consistent with the requirements of both IEC 61094-2 (1992) and ANSI S1.10-1966 (R1997). Although the certificate provided by NIST states that measurements are in accordance with ANSI S1.10-1966 (R1997), this is considered not to cause any systematic difference in results. This specific reference to ANSI S1.10-1966 (R1997) is performed in order more completely to describe the large-volume coupler that was used for the measurements. The dimensions of this coupler (often called the "20-cm^3 coupler") including capillary tubes are shown in Figure 6 in this ANSI standard, but the capillary tube dimensions are not given in the figures for either large-volume or plane-wave couplers in the IEC standard. The same large-volume coupler was used for these measurements at NIST and for the NIST (then named NBS) measurements in the IEC comparison described by Torr and Jarvis [Metrologia 26, 253-256 (1989)].

Recognized (by NIST and the national laboratories of other countries active in IEC) errors in certain equations printed in Annexes A and B of IEC 61094-2 (1992) (as it was originally published as IEC 1094-2 in 1992) were corrected in order to determine the heat conduction effects (departure from adiabatic conditions in the coupler) and capillary tube effects for the gases filling this coupler. Based on these corrected Annexes, NIST wrote its own software for determining the influences of these and other effects, and for including these influences with the data from the various procedural steps of reciprocity calibration to obtain the reported measurements. Corrections for the effects of wave motion for the gases filling this coupler were determined by NIST.

Three microphones are used in the reciprocity procedure. Two of these microphones are used as both transmitters (sound sources) and receivers (microphones), and the third (called an "auxiliary sound source" in IEC 61094-2) is used as a transmitter only, in sequentially performed measurements with each of the other two microphones as receiver to determine the ratio of their sensitivities. At each frequency of calibration, the pressure sensitivity levels of the two reciprocal microphones are obtained as the desired results. Each reported sensitivity level is the average of two independent reciprocity calibrations. An NIST-owned laboratory standard microphone, of the same type as the microphones circulated in this key comparison, is the third microphone. It is used only as a sound source in each calibration. Each microphone under test is calibrated twice: when used only as a receiver in one calibration, and when used sequentially as a receiver and as a sound source in another calibration. For all calibrations, protection grids are removed from the microphones. The coupler is filled with air at frequencies from 63 Hz to 500 Hz. At 1000 Hz and at higher frequencies, the coupler is filled with hydrogen gas.

The measurement system was designed at NIST. Most of its critical components including the transmitter microphone fixture, coupler, apparatus for filling the coupler with hydrogen at the higher frequencies, receiving microphone insert voltage preamplifier, precision resistive attenuator used for the measurement of ac voltage ratios, insert-voltage-matching readout device (an expanded-scale meter), microphone power supplies, switching apparatus, and measuring amplifier, were either designed and purpose-built at NIST, built by contractor to NIST specifications, or modified by NIST from commercially available devices. A critical step in determining the electrical transfer impedance of a coupled microphone pair involves the use of frequency-dependent reference values of resistance placed in series with the transmitting microphone. These values have been chosen to provide suitable signal-to-noise ratios and appropriately small influences of stray capacitance.

Regarding the microphone acoustical impedance and volume, the measurements of modulus of pressure sensitivity in the large-volume coupler require calculations that use values of the frequency-dependent real part of the sum of the front-cavity geometric volumes of the two microphones in the coupler and their complex equivalent volumes at their diaphragms. Nominal values of this real part are added to the previously measured geometric volume of the coupler alone (without microphones) in determining the reported values of microphone sensitivity level.

The reported values of microphone sensitivity level are corrected to reference static pressure, 101.325 kPa, and reference temperature, 23ºC, by interpolating nominal corrections in Table 2 (using 8.1 kHz as the value of the nominal typical resonance frequency, and using the relation between microphone sensitivity and static pressure coefficients at low frequencies given in Section 6) of K. Rasmussen, "The static pressure and temperature coefficients of laboratory standard microphones," Metrologia, **36** No. 4, 1999, 265-273. No correction of sensitivity levels to reference humidity (50 percent relative humidity) is applied. Actual relative humidity (43 percent) during measurements was close to the reference value, the "correction" is considered small, and a reliable "correction" was not available. However, the measured relative humidity is used in the determination of the relevant gas properties (for example, ratio of specific heats for air at this humidity) necessary in obtaining the reported measurements.

<u>ETL, Japan</u> – At ETL absolute pressure calibrations is implemented using a 20 cm^3 large-volume coupler filled with hydrogen at frequencies above 1.6 kHz. In the key comparison, calibrations were done as follows.

First, absolute calibration of a microphone owned by ETL was done according to the description in IEC61094-2, except a slightly different wave-motion correction[2] was used. Secondly, the key comparison microphone was calibrated by the comparative method using a 3 cm^3 plain-wave coupler filled with air, correcting for the difference in effective volume between the key comparison microphone and the ETL microphone as follows. The relative pressure sensitivity level between the two microphones was determined at low frequencies in a 20 cm^3 coupler, where any difference in effective volume has negligible effect. The results from the comparative method in the 3 cm^3 coupler, which *are* influenced by differences in effective volume, were then corrected to have the same relative pressure sensitivity level at low frequency as those observed in the 20 cm^3 coupler. This correction was then applied to all frequencies and these corrected results have been reported. This procedure was used to eliminate the rare possibility of damage to the key comparison microphones by the hydrogen.

In the coupler calibration system used by ETL in the key comparison, the voltage transfer function between the input terminal of the transmitter and the output terminal of the receiver was measured by the substitution method using a precision attenuator. Simultaneously, the electrical impedance of the transmitter was determined by comparison with the standard capacitance. The signal-to-noise ratio was significantly improved by using a synchronous averaging technique in a FFT analyzer and the cross-talk was reduced by careful design of the electrical circuit. In this coupler calibration system, measurement uncertainty related to the electrical circuit was less than 0.003 dB for the frequency range between 50 Hz and 20 kHz.

In the calibration room, temperature was controlled (23.0°C ± 0.5°C), but static pressure and humidity were not.

The measurement facility will be reviewed for accreditation by the National Institute of Technology and Evaluation (NITE) in Japan in autumn 2002.

PTB, Germany - The PTB facility implements a full reciprocity calibration of three microphones according to IEC 61094-2 where each microphone is assumed to be reciprocal and is used both as transmitter and as receiver. The microphones are coupled pair-wise by means of three air-filled plane wave couplers of different lengths (in the range 6 mm to 9 mm) at all frequencies and one air-filled large-volume coupler as recommended in IEC 61094-2 in the frequency range from 63 Hz to 1 kHz.

The sensitivity levels are calculated using software (Calcmp.exe) developed at PTB, following the standard IEC 61094-2 and extended by a correction for radial wave-motion in the plane wave couplers using a Bessel function distribution of the diaphragm displacement.

The electrical transfer impedance of the microphone-coupler-microphone arrangement is determined by comparison with a calibrated relay-operated resistor chain (GDS BSW 100) placed in series with the transmitting microphone. Inevitable stray capacitance is corrected for in the calculation program. The receiver microphone is connected to a preamplifier B&K type 2645, and the transmitter microphone to a unit made at PTB, supplying the correct terminal and ground shield arrangement. The polarising voltages for both microphones are supplied by two modified (equipped with a control for fine-tuning the output voltage) power supplies B&K type 2807. The polarising voltages are adjusted by means of a differential DC voltmeter Fluke type 893A.

Measurements are made with sinusoidal signals by an automated procedure controlled by software developed at PTB. The resistor chain is adjusted to have approximately the resistance value of the electrical transfer impedance. The remaining voltage ratio is measured by means of a measurement chain mainly consisting of a measuring amplifier B&K type 2636, a third-octave band filter Wandel & Goltermann type UN1 and a true RMS digital voltmeter Hewlett Packard type 3458A.

The cavity depth of the microphone is measured with a depth focusing microscope extended by a digimatic indicator. The total effective volume is derived by fitting the sensitivity results in the four couplers in the lower frequency range. The acoustic impedance of the microphones is determined by data fitting of the final results in all couplers, taking into account the wave motion correction for the plane wave couplers.

The environmental conditions during the measurements are not controlled, but the results are corrected to represent the sensitivity levels at standard conditions.

KRISS, Korea - The microphone pressure sensitivities are calibrated by the reciprocity calibration technique using three reciprocal microphones. The microphones are coupled in pairs using two plane-wave couplers with nominal length of 7.5 mm and 15 mm, filled with air at all frequencies. The acoustical transfer impedance is calculated to implement the transmission line analysis and associated models given in IEC 61094-2. The electrical transfer impedance of the coupled microphone pair is determined by measuring the voltage ratio between the receiver and the transmitter. The transmitter current is determined by measuring the voltage across a calibrated capacitor which is connected in series with the transmitter microphone.

The main components are reciprocity calibration apparatus (B&K 5998), sine generator (B&K 1051), band pass filter (B&K 1617) and digital voltmeter (Wavetek 1281). The receiver microphone is connected to a preamplifier (B&K 2673) and the transmitter microphone to a transmitter unit (B&K ZE 0796). The system components are all controlled via their IEEE-488 interface. Measurements are made at discrete frequencies by an automated procedure.

The cavity depth is measured with a depth-focusing microscope. The volume is determined using two couplers with different lengths by changing the volume until convergent results are obtained in both couplers at frequencies in the range 200 Hz to 2 kHz. The microphone pressure sensitivities are calculated according to the equations in manual for B&K 9699.

All of the measurements are done in a temperature and humidity controlled room at $23.0^{o}C \pm 2.0^{o}C$ and $50\% \pm 20\%$, respectively. Atmospheric pressure are not controlled but measurements are conducted when they are in the range 101.325 kPa ± 5 kPa.

The quality system is accredited by the Korea Foundation for Quality (KFQ).

CSIR-NML, South Africa - The NML implements a three-microphone procedure where each is assumed to be reciprocal and is used as both transmitter and receiver at appropriate points in the procedure. The microphones are coupled in pairs using a Brüel & Kjær IEC 3.4 cm^3 plane-wave coupler, filled with air at all frequencies.

The acoustical transfer impedance is calculated by software written by the NML to implement the transmission line analysis and associated models given in IEC 61094-2.

The electrical transfer impedance of the coupled microphone pair is determined using a Brüel & Kjær 4143 reciprocity calibration system. The system determines the electrical transfer impedance by comparison with a calibrated capacitor placed in series with the transmitting microphone. The complete semi-automated system for this measurement has been developed by the NML. The main components being a Brüel & Kjær 4143 reciprocity calibration system, Brüel & Kjær 1617 filter set, Brüel & Kjær 2636 measuring amplifier, Brüel & Kjær 1049 sine generator and an HP 34401 digital multimeter. The receiver microphone is connected to a pre-amplifier Brüel & Kjær type 2673, and the transmitter microphone to the Brüel & Kjær 4143, supplying the correct terminal and ground shield arrangement. Measurements are made manually at discrete frequencies and entered into the control software.

Data for the effective volume of the microphone and cavity depth are measured separately. The volume is determined using an acoustical method where the microphone is compared with a set of known volumes of similar geometry. The cavity depth is measured with a depth-focusing microscope.

Using the following formula for the acoustic impedance of the microphone:

$$Z(\omega) = R_a + j\omega M_a + \frac{1}{j\omega C_a}$$

where: R_a is the lumped acoustic resistance
M_a is the lumped acoustic mass
C_a is the acoustic compliance of the diaphragm

C_a is estimated from a measurement of the low frequency acoustic volume of the front cavity of the microphone. M_a is then derived from C_a and the resonance frequency. R_a is calculated from the C_a value and an approximate measurement of the ratio of the microphone sensitivity at low frequency to that at resonance.

All of the measurements are conducted in a temperature and humidity controlled room at 23.0 ºC ± 1.0 ºC and 50%RH ± 10 %RH respectively. Atmospheric pressure is not controlled. Measurements are corrected for atmospheric pressure using pressure coefficients that were determined by performing measurement at three laboratories located at different heights above sea level.

The measurement facility is accredited by SANAS (South African National Accreditation Service).

CSIRO-NML, Australia - The CSIRO NML results were obtained using the NML designed 3-port coupler. This method is described in some detail in Chapter 5 of the AIP Handbook of Condenser Microphones[2], and will be only summarised here. The system involves a trade-off of wideband results for rapid, automated function.

The 3-port coupler is a 10 cm^3 volume cavity of fairly complex shape arranged so that all three microphones are fitted at once. They are symmetrically oriented at 120° to each other so that each sees a completely equivalent acoustical field. The microphones are driven in a round robin, as is customary, where the drive and receive functions are switched under computer control. The output in each case is measured as a fraction of the drive voltage using in phase and quadrature bridge balance techniques incorporating inductive ratio dividers.

The geometric volume of the coupler was determined from the design drawings and measurements after manufacture. The change in effective volume arising from the replacement of one of the standard set with the test microphone is determined from the apparent changes in the sensitivity of the two standard microphones remaining in the coupler. Thus the equivalent and frontal volumes of the test microphone are not determined as a prerequisite to the measurement. However, the total volume of the test microphone is determined from the measurement.

The complex shape of the coupler means that the wave motion and heat conduction corrections cannot be calculated analytically. In conjunction with the relatively large volume of the coupler this means that measurements are restricted to frequencies less than or equal to 1 kHz. The corrections applied over the system operating frequency range were determined empirically by comparing microphone sensitivities obtained using conventional IEC couplers with those obtained using the 3-port coupler.

As a consequence of these unusual features the uncertainty budget has a number of components not seen in conventional systems. Examples are, the bridge impedances used to find the in phase and quadrature components, the empirically determined wave motion and heat conduction corrections and the inductive dividers' ratios used to balance the bridge. Similarly uncertainties associated with determining the equivalent volume do not appear.

The Acoustics and Vibration standards group holds IEC 17025 accreditation. The test laboratory temperature is maintained at 23°C to within 0.1°C.

NRC, Canada - Procedures for reciprocity pressure calibration of laboratory standard microphones for this key comparison are governed by IEC Standard 1094-2 Ed. 1. The reciprocity method measures the product of sensitivities of each pair of a set of three microphones in terms of related electrical and mechanical quantities, from which the absolute sensitivity of each microphone can be deduced. A Brüel and Kjær 4143EH 4004 reciprocity microphone calibration apparatus was used. The microphones were arranged in pairs with a 3 cm^3 IEC coupler. Three voltage ratios were measured, for each pair of microphones in turn, from the voltage across the reference impedance of the driving microphone (transmitter) and the voltage output of the receiving microphone. The voltages were measured sequentially by a digital voltmeter (Model 1271, Datron Instruments). The calibration apparatus together with the microphone pair were enclosed in an environmental control chamber. After the microphones were coupled together with the coupler in a transmitter-receiver arrangement, the environmental chamber door was closed, and a combined mixture of dry and humid air streams proceeded to purge the chamber. The out-flowing air was monitored with a chill-mirror dew-point hygrometer to achieve the reference condition of 50±5 % RH. Simultaneously, with the help of a constant temperature bath, the temperature was maintained at 23±0.05 ºC. A digital pressure controller was set to control mode to provide the reference pressure of 101.325±0.02 kPa. Acoustical measuring instruments involved with the above measurements were a Brüel & Kjær 1049 signal generator, a Brüel and Kjær 2636 measuring amplifier and a Brüel & Kjær 1617 one-third-octave bandpass filter.

CENAM, Mexico - The absolute pressure calibration of condenser microphones is performed at CENAM by reciprocity, using the Brüel & Kjær reciprocity calibration apparatus type 5998. Three microphones are coupled acoustically in pairs through four air-filled plane wave couplers of four different lengths, namely 4.3 mm, 5.7 mm, 7.5 mm 10 mm. Before the whole calibration procedure, two measurements are performed:

- The polarization voltage supplied by the reciprocity apparatus is verified using a B&K 5981 polarization voltage meter. This is done right before the procedure.

- The front cavity depths of the microphones under calibration are measured using a depth microscope. This is done by a specialized dimensional metrology laboratory.

The calculation of the microphone sensitivity is achieved, according to the reciprocity method, by determining, for every microphone pair, the electrical transfer impedance and the acoustical transfer impedance. To do this, the following measurement procedure is performed at every frequency within the frequency range of interest:

- The receiver microphone is mounted on a Brüel & Kjær 2673 preamplifier.
- The transmitter microphone is mounted on a Brüel & Kjær transmitter unit ZE 0796.
- Transmitter and receiver thus assembled are connected to the reciprocity apparatus.
- The microphone pair under test, properly fitted in a plane wave coupler, is placed inside a chamber that is adjusted to the reference static pressure. The chamber also minimizes the influence of ambient noise.
- A General Eastern Hygro-M3 and a MKS Baratron are used to record respectively temperature and static pressure. The temperature is measured on a spot close and outside the chamber, while the static pressure is measured inside the chamber.
- The test signal, generated by a Fluke 5700A, is fed to the transmitting unit through the reciprocity apparatus.
- The input and output voltages of transmitting and receiving microphones are measured by means of a voltmeter HP 3458A.

The measurement data is recorded and arranged by an acquisition program developed at CENAM, and supplied to the software MP.EXE developed at DTU in accordance with IEC 61094-2. The MP.EXE software gives the resulting pressure sensitivity for every microphone and coupler.

The sensitivities thus obtained for each microphone with all couplers are combined to reach a single resulting pressure sensitivity. To do this, they are averaged over the frequency. According to the IEC 61094-2, the resulting microphone sensitivity is obtained by adjusting the acoustical parameters of the microphone.

The measurements are performed in a temperature controlled room at 23.0 °C ± 1.0 °C, and humidity is monitored but not controlled during the measurements. This control is not necessary considering the usual humidity conditions (35% to 60%) in the laboratory.

GUM, Poland - In the GUM facility the three-microphone method of measurement is applied. Each microphone is assumed to be reciprocal and can be used as both transmitting and receiving microphone. The actually measured pair of microphones is coupled with 3 cm^3 plane wave coupler B&K type DB 1392 filled with air at all frequencies. Software written by NPL is used for calculation of acoustical transfer impedance according to models presented in IEC 61094-2. The electrical transfer impedance of actually measured microphone pair is determined by comparison with properly chosen calibrated resistor connected in series with the transmitting microphone, using the "approximate balance" method developed in NPL. The calibration method complies with the requirements of IEC 61094-2:1992 with an exception concerning the method for determination of the physical properties of air (speed of sound, its temperature dependence, specific heat ratio), where the methodology agreed recently within EUROMET is used.

All measurements are performed in air-conditioned room with temperature maintained at 23.0°C ± 1°C and relative humidity maintained at 50% ± 15%. Measurements are conducted only if the static pressure is between 99 kPa and 103.5 kPa. The environmental parameters are measured continuously during the experiment and the results of measurements are automatically taken into account in calculations. The measuring signal source is the function generator Philips PM5136. For all AC voltage measurements two lock-in amplifiers EG&G 5209 are used. The microphone power supplies are special units designed and constructed according to NPL requirements. Special unit containing set of calibrated resistors with associated selector and two-way switch has been developed by NPL. The transmitting microphone is connected to the purpose-designed unit providing proper terminal and ground shield arrangements, developed by NPL. The receiving microphone is connected to the preamplifier G.R.A.S. 26AG. All measurements necessary for electrical transfer impedance determination are made automatically at specified frequencies. Polarization voltages are verified to be 200 V ± 0,01 V just before the start of experiments by measurement made directly at transmitting unit and preamplifier terminals with Keithley 6517A electrometer. The total volume of the microphone (front cavity volume plus diaphragm equivalent volume) is determined acoustically with computer-aided procedure by comparison with a set of known volumes. The depth-focusing microscope is used for the measurement of the depth of microphone front cavity. For necessary calculations the nominal values of microphone acoustical parameters (mass, compliance and resistance) supplied by NPL are used.

<u>VNIIFTRI, Russian Federation</u> - In VNIIFTRI, pressure calibration of type LS1P microphones is performed according to the reciprocity procedure using three microphones, where each is assumed to be reciprocal and is used as both transmitter and receiver. The microphones are acoustically coupled to each other using a plane-wave couple of normal length 7.5 mm and filled with air.

The current through the transmitter microphone is found by measuring the voltage across a reference capacitor in series with the transmitter microphone. The open-circuit voltage of the receiver microphone is defined at the output of preamplifier type 2645. The sum of the front volumes and equivalent volumes of the microphones are calculated using measurements of the sensitivity product made in plane-wave couplers with 7.5 mm and 5.5 mm length. The microphone front cavity depth is measured with a depth-focusing microscope.

The acoustical transfer impedance is calculated according to IEC 61094-2.

Measurements are made in the common premises with control of temperature, atmosphere pressure and relative humidity range and their rate of change.

The main equipment components are Brüel & Kjær type 4143 reciprocity calibration apparatus, type 1617 filter, type 2636 measuring amplifier, type 5889 switching unit, Datron 1081 multimeter and Philips PM5190 oscillator. The facilities are managed by the computer. The measurements are made automatically at discrete frequencies at interval of one-third octave.

The measurement facility is accredited by Gosstandard (State Standard) and calibrated in corresponding Gosstandard departments.

6. RESULTS AND UNCERTAINTIES

Results for the individual microphones were reported in calibration certificates prepared by each participant. The protocol also asked for data on the values of the various microphone parameters used in the calculation of the pressure sensitivity level. The submitted results for the pressure sensitivity level of each microphone and the data for the microphone parameters are reproduced in Appendix B for reference.

However the absolute values for the sensitivity levels of the microphones are rather superficial as they relate only to the two specific transducers. It is more important to reduce this data to a form that gives a generalised indication of the performance of a participant. So for each of the travelling standards and at each of the specified frequencies, the mean value of the sensitivity level has been determined from all of the submitted data. The result for a given microphone from an individual laboratory can then be expressed as the difference from this mean value. Figure 2 shows this derived data for each of the microphones.

With the results plotted in this form, it becomes apparent that the trend displayed by a particular laboratory is, in general, common to both microphones. This is a good indication of consistent performance by all participants. Therefore, to arrive at a single figure (as a function of frequency) specifying the performance of each laboratory, it is feasible to take the mean of the results for the two microphones. Such data is presented in Figure 3.

In taking this approach, it is important to consider carefully the uncertainty associated with this mean result.

Measurement uncertainties do not vary greatly between calibrations on different microphones of the same type, or indeed between repeated calibrations of the same microphone. In many cases laboratories have chosen to fix their uncertainty, rather than calculate values for every calibration, and to specify limits on the repeatability to be achieved in order to comply with the given uncertainty. All but one participant have declared the same uncertainty for the measurements on each of the microphones. Even where different uncertainties are calculated for individual calibrations, differences amounted to less than 0.01 dB after rounding. Intuitively then, the uncertainty in the mean of the results for a number of calibrations would not be expected to vary much from the uncertainty of an individual calibration. However, this assumption should not be used as a substitute for the additional statistical analysis required to quantify the uncertainty of the mean of the results of a number of calibrations.

For any given participant let the declared results for the sensitivities of the microphones at a particular frequency be M_A and M_B and the associated uncertainty be $u(M_A)$ and $u(M_B)$. The result representing the laboratory is thus

$$M = \tfrac{1}{2}M_A + \tfrac{1}{2}M_B$$

and the associated uncertainty $u(M)$ is given by

$$u^2(M) = \tfrac{1}{4}u^2(M_A) + \tfrac{1}{4}u^2(M_B) + 2\rho \tfrac{1}{2}u(M_A)\tfrac{1}{2}u(M_B)$$

where the last term is the covariance between M_A and M_B.

Frequency (Hz)	NPL UK	DPLA DK	NIST US	ETL JP	PTB DE	KRISS KR	CSIR ZA	CSIRO AU	NRC CA	CENAM MX	GUM PL	VNIIFTRI RU
63	0.02	-0.01	-0.01	0.00	0.01	0.00	0.02		-0.03	-0.01	0.01	-0.01
125	0.01	-0.01	0.00	0.00	0.01	0.00	0.02		-0.04	0.00	0.01	0.00
250	0.01	-0.01	-0.01	-0.01	0.01	0.00	0.03	0.02	-0.04	0.00	0.01	0.00
500	0.01	-0.01	0.00	-0.01	0.01	0.00	0.03	0.01	-0.04	0.00	0.00	0.00
1000	0.01	0.00	-0.02	-0.01	0.02	0.01	0.03	0.02	-0.03	0.00	0.00	0.00
1250	0.01	0.00	-0.02	-0.02	0.01	0.01	0.03		-0.03	0.00	0.00	-0.01
1600	0.02	0.00	-0.02	-0.01	0.02	0.01	0.03		-0.03	0.01	0.01	-0.01
2000	0.01	0.00	-0.02	-0.02	0.02	0.01	0.03		-0.04	0.01	0.01	-0.01
2500	0.01	0.00	-0.01	-0.03	0.02	0.02	0.03		-0.03	0.01	0.00	-0.02
3150	0.01	0.00	0.00	-0.04	0.01	0.01	0.02		-0.03	0.01	0.00	-0.02
4000	0.02	0.01	0.00	-0.04	0.02	0.02	0.03		-0.04	0.01	0.02	-0.02
5000	0.01	0.02	-0.01	-0.05	0.03	0.02	0.03		-0.04	0.02	0.01	-0.02
6300	0.01	0.02	-0.01	-0.07	0.02	0.00	0.03		-0.04	0.01	0.01	-0.01
8000	0.02	0.01	0.00	-0.05	-0.01	0.00	0.01		-0.05	-0.01	0.03	0.01

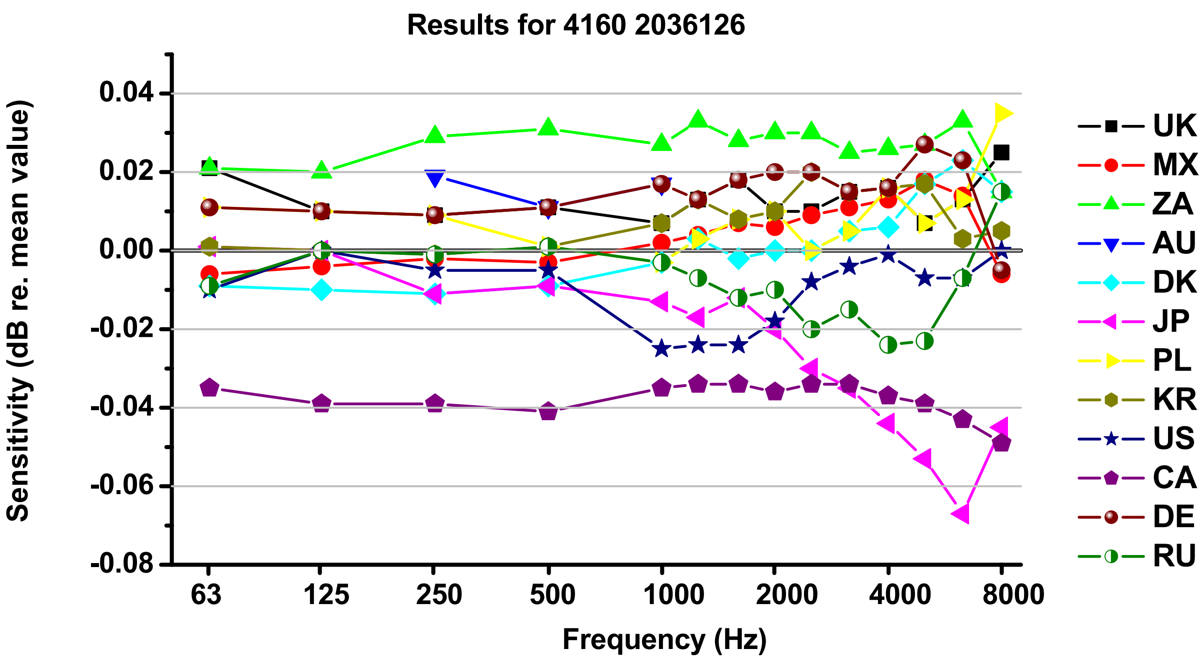

Figure 2(a). Table and graph giving results for travelling standard microphone 4160 2036126.

A table of the absolute sensitivity level values can be found in Appendix B

Frequency (Hz)	NPL UK	DPLA DK	NIST US	ETL JP	PTB DE	KRISS KR	CSIR ZA	CSIRO AU	NRC CA	CENAM MX	GUM PL	VNIIFTRI RU
63	0.02	0.01	-0.01	0.01	0.00	0.00	0.01		-0.04	0.00	0.02	0.00
125	0.01	0.01	0.00	0.01	0.01	0.00	0.01		-0.04	0.00	0.02	0.01
250	0.01	0.01	-0.01	0.00	0.01	0.00	0.01	0.02	-0.04	0.00	0.02	0.01
500	0.00	0.00	0.00	-0.01	0.00	0.00	0.01	0.01	-0.04	0.00	0.01	0.00
1000	0.01	0.01	-0.02	-0.01	0.01	0.00	0.01	0.01	-0.04	0.00	0.01	0.00
1250	0.02	0.02	-0.01	-0.01	0.02	0.01	0.01		-0.03	0.01	0.01	0.00
1600	0.01	0.01	-0.02	-0.02	0.01	0.00	0.00		-0.03	0.01	0.01	-0.01
2000	0.02	0.01	-0.01	-0.01	0.01	0.01	0.00		-0.03	0.01	0.02	-0.01
2500	0.02	0.01	0.00	-0.03	0.01	0.01	0.00		-0.03	0.01	0.01	-0.02
3150	0.02	0.02	0.00	-0.02	0.01	0.02	0.00		-0.03	0.01	0.02	-0.02
4000	0.02	0.01	0.01	-0.04	0.00	0.02	-0.01		-0.03	0.01	0.02	-0.04
5000	0.02	0.02	0.01	-0.04	0.01	0.03	0.00		-0.03	0.01	0.02	-0.04
6300	0.02	0.03	0.00	-0.06	0.01	0.02	0.02		-0.04	0.01	0.03	-0.03
8000	0.04	0.00	-0.03	-0.05	-0.01	0.03	0.02		-0.05	-0.01	0.04	0.03

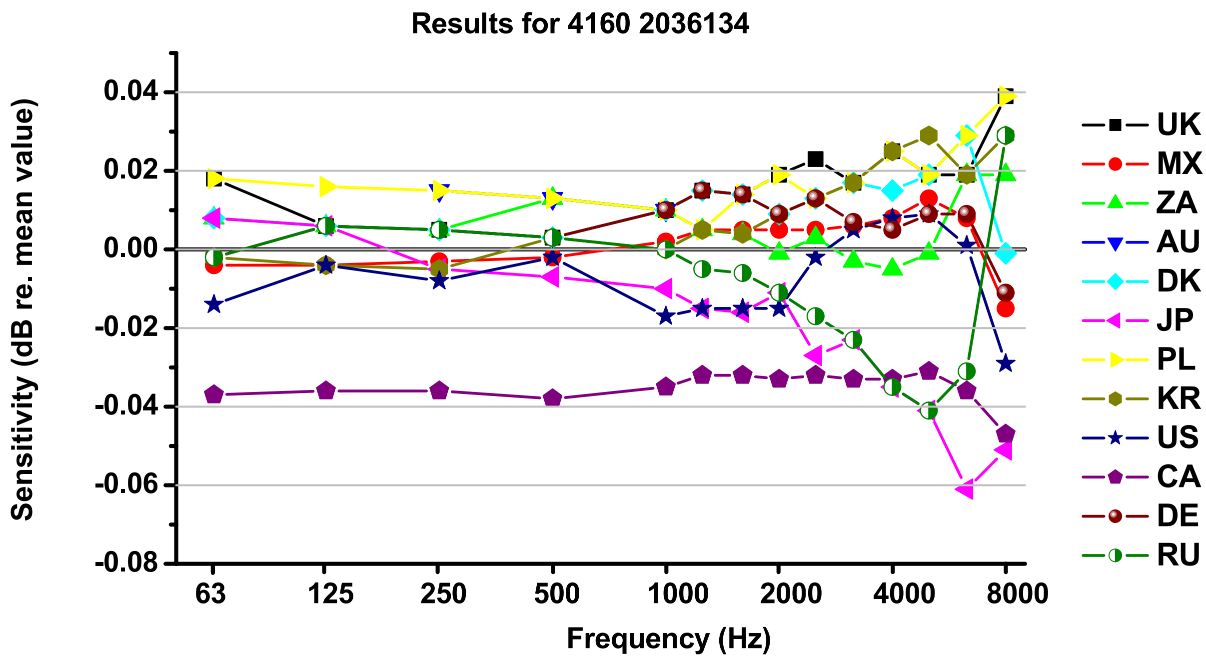

Figure 2(b). Table and graph giving results for travelling standard microphone 4160 2036134.

A table of the absolute sensitivity level values can be found in Appendix B

Frequency (Hz)	NPL UK	DPLA DK	NIST US	ETL JP	PTB DE	KRISS KR	CSIR ZA	CSIRO AU	NRC CA	CENAM MX	GUM PL	VNIIFTRI RU
63	0.02	0.00	-0.01	0.00	0.00	0.00	0.01		-0.04	0.00	0.01	-0.01
125	0.01	0.00	0.00	0.00	0.01	0.00	0.01		-0.04	0.00	0.01	0.00
250	0.01	0.00	-0.01	-0.01	0.01	0.00	0.02	0.02	-0.04	0.00	0.01	0.00
500	0.01	0.00	0.00	-0.01	0.01	0.00	0.02	0.01	-0.04	0.00	0.01	0.00
1000	0.01	0.00	-0.02	-0.01	0.01	0.00	0.02	0.01	-0.03	0.00	0.00	0.00
1250	0.01	0.01	-0.02	-0.02	0.01	0.01	0.02		-0.03	0.00	0.00	-0.01
1600	0.02	0.01	-0.02	-0.01	0.02	0.01	0.02		-0.03	0.01	0.01	-0.01
2000	0.01	0.00	-0.02	-0.02	0.01	0.01	0.01		-0.03	0.01	0.01	-0.01
2500	0.02	0.01	-0.01	-0.03	0.02	0.02	0.02		-0.03	0.01	0.01	-0.02
3150	0.02	0.01	0.00	-0.03	0.01	0.02	0.01		-0.03	0.01	0.01	-0.02
4000	0.02	0.01	0.00	-0.04	0.01	0.02	0.01		-0.04	0.01	0.02	-0.03
5000	0.01	0.02	0.00	-0.05	0.02	0.02	0.01		-0.04	0.02	0.01	-0.03
6300	0.02	0.03	0.00	-0.06	0.02	0.01	0.03		-0.04	0.01	0.02	-0.02
8000	0.03	0.01	-0.01	-0.05	-0.01	0.02	0.02		-0.05	-0.01	0.04	0.02

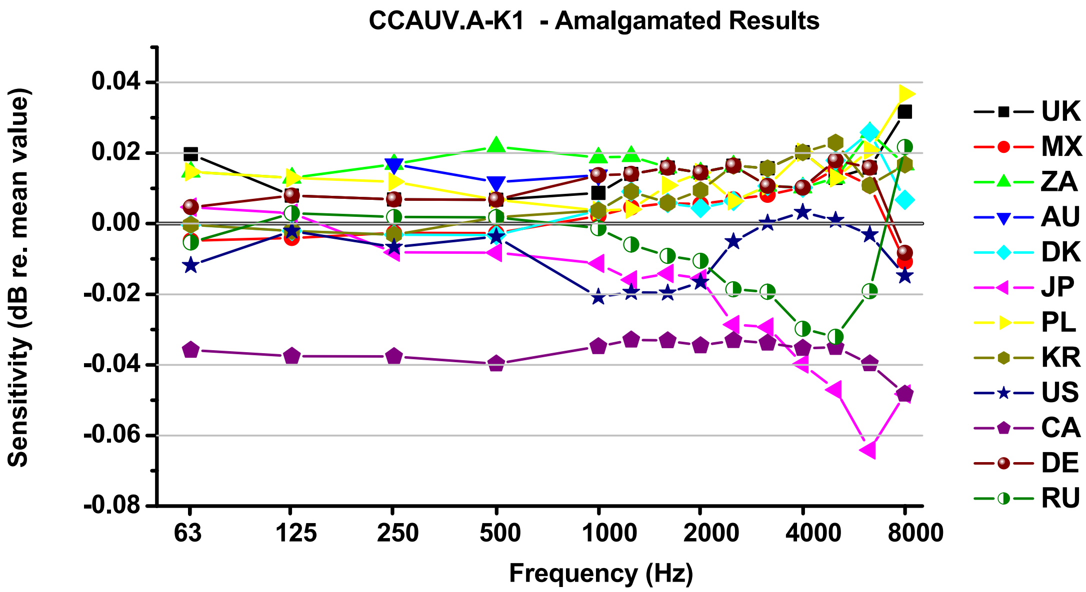

Figure 3. Amalgamated results - deviation of each participant from the arithmetic mean normalised to zero at each frequency.

The factor ρ depends on the degree of correlation between M_A and M_B and has a value between –1 and 1. If the results are completely uncorrelated then ρ=0, and for full correlation ρ=1 (ρ=-1 corresponds to an anti-correlation condition).

Inspection of the data shown in Figures 2(a) and 2(b) show that for many of the laboratories, the trend in the result of one microphone is repeated in the other. This indicates a high degree of correlation between the data for the individual microphones, therefore $\rho \approx 1$. Precise values of ρ have not been calculated. However, given that $u(M_A)$ is typically 0.04 dB over much of the frequency range and $u(M_A) \approx u(M_B)$, it can be shown that values of ρ>0.6 result in less than 0.005 dB difference in the derived uncertainty. So assuming a value of ρ=1 is likely to have an insignificant effect overall, and is therefore a reasonable approximation. In this case it follows that

$$u(M) = \tfrac{1}{2}u(M_A) + \tfrac{1}{2}u(M_B)$$

So the uncertainty in the mean value of the sensitivity of each microphone is simply the mean of the corresponding uncertainties, confirming the intuitive hypothesis made at the outset.

It is therefore not necessary to perform any manipulation on the uncertainty data, since in all but the one case, the relevant uncertainty for the mean sensitivity result is simply that declared for each of the microphones, and is shown in Table 2. This data derives from the uncertainty specified in the certificates used to report the results. Without exception this is given as an expanded uncertainty, and in most cases, represents a value that is rounded to match the measurement precision. Normal practice is to round the result of the calculation upwards (if necessary). However this approach has not been adopted consistently by all participants. In the worst case, rounding effects could produce errors approaching ±0.01 dB in the differences between uncertainties declared by two laboratories. Therefore, comparisons involving differences around this level may not be meaningful.

The components of uncertainty leading to these values can be found in the uncertainty budgets for each participant. These are reproduced in Appendix D.

Frequency (Hz)	NPL UK	DPLA DK	NIST US	ETL JP	PTB DE	KRISS KR	CSIR ZA	CSIRO AU	NRC CA	CENAM MX	GUM PL	VNIIFTRI RU
63	0.03	0.04	0.04	0.05	0.03	0.03	0.05		0.04	0.04	0.03	0.08
125	0.03	0.03	0.04	0.04	0.03	0.03	0.05		0.04	0.04	0.03	0.05
250	0.03	0.03	0.04	0.04	0.03	0.03	0.05	0.04	0.03	0.04	0.03	0.05
500	0.03	0.03	0.04	0.04	0.03	0.03	0.05	0.04	0.04	0.03	0.03	0.05
1000	0.03	0.03	0.04	0.04	0.03	0.03	0.05	0.04	0.04	0.03	0.03	0.05
1250	0.03	0.03	0.04	0.04	0.03	0.03	0.05		0.04	0.03	0.03	0.05
1600	0.03	0.03	0.04	0.04	0.03	0.03	0.05		0.04	0.03	0.03	0.05
2000	0.03	0.03	0.04	0.04	0.03	0.03	0.05		0.04	0.03	0.03	0.05
2500	0.03	0.03	0.04	0.04	0.03	0.03	0.05		0.04	0.03	0.03	0.05
3150	0.04	0.03	0.04	0.04	0.03	0.03	0.05		0.04	0.03	0.03	0.05
4000	0.04	0.03	0.04	0.04	0.03	0.03	0.06		0.04	0.05	0.04	0.06
5000	0.05	0.04	0.04	0.05	0.05	0.03	0.07		0.04	0.05	0.05	0.09
6300	0.05	0.05	0.04	0.06	0.05	0.04	0.06		0.04	0.06	0.05	0.14
8000	0.05	0.06	0.12	0.06	0.05	0.04	0.07		0.04	0.10	0.05	0.23

Table 2. Declared measurement uncertainties at k=2 (dB).

Note: CSIR declared different uncertainties for each microphone. Only the greater value for a given frequency is shown.

7. KEY COMPARISON REFERENCE VALUE

The results and uncertainties presented in this report have been reviewed and discussed by all of the participants involved in the key comparison. Each participant has accepted that their results are an appropriate representation of their performance. The key comparison process allows for additional bilateral comparisons to be made following the main round of measurements however no such additional comparisons were entered in to.

The post-measurement discussions also came to the conclusion that a high degree of confidence could be place in the uncertainties declarations made by all participants. Part of the reasoning for this is that no laboratory declared distinctly high or low values, which could have led to contention. Instead, the declared uncertainties fell within a narrow range of values.

Given the confidence that was placed in the uncertainty claims, it could be argued that key comparison reference values (KCRVs) based on the mean of the measured values, weighted by the associated uncertainty, are most appropriate. However, with the small variation in declared uncertainties, differences between results based on weighted and unweighted means were expected to be insignificant. So merely for simplicity the unweighted mean was proposed as the means of determining the key comparison reference values. This has since been ratified and adopted for this key comparison.

To illustrate that the effect of different calculation approaches is indeed small, the KCRV at each frequency has also been calculated based on both the weighted mean and median. Figure 4 illustrates the dependence (or rather independence) of the KCRVs on the choice of calculation method. In each graph, the heavy black line indicates the re-calculated KCRVs relative to the original. This line would become the ordinate (0 dB axis) if the given analysis method were adopted. Clearly any differences are insignificant, confirming the assertions made during discussions.

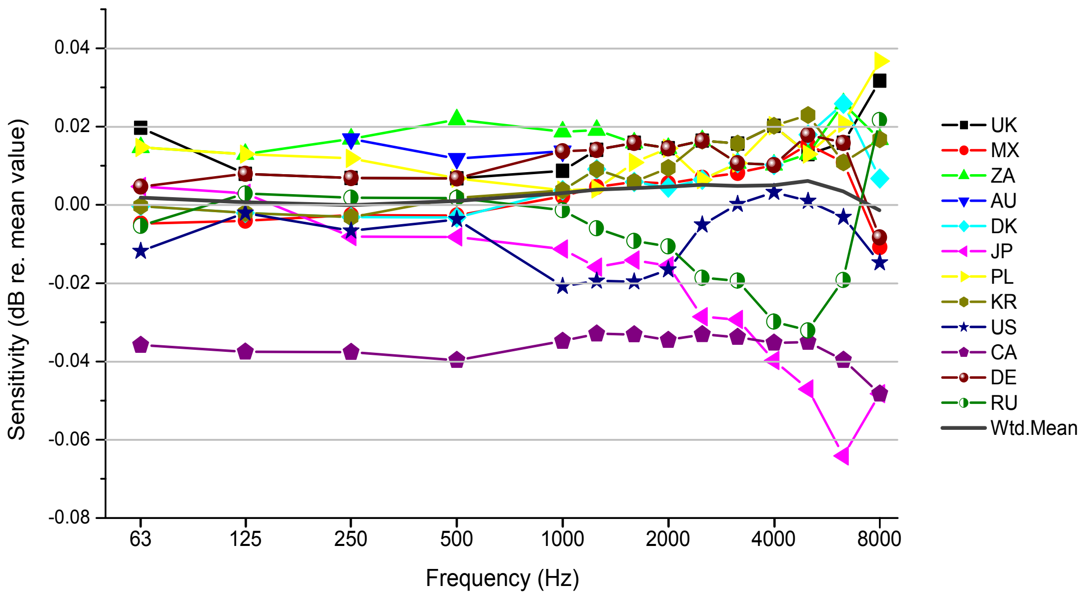

Figure 4(a) The KCRVs based on the weighted mean

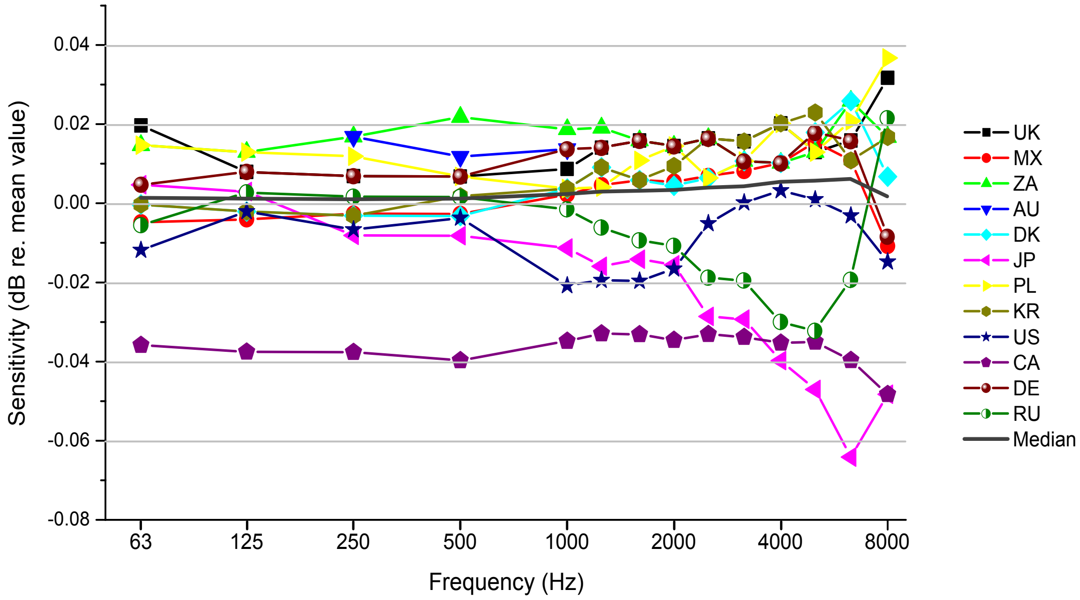

Figure 4(b) The KCRVs based on the median

The KCRV for key comparison CCAUV.A-K1 is thus determined at each of the specified frequencies, from the arithmetic mean of all results, normalized to zero decibels. This normalisation yields key comparison reference values that are independent of the travelling standard devices. Figure 3 therefore represents the results of each participant relative to the KCRV at each frequency, but a more comprehensive account of these results, including the *uncertainty*, the *degrees of equivalence* with the KCRV and the *mutual equivalences* between participants, is given in Appendix A.

Of the 157 values of M_i in Table A1 of Appendix A, 94 do not exceed 0.01 dB in absolute value, and 131 do not exceed 0.02 dB in absolute value. Of the 132 values of D_{ij} in Table A3, 74 do not exceed 0.01 dB in absolute value, and 106 do not exceed 0.02 dB in absolute value.

The uncertainty in the KCRV is calculated by propagating the measurement uncertainties of the data used in its calculation, according to Section 5.1 of the ISO *Guide to the Expression of Uncertainty in Measurement*†. To do this, the results of the uncertainty calculations shown in the **uncertainty budgets** supplied by each participant, have been used. In principle this eliminates the error associated with the inconsistent approaches to rounding the final result that have been adopted by different participants, and bases the KCRV uncertainty on systematically determined data. In practice however, using the uncertainty from the budget calculation or the declared (rounded) value, results in differences in the KCRV uncertainty of approximately 0.005 dB (the rounding uncertainty), which does not change the declared value.

† Specifically, the components have been summed according to Eq. [10] of this section (known as the *law of propagation of uncertainty*), using $^1/_{12}$ as the sensitivity coefficient (12 being the number of participants).

For all other statements of uncertainty, that is for the laboratory results, the degree of equivalence and the degree of mutual equivalence, the uncertainty stated in the **calibration certificate** of each laboratory has been used. It is recognised that there may be some correlation between individual uncertainty estimates, however this has not been accounted for in the uncertainty in the degrees of mutual equivalence, resulting in a potential, but small over-estimate.

8. CONCLUSIONS

The agreement in measured results between laboratories was typically very good, and the uncertainty estimates of the different laboratories are relatively close in value. Consequently, degrees of equivalence of laboratories with respect to the KCRV, as well as the degrees of equivalence between laboratories (mutual equivalence), are characterized by small values that are often very similar, representing close equivalence.

These degrees of equivalence are influenced by cumulative effects from several factors. These include slight instabilities in the travelling standard microphones, minor inconsistencies in numerical rounding practices among individual laboratories that were not specifically addressed during development of the key comparison protocol, slight effects due to the influences of final rounding of very precise calculations of the results presented in this report, and effects of correlations between laboratories.

The state of development of the degrees of equivalence in this report is such that many, if not most, of the inter-laboratory differences in degrees of equivalence with respect to the KCRV, as well as in mutual degrees of equivalence, may not be significant. Further analysis would be required in order to demonstrate conclusively either significance or insignificance.

At the outset, this project was described as a key comparison on microphone calibration, the implication being that this leads to a realisation of the acoustic pascal. However it can be argued that a restrictive protocol, where a specific methodology is prescribed, results in KCRVs that are influenced by systematic assumptions inherent in the procedure. Only when other methods of realising the acoustic pascal can be introduced, will it be fair to make the assumption that the KCRVs relate directly to the acoustic pascal. In reality, no viable alternatives to reciprocity calibration have yet been established by any nation over the specified frequency range. So a key comparison in determining the acoustic pascal will automatically reduce to the format of this key comparison. This is simply the best we can do at present.

9. ACKNOWLEDGMENT

The input from Dr Duncan Jarvis, particularly in developing the protocol for this project, and the efforts of various NPL staff, past and present, in undertaking the extensive set of measurements, is gratefully acknowledged, together with the co-operation received from all those involved in making measurements in the participating institutes. The financial support of the National Measurement System Policy Unit of the UK Department of Trade and Industry has made it possible for NPL to pilot this project.

10. REFERENCES

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2. George S. K. Wong, Tony F. W. Embleton, "AIP Handbook of Condenser Microphones: Theory, Calibration and Measurements", New York, AIP press (1995).

APPENDIX A. RESULTS, KCRV AND DEGREES OF EQUIVALENCE

Key Comparison: CCAUV.A-K1

Measurand: Pressure sensitivity level of laboratory standard microphone type LS1P

Nominal value: 0 dB (see note below)

M_i : Result of measurements carried out by laboratory i †

u_i : Standard uncertainty of M_i ††

Lab i ⇨ / Frequency (Hz) ⇩	NPL		CENAM		CSIR		CSIRO		DPLA		ETL		GUM		KRISS		NIST		NRC		PTB		VNIIFTRI			
	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_i	$2u_i$	M_{ref}	u_{ref}
	dB		dB		dB		dB		dB		dB		dB		dB		dB		dB		dB		dB		dB	
63	**0.02**	0.03	**0.00**	0.04	**0.01**	0.05	-	-	**0.00**	0.04	**0.00**	0.05	**0.01**	0.03	**0.00**	0.03	**-0.01**	0.04	**-0.04**	0.04	**0.00**	0.03	**-0.01**	0.08	**0.00**	0.006
125	**0.01**	0.03	**0.00**	0.04	**0.01**	0.05	-	-	**0.00**	0.03	**0.00**	0.04	**0.01**	0.03	**0.00**	0.03	**0.00**	0.04	**-0.04**	0.04	**0.01**	0.03	**0.00**	0.05	**0.00**	0.006
250	**0.01**	0.03	**0.00**	0.04	**0.02**	0.05	**0.02**	0.04	**0.00**	0.03	**-0.01**	0.04	**0.01**	0.03	**0.00**	0.03	**-0.01**	0.04	**-0.04**	0.03	**0.01**	0.03	**0.00**	0.05	**0.00**	0.005
500	**0.01**	0.03	**0.00**	0.03	**0.02**	0.05	**0.01**	0.04	**0.00**	0.03	**-0.01**	0.04	**0.01**	0.03	**0.00**	0.03	**0.00**	0.04	**-0.04**	0.04	**0.01**	0.03	**0.00**	0.05	**0.00**	0.005
1000	**0.01**	0.03	**0.00**	0.03	**0.02**	0.05	**0.01**	0.04	**0.00**	0.03	**-0.01**	0.04	**0.00**	0.03	**0.00**	0.03	**-0.02**	0.04	**-0.03**	0.04	**0.01**	0.03	**0.00**	0.05	**0.00**	0.005
1250	**0.01**	0.03	**0.00**	0.03	**0.02**	0.05	-	-	**0.01**	0.03	**-0.02**	0.04	**0.00**	0.03	**0.01**	0.03	**-0.02**	0.04	**-0.03**	0.04	**0.01**	0.03	**-0.01**	0.05	**0.00**	0.006
1600	**0.02**	0.03	**0.01**	0.03	**0.02**	0.05	-	-	**0.01**	0.03	**-0.01**	0.04	**0.01**	0.03	**0.01**	0.03	**-0.02**	0.04	**-0.03**	0.04	**0.02**	0.03	**-0.01**	0.05	**0.00**	0.006
2000	**0.01**	0.03	**0.01**	0.03	**0.01**	0.05	-	-	**0.00**	0.03	**-0.02**	0.04	**0.01**	0.03	**0.01**	0.03	**-0.02**	0.04	**-0.03**	0.04	**0.01**	0.03	**-0.01**	0.05	**0.00**	0.006
2500	**0.02**	0.03	**0.01**	0.03	**0.02**	0.05	-	-	**0.01**	0.03	**-0.03**	0.04	**0.01**	0.03	**0.02**	0.03	**-0.01**	0.04	**-0.03**	0.04	**0.02**	0.03	**-0.02**	0.05	**0.00**	0.006
3150	**0.02**	0.04	**0.01**	0.03	**0.01**	0.05	-	-	**0.01**	0.03	**-0.03**	0.04	**0.01**	0.03	**0.02**	0.03	**0.00**	0.04	**-0.03**	0.04	**0.01**	0.03	**-0.02**	0.05	**0.00**	0.006
4000	**0.02**	0.04	**0.01**	0.05	**0.01**	0.06	-	-	**0.01**	0.03	**-0.04**	0.04	**0.02**	0.04	**0.02**	0.03	**0.00**	0.04	**-0.04**	0.04	**0.01**	0.03	**-0.03**	0.06	**0.00**	0.006
5000	**0.01**	0.05	**0.02**	0.05	**0.01**	0.07	-	-	**0.02**	0.04	**-0.05**	0.05	**0.01**	0.05	**0.02**	0.03	**0.00**	0.04	**-0.04**	0.04	**0.02**	0.05	**-0.03**	0.09	**0.00**	0.007
6300	**0.02**	0.05	**0.01**	0.06	**0.03**	0.06	-	-	**0.03**	0.05	**-0.06**	0.06	**0.02**	0.05	**0.01**	0.04	**0.00**	0.04	**-0.04**	0.04	**0.02**	0.05	**-0.02**	0.14	**0.00**	0.008
8000	**0.03**	0.05	**-0.01**	0.10	**0.02**	0.07	-	-	**0.01**	0.06	**-0.05**	0.06	**0.04**	0.05	**0.02**	0.04	**-0.01**	0.12	**-0.05**	0.04	**-0.01**	0.05	**0.02**	0.23	**0.00**	0.011

† Note 1: The quoted pressure sensitivity levels are the mean of measurements on two microphones, relative to the arithmetic mean value of all such measurement made in this key comparison. The nominal value is therefore 0 dB, the KCRV.

†† Note 2: The uncertainty quoted in the table is $2u_i$ so that it can be given at a resolution consistent with the measured data

Table A1. Reported results for the normalised mean pressure sensitivity level of the traveling standard microphones

The key comparison reference value M_{ref} for this comparison is obtained as the arithmetic mean of all measurements, normalized to zero decibels at each frequency. The standard uncertainty u_{ref} in the KCRV was determined by propagating the individual measurement uncertainties.

Degrees of equivalence with the KCRV are given in the table below.

lab *i* ⇨	NPL		CENAM		CSIR		CSIRO		DPLA		ETL		GUM		KRISS		NIST		NRC		PTB		VNIIFTRI	
Frequency (Hz) ⇩	D_i dB	U_i	D_i dB	U_i	D_i dB	U_i	D_i dB	U_i	D_i dB	U_i	D_i dB	U_i	D_i dB	U_i	D_i dB	U_i	D_i dB	U_i	D_i dB	U_i	D_i dB	U_i	D_i dB	U_i
63	**0.02**	0.03	**0.00**	0.04	**0.01**	0.05	-	-	**0.00**	0.04	**0.00**	0.05	**0.01**	0.03	**0.00**	0.03	**-0.01**	0.04	**-0.04**	0.04	**0.00**	0.03	**-0.01**	0.07
125	**0.01**	0.03	**0.00**	0.04	**0.01**	0.05	-	-	**0.00**	0.03	**0.00**	0.04	**0.01**	0.03	**0.00**	0.03	**0.00**	0.04	**-0.04**	0.04	**0.01**	0.03	**0.00**	0.05
250	**0.01**	0.03	**0.00**	0.04	**0.02**	0.05	**0.02**	0.04	**0.00**	0.03	**-0.01**	0.04	**0.01**	0.03	**0.00**	0.03	**-0.01**	0.04	**-0.04**	0.03	**0.01**	0.03	**0.00**	0.05
500	**0.01**	0.03	**0.00**	0.03	**0.02**	0.05	**0.01**	0.04	**0.00**	0.03	**-0.01**	0.04	**0.01**	0.03	**0.00**	0.03	**0.00**	0.04	**-0.04**	0.04	**0.01**	0.03	**0.00**	0.05
1000	**0.01**	0.03	**0.00**	0.03	**0.02**	0.05	**0.01**	0.04	**0.00**	0.03	**-0.01**	0.04	**0.00**	0.03	**0.00**	0.03	**-0.02**	0.04	**-0.03**	0.04	**0.01**	0.03	**0.00**	0.05
1250	**0.01**	0.03	**0.00**	0.03	**0.02**	0.05	-	-	**0.01**	0.03	**-0.02**	0.04	**0.00**	0.03	**0.01**	0.03	**-0.02**	0.04	**-0.03**	0.04	**0.01**	0.03	**-0.01**	0.05
1600	**0.02**	0.03	**0.01**	0.03	**0.02**	0.05	-	-	**0.01**	0.03	**-0.01**	0.04	**0.01**	0.03	**0.01**	0.03	**-0.02**	0.04	**-0.03**	0.04	**0.02**	0.03	**-0.01**	0.05
2000	**0.01**	0.03	**0.01**	0.03	**0.01**	0.05	-	-	**0.00**	0.03	**-0.02**	0.04	**0.01**	0.03	**0.01**	0.03	**-0.02**	0.04	**-0.03**	0.04	**0.01**	0.03	**-0.01**	0.05
2500	**0.02**	0.03	**0.01**	0.03	**0.02**	0.05	-	-	**0.01**	0.03	**-0.03**	0.04	**0.01**	0.03	**0.02**	0.03	**-0.01**	0.04	**-0.03**	0.04	**0.02**	0.03	**-0.02**	0.05
3150	**0.02**	0.04	**0.01**	0.03	**0.01**	0.05	-	-	**0.01**	0.03	**-0.03**	0.04	**0.01**	0.03	**0.02**	0.03	**0.00**	0.04	**-0.03**	0.04	**0.01**	0.03	**-0.02**	0.05
4000	**0.02**	0.04	**0.01**	0.05	**0.01**	0.06	-	-	**0.01**	0.03	**-0.04**	0.04	**0.02**	0.04	**0.02**	0.03	**0.00**	0.04	**-0.04**	0.04	**0.01**	0.03	**-0.03**	0.06
5000	**0.01**	0.05	**0.02**	0.05	**0.01**	0.07	-	-	**0.02**	0.04	**-0.05**	0.05	**0.01**	0.05	**0.02**	0.03	**0.00**	0.04	**-0.04**	0.04	**0.02**	0.05	**-0.03**	0.08
6300	**0.02**	0.05	**0.01**	0.06	**0.03**	0.06	-	-	**0.03**	0.05	**-0.06**	0.06	**0.02**	0.05	**0.01**	0.04	**0.00**	0.04	**-0.04**	0.04	**0.02**	0.05	**-0.02**	0.13
8000	**0.03**	0.05	**-0.01**	0.09	**0.02**	0.07	-	-	**0.01**	0.06	**-0.05**	0.06	**0.04**	0.05	**0.02**	0.04	**-0.01**	0.11	**-0.05**	0.04	**-0.01**	0.05	**0.02**	0.21

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of numbers:
$D_i = (M_i - M_{ref})$ and U_i, its expanded uncertainty (k = 2), $U_i^2 = 2^2((1-2/n)^2 u_i^2 + u_{ref}^2)$, where n is the number of participants, both expressed in dB

Note. Many of the values for U_i in the table appear to be the same as the corresponding value for u_i in Table A1. This is due to the variation in uncertainty u_i being small between participants, the relatively low value of u_{ref} compared to u_i, and the rounding of the data to two decimal places that has been adopted in the tables. If the data were expressed with greater precision it would be apparent that they have different numerical values.

Table A2. Degrees of equivalence with the KCRV.

Degrees of equivalence at 250 Hz are given in the table below.

Lab *j* ⇒

Lab *i* ⇓	D_i	U_i	**NPL** D_{ij}	U_{ij}	**CENAM** D_{ij}	U_{ij}	**CSIR** D_{ij}	U_{ij}	**CSIRO** D_{ij}	U_{ij}	**DPLA** D_{ij}	U_{ij}	**ETL** D_{ij}	U_{ij}	**GUM** D_{ij}	U_{ij}	**KRISS** D_{ij}	U_{ij}	**NIST** D_{ij}	U_{ij}	**NRC** D_{ij}	U_{ij}	**PTB** D_{ij}	U_{ij}	**VNIIFTRI** D_{ij}	U_{ij}
	dB		dB		dB		dB		dB		dB		dB		dB		dB		dB		dB		dB		dB	
NPL	**0.01**	0.03			**0.01**	0.05	**-0.01**	0.06	**-0.01**	0.05	**0.01**	0.04	**0.02**	0.05	**-0.01**	0.04	**0.01**	0.04	**0.01**	0.05	**0.04**	0.04	**0.00**	0.04	**0.01**	0.06
CENAM	**0.00**	0.04	**-0.01**	0.05			**-0.02**	0.06	**-0.02**	0.06	**0.00**	0.05	**0.01**	0.06	**-0.01**	0.05	**0.00**	0.05	**0.00**	0.06	**0.04**	0.05	**-0.01**	0.05	**0.00**	0.06
CSIR	**0.02**	0.05	**0.01**	0.06	**0.02**	0.06			**0.00**	0.06	**0.02**	0.06	**0.03**	0.06	**0.00**	0.06	**0.02**	0.06	**0.02**	0.07	**0.05**	0.06	**0.01**	0.06	**0.02**	0.07
CSIRO	**0.02**	0.04	**0.01**	0.05	**0.02**	0.06	**0.00**	0.06			**0.02**	0.05	**0.03**	0.06	**0.00**	0.05	**0.02**	0.05	**0.02**	0.06	**0.05**	0.05	**0.01**	0.05	**0.02**	0.06
DPLA	**0.00**	0.03	**-0.01**	0.04	**0.00**	0.05	**-0.02**	0.06	**-0.02**	0.05			**0.00**	0.05	**-0.02**	0.04	**0.00**	0.04	**0.00**	0.05	**0.03**	0.04	**-0.01**	0.04	**-0.01**	0.06
ETL	**-0.01**	0.04	**-0.02**	0.05	**-0.01**	0.06	**-0.03**	0.06	**-0.03**	0.06	**0.00**	0.05			**-0.02**	0.05	**-0.01**	0.05	**0.00**	0.06	**0.03**	0.05	**-0.02**	0.05	**-0.01**	0.06
GUM	**0.01**	0.03	**0.01**	0.04	**0.01**	0.05	**0.00**	0.06	**0.00**	0.05	**0.02**	0.04	**0.02**	0.05			**0.02**	0.04	**0.02**	0.05	**0.05**	0.04	**0.01**	0.04	**0.01**	0.06
KRISS	**0.00**	0.03	**-0.01**	0.04	**0.00**	0.05	**-0.02**	0.06	**-0.02**	0.05	**0.00**	0.04	**0.01**	0.05	**-0.02**	0.04			**0.00**	0.05	**0.03**	0.04	**-0.01**	0.04	**0.00**	0.06
NIST	**-0.01**	0.04	**-0.01**	0.05	**0.00**	0.06	**-0.02**	0.07	**-0.02**	0.06	**0.00**	0.05	**0.00**	0.06	**-0.02**	0.05	**0.00**	0.05			**0.03**	0.05	**-0.01**	0.05	**-0.01**	0.07
NRC	**-0.04**	0.03	**-0.04**	0.04	**-0.04**	0.05	**-0.05**	0.06	**-0.05**	0.05	**-0.03**	0.04	**-0.03**	0.05	**-0.05**	0.04	**-0.03**	0.04	**-0.03**	0.05			**-0.04**	0.04	**-0.04**	0.06
PTB	**0.01**	0.03	**0.00**	0.04	**0.01**	0.05	**-0.01**	0.06	**-0.01**	0.05	**0.01**	0.04	**0.02**	0.05	**-0.01**	0.04	**0.01**	0.04	**0.01**	0.05	**0.04**	0.04			**0.01**	0.06
VINIFTRI	**0.00**	0.05	**-0.01**	0.06	**0.00**	0.06	**-0.02**	0.07	**-0.02**	0.06	**0.01**	0.06	**0.01**	0.06	**-0.01**	0.06	**0.00**	0.06	**0.01**	0.07	**0.04**	0.06	**-0.01**	0.06		

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of numbers:
$D_i = (M_i - M_{ref})$ and U_i, its expanded uncertainty (k = 2), $U_i^2 = 2^2((1-2/n)^2 u_i^2 + u_{ref}^2)$, where n is the number of participants, both expressed in dB

The degree of equivalence between two laboratories is given by a pair of numbers:
$D_{ij} = M_i - M_j$ and U_{ij}, its expanded uncertainty (k = 2), $U_{ij}^2 = 2^2(u_i^2 + u_j^2)$, both expressed in dB

Note. Data for mutual equivalence at other frequencies can be derived from Table A1. However the data at 250 Hz is characteristic of frequencies up to 2 kHz.

Table A3. Degrees of mutual equivalence at 250 Hz.

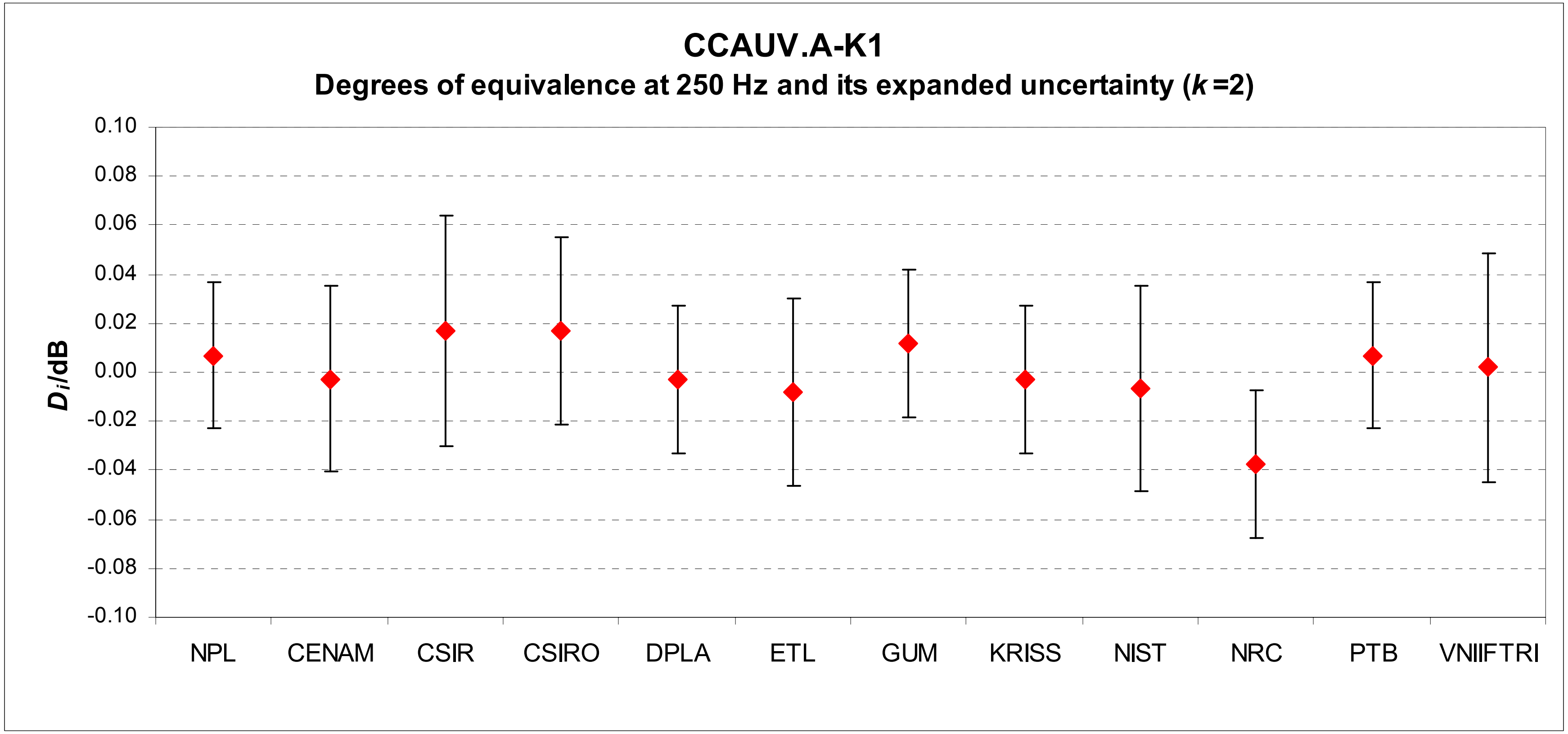

Figure A1 Illustration of the degrees of equivalence with the KCRV at 250 Hz and the associated expanded uncertainty (k=2)

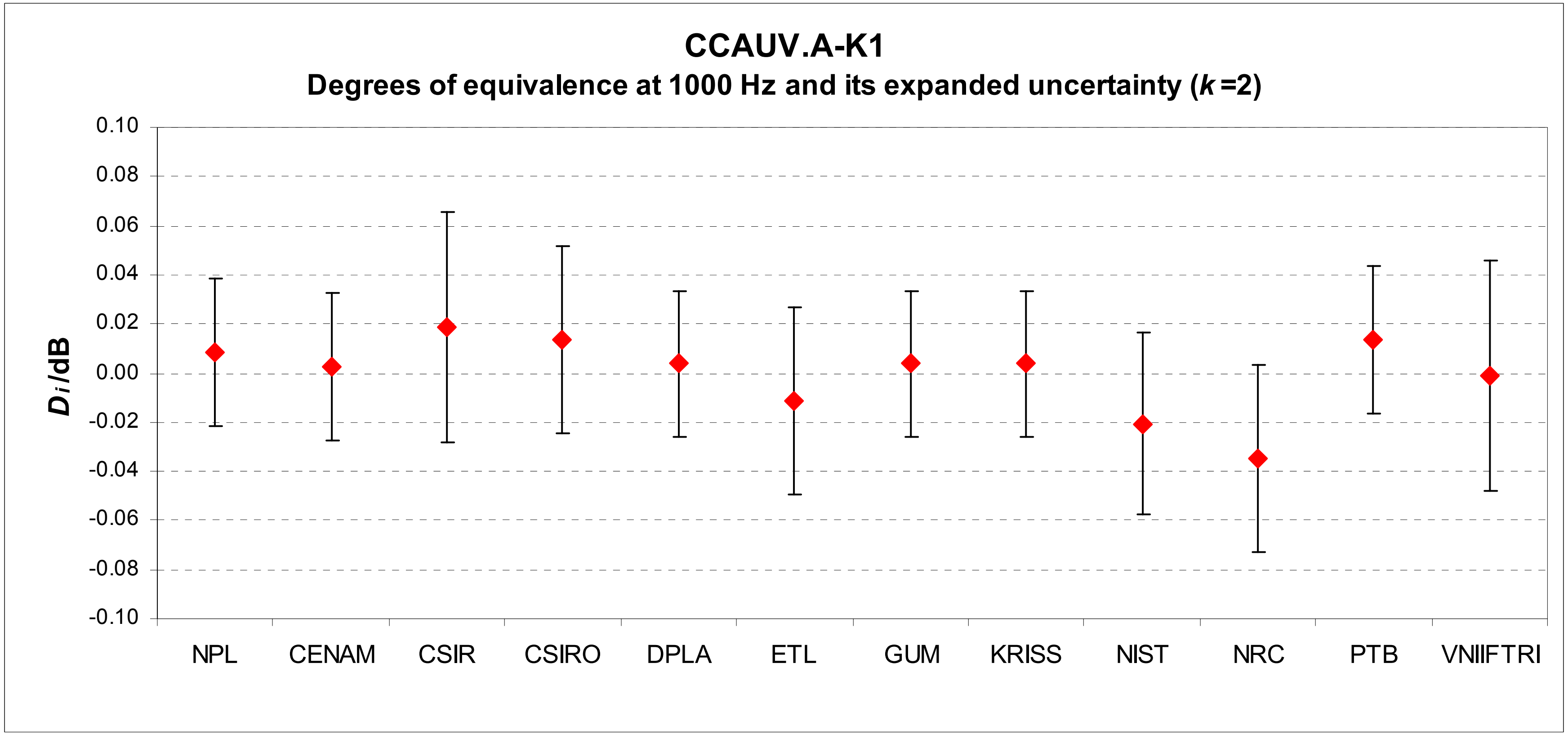

Figure A2 Illustration of the degrees of equivalence with the KCRV at 1000 Hz and the associated expanded uncertainty (k=2)

APPENDIX B. PRESSURE SENSITIVITY LEVEL FOR THE TRAVELLING STANDARD MICROPHONES

Tables B1(a) and B1(b) show the results reported by each participant for the individual travelling standard microphones. Tables B2(a) and B2(b) show the values of the microphone parameters used by each participant in their determination of the sensitivity levels.

Frequency (Hz)	NPL UK	DPLA DK	NIST US	ETL JP	PTB DE	KRISS KR	CSIR ZA	CSIRO AU	NRC CA	CENAM MX	GUM PL	VNIIFTRI RU
63	-27.43	-27.46	-27.46	-27.45	-27.44	-27.45	-27.43		-27.49	-27.46	-27.44	-27.46
125	-27.47	-27.49	-27.48	-27.48	-27.47	-27.48	-27.46		-27.52	-27.48	-27.47	-27.48
250	-27.49	-27.51	-27.50	-27.51	-27.49	-27.50	-27.47	-27.48	-27.54	-27.50	-27.49	-27.50
500	-27.49	-27.51	-27.51	-27.51	-27.49	-27.50	-27.47	-27.49	-27.54	-27.51	-27.50	-27.50
1000	-27.47	-27.48	-27.50	-27.49	-27.46	-27.47	-27.45	-27.46	-27.51	-27.48	-27.48	-27.48
1250	-27.44	-27.45	-27.48	-27.47	-27.44	-27.44	-27.42		-27.49	-27.45	-27.45	-27.46
1600	-27.39	-27.41	-27.43	-27.42	-27.39	-27.40	-27.38		-27.44	-27.40	-27.40	-27.42
2000	-27.33	-27.34	-27.36	-27.36	-27.32	-27.33	-27.31		-27.38	-27.33	-27.33	-27.35
2500	-27.23	-27.24	-27.25	-27.27	-27.22	-27.22	-27.21		-27.27	-27.23	-27.24	-27.26
3150	-27.07	-27.08	-27.09	-27.12	-27.07	-27.07	-27.06		-27.12	-27.07	-27.08	-27.10
4000	-26.85	-26.86	-26.87	-26.91	-26.85	-26.85	-26.84		-26.90	-26.85	-26.85	-26.89
5000	-26.64	-26.63	-26.65	-26.70	-26.62	-26.63	-26.62		-26.69	-26.63	-26.64	-26.67
6300	-26.59	-26.58	-26.61	-26.67	-26.58	-26.60	-26.57		-26.65	-26.59	-26.59	-26.61
8000	-27.42	-27.43	-27.45	-27.49	-27.45	-27.44	-27.43		-27.49	-27.46	-27.41	-27.43

Table B1(a) Pressure sensitivity level (dB re 1V/Pa) for microphone 4160 2036126.

Frequency (Hz)	NPL UK	DPLA DK	NIST US	ETL JP	PTB DE	KRISS KR	CSIR ZA	CSIRO AU	NRC CA	CENAM MX	GUM PL	VNIIFTRI RU
63	-27.31	-27.32	-27.34	-27.32	-27.33	-27.33	-27.32		-27.37	-27.33	-27.31	-27.33
125	-27.35	-27.35	-27.36	-27.35	-27.35	-27.36	-27.35		-27.39	-27.36	-27.34	-27.35
250	-27.37	-27.37	-27.38	-27.38	-27.37	-27.38	-27.37	-27.36	-27.41	-27.38	-27.36	-27.37
500	-27.38	-27.38	-27.39	-27.39	-27.38	-27.38	-27.37	-27.37	-27.42	-27.39	-27.37	-27.38
1000	-27.36	-27.36	-27.39	-27.38	-27.36	-27.37	-27.36	-27.36	-27.41	-27.37	-27.36	-27.37
1250	-27.34	-27.34	-27.37	-27.37	-27.34	-27.35	-27.35		-27.39	-27.35	-27.35	-27.36
1600	-27.31	-27.31	-27.34	-27.34	-27.31	-27.32	-27.32		-27.36	-27.32	-27.31	-27.33
2000	-27.26	-27.27	-27.29	-27.29	-27.27	-27.27	-27.28		-27.31	-27.27	-27.26	-27.29
2500	-27.19	-27.20	-27.22	-27.24	-27.20	-27.20	-27.21		-27.25	-27.21	-27.20	-27.23
3150	-27.10	-27.10	-27.11	-27.14	-27.11	-27.10	-27.12		-27.15	-27.11	-27.10	-27.14
4000	-26.97	-26.98	-26.99	-27.03	-26.99	-26.97	-27.00		-27.03	-26.99	-26.97	-27.03
5000	-26.89	-26.89	-26.90	-26.95	-26.90	-26.88	-26.91		-26.94	-26.89	-26.89	-26.95
6300	-27.00	-26.99	-27.02	-27.08	-27.01	-27.00	-27.00		-27.06	-27.01	-26.99	-27.05
8000	-27.83	-27.87	-27.90	-27.92	-27.88	-27.84	-27.85		-27.92	-27.88	-27.83	-27.84

Table B1(b) Pressure sensitivity level (dB re 1V/Pa) for microphone 4160 2036134.

	NPL	CENAM	CSIR	CSIRO	DPLA	ETL	GUM	KRISS	NIST	NRC	PTB	VNIIFTRI
total volume (mm^3)	663.0	*664.9*	*643.7*	662.3	*665.0*	-	659.0	*666.2*	**676.1**	**640.0**	672.0	*671.0*
front volume (mm^3)	*530.2*	543.4	534.0	-	545.0	529.0	*526.2*	532.9	-	-	*552.0*	535.0
cavity depth (mm)	1.98	1.944	1.964	-	1.942	1.948	1.958	1.942	-	-	1.959	1.95
acoustic mass ($kg\ m^{-4}$)	**406**	-	398.6	-	-	-	**406**	-	-	nominal	386.7	**392.7**
acoustic compliance ($kg^{-1}\ m^4\ s^2$)	**9.36E-13**	-	8.60E-13	-	-	-	**9.36E-13**	-	-	nominal	8.46E-13	**9.59E-13**
acoustic resistance ($kg\ m^{-4}\ s^{-1}$)	**2.20E+07**	-	2.30E+07	-	-	-	**2.20E+07**	-	-	nominal	2.25E+07	**2.12E+07**
loss factor	-	1		-	1.05	-	-	not declared	-	nominal		
res. frequency (kHz)	*8.16*	8.78	*8.60E+00*	-	8.7	-	*8.16*	8.2	-	nominal	*8.80*	*8.20*
equivalent volume (mm^3)	*132.78*	121.5	109.7	-	120	-	*132.78*	133.3	-	nominal	*120.00*	*136.04*
temp. coeff. at 250 Hz (dB/K)	-0.0062	-0.0023	-0.0003	-0.0060	-0.0014	-0.0040	*-0.0027*	-0.0030	0	not applicable	-0.0030	-0.0020
press. coeff. at 250 Hz (dB/kPa)	-0.0136	-0.0144	-0.0150	-0.0160	-0.0146	-0.0190	*-0.0150*	-0.0152	-0.0148	not applicable	-0.0150	-0.0160

Table B2(a) Declared parameters for microphone 4160 2036126

	NPL	CENAM	CSIR	CSIRO	DPLA	ETL	GUM	KRISS	NIST	NRC	PTB	VNIIFTRI
total volume (mm^3)	662.0	*663.9*	*641.0*	661.3	*665.0*	-	659.0	*668.1*	**676.1**	**640.0**	670.0	*671.0*
front volume (mm^3)	*529.2*	544.4	533.7	-	543.0	530.0	*526.2*	532.9	-	-	*550.0*	535.0
cavity depth (mm)	1.98	1.964	1.963	-	1.944	1.951	1.963	1.943	-	-	1.961	1.95
acoustic mass ($kg\ m^{-4}$)	**406**	-	363.3	-	-	-	**406**	-	-	nominal	378	**392.7**
acoustic compliance ($kg^{-1}\ m^4\ s^2$)	**9.36E-13**	-	8.80E-13	-	-	-	**9.36E-13**	-	-	nominal	8.46E-13	**9.59E-13**
acoustic resistance ($kg\ m^{-4}\ s^{-1}$)	**2.20E+07**	-	2.40E+07	-	-	-	**2.20E+07**	-	-	nominal	2.43E+07	**2.12E+07**
loss factor	-	1.1		-	1.07	-	-	not declared	-	nominal		
res. frequency (kHz)	*8.16*	8.99	*8.90*	-	9.05	-	*8.16*	8.20	-	nominal	*8.90*	*8.20*
equivalent volume (mm^3)	*132.8*	119.5	107.3	-	122.0	-	*132.8*	135.2	-	nominal	*120.0*	*136.0*
temp. coeff. at 250 Hz (dB/K)	-0.0062	-0.0023	-0.0003	-0.0060	-0.0030	-0.0040	*-0.0027*	-0.0030	0	not applicable	-0.0030	-0.0020
press. coeff. at 250 Hz (dB/kPa)	-0.0154	-0.0144	-0.0150	-0.0160	-0.0144	-0.0190	*-0.0150*	-0.0152	-0.0150	not applicable	-0.0150	-0.0160

Table B2(b) Declared parameters for microphone 4160 2036134

Note - Values in *italic* are derived from other data, values in **bold** are declared as nominal, blank entries are shown where the parameter does not feature in the calculation

APPENDIX C. REVIEW OF ANOMALIES AND AGREED CHANGES TO DECLARED RESULTS.

CIPM Guidelines task the pilot laboratory with deciding if the results of any laboratory are anomalous before declaring the complete set of results to all participants. No results were considered to be absolutely anomalous, but NRC, ETL and KRISS were advised that their results were tending towards being anomalous, in some or all of the frequency range. These laboratories were therefore given the chance to review their data without any indication of the nature of the possible discrepancy.

NRC and ETL chose to keep their original data. KRISS discovered that data from an inappropriate coupler had been included erroneously in their declared results above 2 kHz. The data from this coupler was removed from the calculation of the microphone sensitivities and new calibration certificates were issued quoting the revised results. The pilot laboratory was provided with the data from the individual coupler measurements and the revised calculation for the mean sensitivity levels. The original and revised data are shown in Table B1. The changes were accepted before publication of the Draft A report and results shown for KRISS in the main part of this report are based on the *revised* data only.

	4160 2036126		4160 2036134	
Frequency (Hz)	original	revised	original	revised
63	-27.45	-27.45	-27.33	-27.33
125	-27.48	-27.48	-27.36	-27.36
250	-27.50	-27.50	-27.38	-27.38
500	-27.50	-27.50	-27.38	-27.38
1000	-27.47	-27.47	-27.37	-27.37
1250	-27.44	-27.44	-27.35	-27.35
1600	-27.40	-27.40	-27.32	-27.32
2000	-27.33	-27.33	-27.27	-27.27
2500	-27.22	-27.22	-27.20	-27.20
3150	-27.06	**-27.07**	-27.10	**-27.10**
4000	-27.84	**-27.85**	-26.98	**-26.97**
5000	-26.62	**-26.63**	-26.88	**-26.88**
6300	-26.56	**-26.60**	-26.98	**-27.00**
8000	-27.33	**-27.44**	-27.73	**-27.84**

Table B1. Change in results reported by KRISS following post-submission review

A request was also received from CSIRO to make a change in their declared data resulting from the use of an incorrect temperature coefficient. This request was received before publication of the Draft A report. All participants agreed that the changes should be allowed. Details are shown in Table B2.

	4160 2036126		4160 2036134	
Temperature coefficient (dB/K)				
Original	-0.003		-0.003	
Revised	-0.006		-0.006	
Frequency (Hz)	Pressure sensitivity level (dB)			
	original	revised	original	revised
250	-27.47	**-27.48**	-27.35	**-27.36**
500	-27.48	**-27.49**	-27.36	**-27.37**
1000	-27.45	**-27.46**	-27.35	**-27.36**

Table B2. Change in results reported by CSIRO post-submission

Results shown for CSIRO in the main part of this report are based on the *revised* data only.

APPENDIX D. UNCERTAINTY BUDGETS

The following pages show the uncertainty budgets submitted to the pilot laboratory by each participant. These have been scanned from original paper copies so reproduction quality may not be perfect in some cases. Where a laboratory submitted different uncertainty budgets for each microphone, both are shown.

Uncertainty budget for NPL, UK

COMPONENTS OF TYPE B UNCERTAINTY EXPRESSED AS SEMI-RANGES (10^{-4} dB)

SOURCE	Frequency (Hz)													
Rectangular distribution applies unless stated	63	125	250	500	1k	2k	2.5k	3.15k	4k	5k	6.3k	8k	10k	12.5k
Resistance Box Accuracy	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Stray Capacitance	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Non Linearity	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Radius of Coupler	8	8	9	8	9	9	9	9	9	9	9	9	9	9
Velocity of Sound (dry air)	40	40	40	40	40	39	38	37	35	32	27	18	1	60
Ratio of Specific Heats	2	2	1	1	1	0	0	0	0	0	0	0	0	0
Ambient Pressure	12	12	12	12	12	12	12	12	12	12	13	13	12	12
Density of air	10	10	10	10	10	10	10	10	10	10	11	11	10	10
Length of Coupler	21	21	21	21	20	19	18	17	15	11	6	4	24	85
Cavity Depth	0	0	0	0	0	0	1	1	1	2	2	1	0	1
Front Cavity Volume	25	25	26	25	25	24	23	22	19	15	9	4	29	104
Theory of Adding Volume	0	0	0	1	2	6	9	14	22	35	58	102	187	437
Compliance	0	0	0	2	9	40	66	111	187	268	232	118	593	1686
Mass	0	0	0	1	3	11	16	21	19	1	25	31	97	21
Resistance	0	0	1	4	14	56	86	128	177	196	120	46	237	571
Heat Conduction Theory	1	1	1	0	3	11	16	24	36	51	72	108	182	384
Thermal Diffusivity	24	17	12	8	6	4	4	3	3	3	2	2	2	2
Capillary Radius	35	43	35	16	3	1	3	1	1	0	0	0	0	0
Air Viscosity	7	8	6	3	1	0	0	0	0	0	0	0	0	0
Humidity Determination	1	1	1	1	1	1	2	2	2	3	3	5	7	15
Polarising Voltage	22	22	22	22	22	22	22	22	22	22	22	22	22	22
Temperature	1	1	1	0	1	1	2	3	4	7	10	17	29	66
Pressure Radial Non-Unif	0	0	0	0	1	2	3	5	9	13	20	31	42	46
Mic. Temp. Dependence	23	23	23	23	23	23	23	23	23	23	23	23	23	23
Mic. Press. Dependence	34	34	34	34	34	34	34	34	34	34	34	34	34	34
Transmitter Ground Shield	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Receiver Ground Shield	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Rounding Error	50	50	50	50	50	50	50	50	50	50	50	50	50	50
ESTIMATE OF S.D. (σ_B) $\sigma_B = [\Sigma (a^2/3)]^{1/2}$	70	71	69	66	66	77	91	119	164	205	172	130	408	1087

COMPONENTS OF TYPE A UNCERTAINTY EXPRESSED AS STANDARD DEVIATIONS (10^{-4} dB)

SOURCE	Frequency (Hz)													
Normal distribution with *n*[illegible] applies unless stated	63	125	250	500	1k	2k	2.5k	3.15k	4k	5k	6.3k	8k	10k	12.5k
Allowed Repeatability	100	100	100	100	100	100	100	100	100	125	150	175	175	175
Front Cavity Volume	38	38	39	38	38	36	35	33	29	23	13	6	44	155
ESTIMATE OF S.D. (σ_A) $\sigma_A = [\Sigma (a^2)]^{1/2}$	107	107	107	107	107	106	106	105	104	127	151	175	180	234

OVERALL UNCERTAINTY (10^{-4} dB)

SOURCE	Frequency (Hz)													
	63	125	250	500	1k	2k	2.5k	3.15k	4k	5k	6.3k	8k	10k	12.5k
Type B at k=2 ($2\sigma_B$)	139	141	138	132	132	153	182	237	328	409	344	260	816	2174
Type A at k=2 ($2\sigma_A$)	214	214	215	214	214	213	212	211	208	254	301	350	361	468
Overall Uncertainty at k=2 $\sigma = 2(\sigma_A^2+\sigma_B^2)^{1/2}$	255	256	255	251	251	262	279	317	388	482	457	436	892	2224

Uncertainty budget for DPLA, Denmark

Components of type B uncertainties in dB*1000

	Source	63	125	250	500	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
		Frequency Hz														
1	Coupler dimensions	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
2	Microphone parameters	7.8	7.9	8.0	8.0	7.9	7.9	7.8	7.8	7.9	8.3	9.2	9.9	7.5	3.0	15.0
3	Electrical transfer impedance	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
4	Environmental parameters	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
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
6	Radial wave-motion correction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.5	1.0	3.0	6.0
7	Viscosity losses	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.5	1.0	3.0	5.0	10.0
8	Microphone thread	12.0	8.0	6.0	4.5	3.5	3.1	2.8	2.6	2.4	2.2	2.0	1.9	1.8	1.7	1.5
9	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
10	Rounding of results	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	$\sigma_B = \left(\sum u^2/3\right)^{1/2}$	9.3	7.7	7.0	6.6	6.4	6.3	6.3	6.3	6.3	6.5	7.1	7.9	8.1	9.4	16.5

Components of type A uncertainties in dB*1000

11	Allowed reproducibility σ_A	15	10	10	10	10	10	10	10	10	10	10	10	15	20	30

Overall uncertainty in dB*1000 at measurement conditions (k=2)

	$\sigma = 2\cdot\left(\sigma_A^2 + \sigma_B^2\right)^{1/2}$	35.3	25.2	24.4	24.0	23.7	23.6	23.6	23.6	23.7	23.9	24.5	25.5	34.1	44.2	68.4

Uncertainty on corrections to reference environmental conditions in dB*1000 (k=2)

12	Static pressure and temperature corrections	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

Overall uncertainty in dB*1000 at reference conditions (k=2)

		35.6	25.6	24.8	24.4	24.1	24.1	24.0	24.0	24.1	24.3	25.0	26.0	34.4	44.9	69.6

Uncertainty budget for NIST, USA

F.v.unc. rec. PRL LS1P (2)

Column A below lists uncertainty components (values in columns B through E are expressed as semi-ranges in dB).	Column B below is value for:	Column C below is value for:	Column D below is value for:	Column E below is value for:
The entered values include multiplication by 0.577 = 1/(SQRT3), i.e., rectangular distribution applies so that the root-sum-square of these entries is the combined standard uncertainty (coverage factor k = 1) in pressure cal. of LS1P mic. by reciprocity:	Frequency Range (Hz) 50 to 499	Frequency Range (Hz) 500 to 4000	Frequency Range (Hz) 4001 to 7000	Frequency Range (Hz) 7001 to 10000
Voltage ratio I	0.0046	0.0029	0.0029	0.0046
Voltage ratio II	0.0046	0.0029	0.0029	0.0046
Voltage ratio III	0.0046	0.0029	0.0029	0.0046
Driving-point electrical impedance of source microphone	0.0081	0.0052	0.0052	0.0075
Angular frequency of sine-wave excitation	0.00029	0.00029	0.00029	0.00029
Sum of geometric volume of coupler (including microphone front-cavity volumes) and equivalent volumes of microphones	0.0115	0.0115	0.0115	0.0115
Ambient static (barometric) pressure	0.0029	0.0029	0.0029	0.0029
Ratio of specific heats of gas in coupler	0.0087	0.0087	0.0046	0.0046
Heat conduction correction	0.0087	0.0058	0.0029	0.0029
Capillary tube correction	0.0058	0.0029	0.0029	0.0029
Wave pattern correction	0	0.0049	0.0127	0.0583
Microphone polarizing voltage	0.0058	0.0058	0.0058	0.0058
Sum of squares of entered values	0.00048849	0.0003684	0.00042592	0.003730984
Estimate of combined standard uncertainty (k=1) in dB in columns B through E	0.022	0.019	0.021	0.061
Expanded uncertainty with coverage factor k=2, values in dB in columns B through E	0.044	0.038	0.041	0.122

Uncertainty budget for ETL, Japan

? Components of uncertainty and overall uncertainty(□~0.001dB)

No	63	125	250	500	1K	1.25	1.6	2	2.5	3.15	4	5	6.3	8
1a	4	4	4	4	4	4	4	4	4	4	4	9	9	9
1b	10	10	10	10	10	10	10	10	10	10	10	10	10	10
1c	3	3	3	3	3	3	3	3	3	3	3	3	3	3
1d	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1e	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2a	7	7	7	7	7	7	7	7	7	7	7	14	14	14
2b	3	3	3	3	3	3	3	3	3	3	3	3	3	3
3	4	4	4	4	4	4	4	4	4	4	4	4	4	4
4a	3	3	3	3	3	3	3	3	3	3	3	3	3	3
4b	3	3	3	3	3	3	3	3	3	3	3	3	3	3
4c	3	3	3	3	3	3	3	3	3	3	3	3	3	3
4d	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	15	13	9	9	8	9	9	10	10	10	11	12	14	17
6	2	2	2	2	2	2	2	2	2	2	2	2	2	2
7	21	20	18	18	17	18	18	18	18	18	19	24	25	27
8	43	40	35	35	34	35	35	36	36	36	38	48	51	54

Explanation of each component No. is as follows.

1. Acoustical (Non-electrical) uncertainty in absolute calibration
1a. Repeatability of voltage ratio measurement
1b. Stability of microphones
1c. Repeatability of capacitance measurement in transmitter microphones
1d. Temperature coefficient measurement
1e. Pressure coefficient measurement

2. Acoustical uncertainty in comparative calibration
2a. Repeatability of voltage ratio measurement
2b. Acoustic impedance difference measurement

3. Electrical uncertainty (noise, cross-talk, linearity, calibration of attenuator, stray capacitance etc.)

4. Parameter measurement uncertainty
4a. Coupler volume
4b. Ratio of specific heats
4c. Static pressure
4d. Polarizing voltage

5. Coupler correction uncertainty
6. Uncertainty in calculation

7. Overall uncertainty
8. Expanded overall uncertainty (factor k=2)

Uncertainty budget for PTB, Germany

LS1P microphones		Frequency in Hz								
		63	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**10k**
Type A uncertainty, as standard deviation (10^{-4} dB)										
Source of uncertainty										
Normal distribution										
	Repeatibility of electrical transfer impedance measurement	50	50	50	50	50	50	75	100	160
Estimate of a type A uncertainty (S.D.), k=1		50	50	50	50	50	50	75	100	160
Type B uncertainty, as semi-ranges (10^{-4} dB)										
Source of uncertainty										
Rectangular distribution										
Measurement	Resistance box	10	10	10	10	10	10	10	10	10
	Stray capacitance	30	30	30	30	30	30	30	30	30
	Polarization Voltage	22	22	22	22	22	22	22	22	22
Microphone parameters	Acoustic impedance (fit)	200	200	200	200	200	200	200	400	600
	Cavity depth	1	1	1	1	1	1	1	2	2
Couplers	Diameter	10	10	10	10	10	10	10	10	10
	Length	20	20	20	20	20	15	15	15	20
Correction of results to normal environmental conditions	Static pressure	30	30	30	30	30	30	30	30	30
	Temperature	20	20	20	20	20	20	20	20	20
Environmental conditions	Static pressure	30	30	30	30	30	30	30	30	30
	Temperature	5	5	5	5	5	5	5	5	10
	Humidity	5	5	5	5	5	5	5	10	15
Rounding error		50	50	50	50	50	50	50	50	50
Estimate of type B uncertainty (S.D.), k=1		125	125	125	125	125	125	125	236	350
Overall uncertainty (10^{-4} dB)										
	Type A, k=2	100	100	100	100	100	100	150	200	320
	Type B, k=2	250	250	250	250	250	249	249	471	700
	Overall uncertainty, k=2	269	269	269	269	269	268	291	512	769
		63	125	250	500	1k	2k	4k	8k	10k

Uncertainty budget for KRISS, South Korea

Components of Uncertainty (10^{-4} dB)

Input Parameter	Frequency[Hz]														
Source	63	125	250	500	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
Ambient Conditions															
Static Pressure	7	7	7	7	7	7	7	7	7	7	7	7	8	8	7
Temperature	0	0	0	0	0	0	1	1	2	3	4	7	11	17	29
Relative Humidity	1	1	1	1	1	1	1	1	2	2	2	3	4	6	9
ESTIMATE OF S.D.	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**7**	**8**	**8**	**8**	**10**	**14**	**20**	**31**
Coupler															
Coupler Length	3	3	3	3	3	3	3	3	3	3	3	2	1	1	4
Coupler Diameter	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Coupler Volume	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Coupler Surface Area	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ESTIMATE OF S.D.	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**10**	**9**	**9**	**9**	**10**
Microphone															
Front Cavity Length	0	0	0	0	0	1	1	2	2	4	6	10	16	26	45
Front Cavity Volume	22	22	22	22	22	22	22	22	22	22	23	23	23	24	23
LF Equivalent Volume	20	20	20	20	20	20	20	19	18	17	15	11	5	3	9
Resonance Frequency	0	0	0	0	0	0	0	1	3	8	19	40	50	23	65
Damping Factor	0	0	0	1	4	6	10	16	25	38	54	66	47	17	94
ESTIMATE OF S.D.	**30**	**30**	**30**	**30**	**30**	**30**	**31**	**33**	**38**	**48**	**64**	**82**	**74**	**46**	**125**
Electrical Parameter															
Serise Capacitance	47	46	44	27	18	27	27	27	27	44	44	44	44	44	44
Volt, Ratio, DVM	6	4	4	4	4	4	4	4	6	6	6	6	6	6	6
Volt, Ratio, Cr-talk	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
Volt, Ratio, Noise	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Volt, Ratio, Distort.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Polarization Voltage	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
ESTIMATE OF S.D.	**54**	**53**	**51**	**38**	**32**	**38**	**38**	**38**	**38**	**52**	**52**	**52**	**52**	**52**	**52**
Repeatability	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**90**	**110**	**130**	**150**
Rounding Error	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**
Overall Uncertainty (k=2) at Measurement Conditions	**227**	**226**	**224**	**213**	**209**	**213**	**214**	**215**	**219**	**237**	**251**	**284**	**303**	**313**	**421**
Sensitivity Correction for Static Pressure	15	15	15	15	14	14	13	13	12	10	8	8	8	8	66
Sensitivity Correction for Temperature	7	7	7	7	7	8	10	13	18	24	31	38	46	55	31
Overall Uncertainty (k=2) at Reference Conditions	**229**	**228**	**227**	**216**	**212**	**216**	**217**	**218**	**223**	**242**	**259**	**294**	**317**	**333**	**445**

* All values are 1 sigma limit.

Uncertainty budget for CSIR, South Africa

UNCERTAINTY BUDGET

References: ISO/TAG4 Guide to the Expression of Uncertainty in Measurement 1993 (BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML), NIS 3003, EAL R2

Description: Reciprocity calibration of 1" condenser microphone | **Type: 4160 SN: 2036126** | **Range: 63 Hz to 8 kHz** | **Metrologist: Ian Veldman**

Symbol	Source of Uncertainty	63 Hz Ui	125 Hz Ui	250 Hz Ui	500Hz Ui	1 000 Hz Ui	1 250 Hz Ui	1 600 Hz Ui	2 000Hz Ui	2 500 Hz Ui	3 150 Hz Ui	4 000 Hz Ui	5 000 Hz Ui	6 300 Hz Ui	8 000 Hz Ui
U_R	U/I resolution	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
U_A	U/I accuracy	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
U_r	Coupler radius	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
U_l	Coupler length	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
U_d	Cavity depth	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
E_R	Rounding error	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.002	0.003	0.003	0.003
U_V	Sound velocity	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.003	0.005
U_P	Ambient pressure	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
U_T	Ambient temperature	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.003	0.004
U_H	Ambient humidity	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003
E_{RNU}	Pressure radial non-uniformity	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.003	0.005	0.006	0.009
U_{SH}	Ratio of specific heats	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.005	0.003
C_{HC}	Heat conduction correction	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.004	0.005	0.015	0.025
E_{PolV}	Polarization voltage	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E_{CP}	Pressure correction	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
UUT	Repeatability (Type "A")	0.016	0.016	0.017	0.017	0.017	0.017	0.017	0.017	0.016	0.016	0.015	0.014	0.011	0.016
U_{FV}	Front cavity volume	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.009	0.009	0.007	0.005	0.002
U_{CA}	Acoustic compliance	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002	0.003	0.005	0.008	0.010	0.015	0.007
U_{MA}	Acoustic mass	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.003	0.004	0.005	0.005	0.002	0.006	0.008
U_{RA}	Acoustic resistance	0.000	0.000	0.000	0.000	0.001	0.002	0.003	0.005	0.008	0.010	0.017	0.018	0.010	0.005
	Normal	0.022	0.022	0.023	0.023	0.023	0.023	0.023	0.024	0.024	0.025	0.029	0.029	0.030	0.036
	Normal (k=2)	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.06**	**0.07**	**0.06**	**0.07**

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UNCERTAINTY BUDGET

References: ISO/TAG4 Guide to the Expression of Uncertainty in Measurement 1993 (BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML), NIS 3003, EAL R2

Description: Reciprocity calibration of 1" condenser microphone | **Type: 4160 SN: 2036134** | **Range: 63 Hz to 8 kHz** | **Metrologist: Ian Veldman**

Symbol	Source of Uncertainty	63 Hz Ui	125 Hz Ui	250 Hz Ui	500Hz Ui	1 000 Hz Ui	1 250 Hz Ui	1 600 Hz Ui	2 000Hz Ui	2 500 Hz Ui	3 150 Hz Ui	4 000 Hz Ui	5 000 Hz Ui	6 300 Hz Ui	8 000 Hz Ui
U_R	U/I resolution	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
U_A	U/I accuracy	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
U_r	Coupler radius	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
U_l	Coupler length	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
U_d	Cavity depth	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
E_R	Rounding error	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.002	0.003	0.003	0.003
U_V	Sound velocity	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.003	0.005
U_P	Ambient pressure	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
U_T	Ambient temperature	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.003	0.004
U_H	Ambient humidity	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003
E_{RNU}	Pressure radial non-uniformity	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.003	0.005	0.006	0.009
U_{SH}	Ratio of specific heats	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.005	0.003
C_{HC}	Heat conduction correction	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.004	0.005	0.015	0.025
E_{PolV}	Polarization voltage	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E_{CP}	Pressure correction	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
UUT	Repeatability (Type "A")	0.009	0.010	0.011	0.010	0.010	0.010	0.010	0.011	0.012	0.010	0.011	0.012	0.009	0.007
U_{FV}	Front cavity volume	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.009	0.009	0.007	0.005	0.002
U_{CA}	Acoustic compliance	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.002	0.003	0.005	0.008	0.010	0.015	0.007
U_{MA}	Acoustic mass	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.003	0.004	0.005	0.005	0.002	0.006	0.008
U_{RA}	Acoustic resistance	0.000	0.000	0.000	0.000	0.001	0.002	0.003	0.005	0.008	0.010	0.017	0.018	0.010	0.005
	Normal	0.018	0.018	0.019	0.018	0.018	0.018	0.018	0.020	0.022	0.022	0.027	0.028	0.030	0.032
	Normal (k=2)	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.05**	**0.05**	**0.06**	**0.06**	**0.06**	**0.06**

Uncertainty analysis for CSIRO, Australia

None of the wave motion and heat conduction corrections in the IEC standard can readily be calculated for the 3-port coupler. Instead a set of empirical corrections originally obtained by comparing measurements of standard microphones in IEC couplers with 3-port coupler results is used. With this arrangement good results in comparisons have been achieved.

Uncertainties arising from the arrangements for the electrical measurements are discussed in detail by Gibbings and Gibson. In particular the uncertainties arising from the effects of finite amplifier gain, stray capacitance across the amplifier stage and stray capacitance associated with the 200 V supply, which is connected to the outer microphone electrode, are estimated to contribute $U_{Exp} = \pm 2.5 \times 10^{-4}$ dB.

The uncertainty budget is summarised in Table 1. The top area contains estimates of uncertainty for quantities in the model that were evaluated using Equations 1, 2 and 3 to derive influence coefficients. The dominant source of uncertainty is the total volume, V_{Total}. The various electrical components contribute negligible uncertainty. The ratio dividers, X_2 and X_3, can be set repeatably to 1 in 10^5 which also makes a negligible contribution. The expressions are linear with respect to the various measurands within the range of the uncertainties.

The next region contains the uncertainties associated with the temperature, pressure and polarising voltage corrections. The temperature and pressure coefficients are shown on the spreadsheet. Temperature is measured in the coupler during a calibration and, due to the large thermal mass of the coupler and the minimal amount of microphone handling involved, the stability is better than 0.1 °C. A mean value is used for the temperature correction.

Pressure is measured at the moment of bridge balance so that three pressure measurements are performed during the program. These are used as indicated in Equation 1. The pressure correction in the result uses the mean of these measurements. The spreadsheet shows the mean temperature and pressure for each calibration.

The polarising voltage is measured with an expanded uncertainty $U_{Vexp} = \pm 1$mV. The control program monitors the polarising voltage and stops for corrective action if the voltage deviates by more than 10 mV from 200.00 V.

The next item in the budget is the composite correction factors, mentioned above, used to include the wave motion and heat conduction corrections. They are the other significant source of uncertainty in the result, contributing 0.014 dB.

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Table 1

Summary of Uncertainty Estimation Values are Standard Uncertainties in dB				
		250 Hz	**500 Hz**	**1000 Hz**
Coupler Model, Figure 1, Equations 1, 2, 3.				
X_2	0.15000 (typ)	2.88×10^{-4}	2.85×10^{-4}	2.74×10^{-4}
X_3	0.06000 (typ)	5.32×10^{-6}	2.12×10^{-5}	8.38×10^{-5}
X_2	0.15000 (typ)	2.88×10^{-4}	2.85×10^{-4}	2.74×10^{-4}
X_3	0.06000 (typ)	5.32×10^{-6}	2.12×10^{-5}	8.38×10^{-5}
X_2	0.15000 (typ)	2.88×10^{-4}	2.85×10^{-4}	2.74×10^{-4}
X_3	0.06000 (typ)	5.31×10^{-6}	2.12×10^{-5}	8.38×10^{-5}
R_1	995519 Ω	5.06×10^{-6}	5.06×10^{-6}	5.09×10^{-6}
R_2	997.76 Ω	4.79×10^{-6}	4.79×10^{-6}	4.78×10^{-6}
C_q	968.295 pF	8.22×10^{-7}	3.28×10^{-6}	1.30×10^{-5}
C_{sc}	50.0610 pF	2.17×10^{-4}	2.17×10^{-4}	2.17×10^{-4}
P	101212 Pa	2.15×10^{-4}	2.15×10^{-4}	2.15×10^{-4}
Volume	9.771×10^{-6} m^3	1.4×10^{-2}	1.4×10^{-2}	1.4×10^{-2}
P, T and V Sensitivity Corrections				
Mic P dep.		2.53×10^{-4}	2.53×10^{-4}	2.53×10^{-4}
Mic T dep.		5.01×10^{-4}	5.01×10^{-4}	5.01×10^{-4}
Polarising Volt		3.46×10^{-4}	3.46×10^{-4}	3.46×10^{-4}
10cc Coupler Correction				
Coupler correction		(+0.03)	(-0.02)	(-0.12)
Uncertainty		1.41×10^{-2}	1.410×10^{-2}	1.41×10^{-2}
Circuit design		1.25×10^{-4}	1.25×10^{-4}	1.25×10^{-4}
Rounding		3×10^{-3}	3×10^{-3}	3×10^{-3}
Type A				
ESDM		1×10^{-3}	1×10^{-3}	1×10^{-3}
Expanded Uncertainty (k=2)		**0.041**	**0.041**	**0.041**

Uncertainty budget for NRC, Canada

Reciprocity Calibration CCAUV.A-K1	**1" B&K 4160 microphones** Uncertainty budget
Source	63 Hz to 8 kHz (dB)
Equivalent volume	0.025
Voltage ratio	0.006
Reference impedance	0.0042
Specific heat ratio	0.002
Density of air	0.001
Barometric pressure	0.002
Heat-conduction correction	0.015
Insert voltage	0.001
Polarizing voltage	0.0002
Temperature	0.0005
Humidity coefficient	0.001
Others (wave motion, etc.)	0.015
Estimate of S.D.	0.017

Repeatability	0.012
Combined standard uncertainty	0.021
Expanded uncertainty (k=2)	**0.042**

Uncertainty budget for GUM, Poland

5. Summary of the uncertainty evaluation

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

No	Uncertainty source	Components of Type B uncertainty expressed as distribution halfwidths (mB) at frequency											
		63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	2,5 kHz	3,15 kHz	4 kHz	5 kHz	6,3 kHz	8 kHz
1	Resistance box accuracy	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
2	Res. box stray capacitance	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
3	Res. box nonlinearity	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
4	Speed of sound (dry air)	0	0	0	0	0	0	0,01	0,01	0,02	0,03	0,04	0,07
5	Change of sound speed with humidity	0	0	0	0	0	0,01	0,01	0,02	0,04	0,06	0,09	0,15
6	Specific heats ratio	0,27	0,27	0,28	0,28	0,28	0,28	0,28	0,29	0,29	0,29	0,30	0,31
7	Coupler radius	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09
8	Coupler length	0,20	0,21	0,20	0,20	0,21	0,20	0,18	0,17	0,15	0,11	0,06	0,04
9	Cavity depth	0	0	0	0	0	0	0	0	0	0,02	0,02	0,02
10	Front cavity volume	0,26	0,26	0,26	0,26	0,26	0,24	0,24	0,22	0,20	0,16	0,08	0,04
11	Theory of adding volume	0	0	0	0,01	0,02	0,06	0,09	0,14	0,22	0,35	0,58	1,01
12	Acoustic compliance	0	0	0,01	0,03	0,08	0,36	0,60	1,01	1,70	2,43	2,11	1,10
13	Acoustic mass	0	0	0,01	0,03	0,13	0,51	0,78	1,17	1,62	1,80	1,11	0,43
14	Acoustic resistance	0	0	0	0,01	0,03	0,12	0,16	0,20	0,20	0,02	0,25	0,31
15	Heat conduction theory	0,01	0,01	0	0	0,03	0,11	0,16	0,24	0,36	0,51	0,72	1,08
16	Thermal diffusivity	0,22	0,16	0,11	0,08	0,05	0,04	0,04	0,03	0,03	0,03	0,02	0,02
17	Capillary radius	0,43	0,48	0,38	0,17	0,03	0,02	0,03	0,01	0,01	0	0	0
18	Air viscosity	0,08	0,08	0,06	0,03	0,01	0	0	0	0	0	0	0
19	Static pressure determination	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,13	0,13
20	Humidity determination	0,01	0,01	0,01	0,01	0,01	0,01	0,02	0,02	0,03	0,03	0,05	0,07
21	Temperature determination	0	0	0	0	0,01	0,03	0,05	0,07	0,13	0,20	0,31	0,50
22	Polarizing voltage	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
23	Pressure radial non-uniformity	0	0	0	0	0	0,01	0,05	0,08	0,11	0,18	0,26	0,38
24	Temperature dependence of microphone parameters	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23	0,23
25	Static pressure dependence of microphone parameters	0,34	0,34	0,34	0,34	0,34	0,34	0,34	0,34	0,34	0,34	0,34	0,34
26	Transmitter ground shield	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
27	Receiver ground shield	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07
28	Rounding error	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
Resultant Type B uncertainty expressed as distribution halfwidth		1,251	1,2616	1,221	1,17	1,168	1,32	1,533	1,956	2,656	3,297	2,833	2,313
Resultant Type B uncertainty expressed as standard deviation		0,722	0,728	0,705	0,675	0,674	0,762	0,885	1,129	1,534	1,904	1,636	1,336

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5.2. Type A uncertainty components (normal probability distribution assumed, large number of repetitions)

No	Uncertainty source	Components of Type A uncertainty expressed as standard deviations (mB) at frequency											
		63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	2,5 kHz	3,15 kHz	4 kHz	5 kHz	6,3 kHz	8 kHz
1	Allowed repeatability	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,25	1,50	1,75
2	Front cavity volume	0,78	0,78	0,78	0,78	0,78	0,72	0,72	0,66	0,60	0,48	0,24	0,12
Resultant Type A uncertainty expressed as standard deviation		1,27	1,27	1,27	1,27	1,27	1,23	1,23	1,20	1,17	1,34	1,52	1,75

5.3. Overall uncertainty

Type of uncertainty	Uncertainty (mB) at frequency											
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	2,5 kHz	3,15 kHz	4 kHz	5 kHz	6,3 kHz	8 kHz
Resultant Type B uncertainty expressed as standard deviation	0,722	0,728	0,705	0,675	0,674	0,762	0,885	1,129	1,534	1,904	1,636	1,336
Resultant Type A uncertainty expressed as standard deviation	1,27	1,27	1,27	1,27	1,27	1,23	1,23	1,20	1,17	1,34	1,52	1,75
Expanded Type B uncertainty at k=2	1,444	1,456	1,41	1,35	1,348	1,524	1,77	2,258	3,068	3,808	3,272	2,672
Expanded Type A uncertainty at k=2	2,54	2,54	2,54	2,54	2,54	2,46	2,46	2,40	2,34	2,68	3,04	3,50
Overall uncertainty at k=2	2,92	2,93	2,90	2,87	2,87	2,90	3,03	3,29	3,85	4,66	4,46	4,40
Overall uncertainty rounded, dB	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,04	0,05	0,04	0,04

Uncertainty analysis for VNIIFTRI, Russia

The expression for expanded uncertainty U is:

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

where:

$$U_A = \sqrt{\frac{\sum_i^n (M_i - \overline{M})^2}{n \cdot (n-1)}} \quad ;$$

M_i- pressure sensitivity level, dB re 1V/Pa;

$$\overline{M} = \frac{1}{n} \cdot \sum_i^n M_i \quad ; \qquad n=6;$$

$$U_B = \frac{1}{\sqrt{3}} \cdot \sqrt{\sum_j^N C_j \cdot \Theta_j^2} \quad ; \quad N=8;$$

$$\Theta_j = \frac{\partial M}{\partial X_j} \cdot \Delta X_j \quad ;$$

X_1 – is the electrical transfer impedance, which are valid for the three pairs microphones (1 and 2, 1 and 3, 2 and 3), dB; ΔX_1 = 0,004dB; C_1=3;

X_2 – is the actual coupler volume, including front and equivalent volumes of pairs microphones, m; ΔX_2=5·10^{-9}m; C_2=3;

X_3 – is the geometrical distance between the microphone diaphragms, m; ΔX_3=4·10^{-5} m; C_3=3;

X_4 – is the temperature, ^oC; ΔX_4=5°C; C_4=1;

X_5 – is the ambient pressure, Pa; ΔX_5=20Pa; C_5=1;

X_6 – is the relative humidity, %; ΔX_6=20%; C_6=1;

X_7 – is the internal diameter of capillary tube, m; ΔX_7= 1,5·10^{-5}m; C_7=1;

X_8 – is the polarization voltage,V; ΔX_8=0.5V; C_8=1.

Θ_j, U_A and U are given in table.

(continued..)

(..continued)

Table. Calculated uncertainties

Hz	$\Theta j \cdot 10^3$, dB								$U_A \cdot 10^3$, dB	U,dB
	Θ_1	Θ_2	Θ_3	Θ_4	Θ_5	Θ_6	Θ_7	Θ_8		
63	6.4	20.8	0.1	2.9	0.9	1.2	5.6	20.0	10.0	0.05
80	6.5	20.8	0.1	1.8	0.9	1.2	9.5	20.0	10.0	0.05
100	6.5	20.8	0.1	1.1	0.9	1.2	11.8	20.0	10.0	0.05
125	6.6	20.8	0.1	0.7	0.9	1.1	12.9	20.0	10.0	0.05
160	6.6	20.8	0.1	0.5	0.9	1.1	13.1	20.0	10.0	0.05
200	6.6	20.8	0.1	0.4	0.9	1.2	12.7	20.0	10.0	0.05
250	6.6	20.8	0.1	0.5	0.9	1.2	11.6	20.0	10.0	0.05
315	6.6	20.8	0.1	0.7	0.9	1.2	9.9	20.0	10.0	0.05
400	6.5	20.8	0.2	1.1	0.9	1.2	7.9	20.0	10.0	0.05
500	6.5	20.8	0.2	1.4	0.9	1.2	5.9	20.0	10.0	0.05
630	6.5	20.8	0.3	1.7	0.9	1.3	4.1	20.0	10.0	0.05
800	6.5	20.8	0.5	2.1	0.9	1.3	2.7	20.0	10.0	0.05
1000	6.5	20.8	0.7	2.6	0.9	1.4	1.7	20.0	10.0	0.05
1250	6.4	20.8	1.1	3.3	0.9	1.4	1.1	20.0	10.0	0.05
1600	6.4	20.8	1.8	4.3	0.9	1.5	0.6	20.0	10.0	0.05
2000	6.3	20.8	2.8	6.2	0.9	1.7	0.4	20.0	10.0	0.05
2500	6.1	20.8	4.3	9.1	0.9	2.0	0.2	20.0	10.0	0.05
3150	6.0	20.8	6.7	13.5	0.9	2.5	0.1	20.0	10.0	0.05
4000	5.7	20.8	10.3	20.4	0.9	3.2	0.1	20.0	10.0	0.06
5000	5.3	20.8	15.7	31.1	0.9	4.2	0.1	20.0	10.0	0.07
6300	4.8	20.8	23.6	47.7	0.9	5.9	0.1	20.0	10.0	0.09
8000	4.1	20.8	35.5	74.7	0.9	8.6	0.1	20.0	10.0	0,12
10000	3.4	20.8	55.3	124.6	0.9	13.6	0.1	20.0	10.0	0,20