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REPORT

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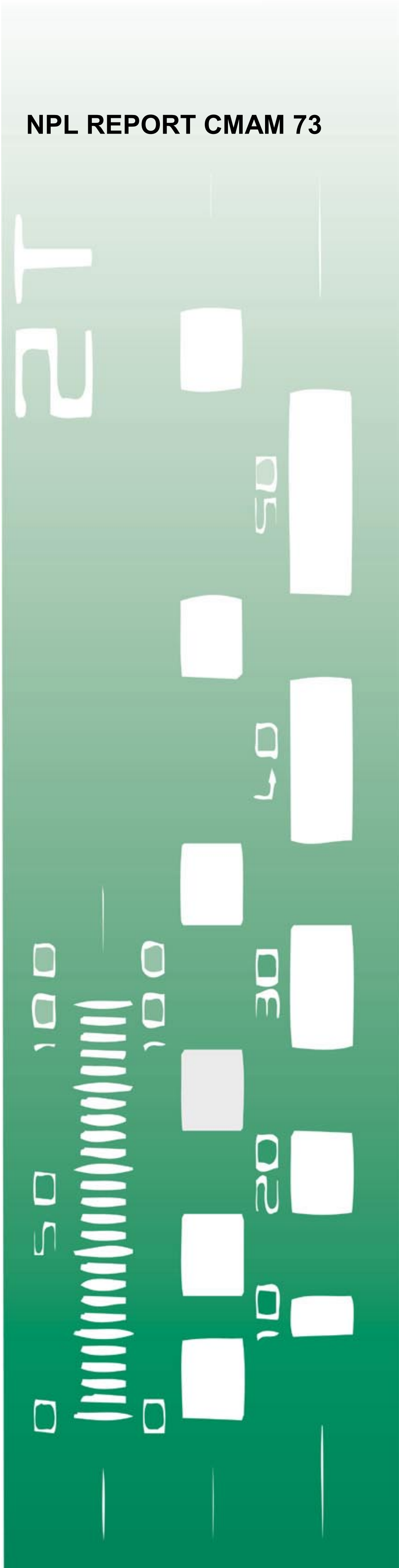

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COMPARISON OF MEASUREMENT UNCERTAINTY BUDGETS FOR CALIBRATION OF SOUND CALIBRATORS: EUROMET PROJECT 576

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ABSTRACT

Sound calibrators are designed to produce a known sound pressure level and their main use is to calibrate acoustical measurement systems. IEC 60942:1997 specifies various performance classes for sound calibrators and gives maximum permitted uncertainties of measurement for determining the output sound pressure level. Thirteen national measurement laboratories participated in a Euromet project to compare the measurement uncertainties of calibration of sound calibrators.

Inspection of the submissions shows that the budgets are numerically correct, and generally follow the recommendations of the relevant ISO Guide. For almost all the participants, the greatest contribution to the measurement uncertainty is the uncertainty in calibration of the reference device. Few omissions of significant sources of uncertainty were identified. Tables of numeric values of uncertainties for calibration of pistonphones are supplied. The reported expanded uncertainties exceed the maximum permitted uncertainties for class 0 calibrators that are specified in IEC 60942:1997 in only one case. The report gives recommendations to the participants for improving clarity and obtaining better mutual agreement.

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2. INTRODUCTION

2.1 CALIBRATION OF SOUND CALIBRATORS BY NATIONAL MEASUREMENT INSTITUTES

Sound calibrators, including pistonphones and multi-frequency calibrators[*], are designed to produce a known sound pressure level at the diaphragm of a measurement microphone that is coupled to the calibrator and their main use is to calibrate acoustical measurement systems. The International Standard IEC 60942:1997 specifies various performance classes for sound calibrators, in which the tolerance of the sound pressure level around a specified level varies with the class[1]. The sound pressure level produced by the calibrator when coupled to the microphone may be determined in two ways: by measuring (usually by an insert voltage technique[2]) the open-circuit output voltage of the microphone where the sensitivity of the microphone is known, or by sequential comparison of the output voltage of the microphone coupled to the calibrator with the output of the same microphone when coupled to a previously calibrated calibrator.

Testing the conformance of a model of sound calibrator or an individual example requires calibration of the output (sound pressure level, fundamental frequency and distortion) of the calibrator, and IEC 60942:1997 gives maximum permitted uncertainties of measurement for all three measured quantities. The sound pressure level generated by the sound calibrator is its most important characteristic because the device is not used as a transfer standard for frequency or distortion. Conformance testing of a class 0 model of sound calibrator requires the use of the insert voltage technique or an equivalent method to determine the sound pressure level, and periodic tests "shall be made using the insert voltage technique or equivalent method, or by using a comparison method".

Most acoustical calibration laboratories, as well as national measurement institutes, undertake calibrations of sound calibrators because of the widespread use of the sound calibrator in making traceable acoustical measurements. In order to provide reliable quantitative information on the comparability of national metrology services, a number of national metrology institutes are party to a Mutual Recognition Arrangement (MRA), drawn up by the International Committee of Weights and Measures (CIPM), for national measurement standards and calibration and measurement certificates issued by national metrology institutes[3]. Appendix C of the MRA provides information on Calibration and Measurement Capabilities of the national metrology institutes and will be updated to include details for Acoustics, Ultrasound and Vibration. The process of gathering these details for laboratories in the Euromet area is well advanced, and many national measurement laboratories have submitted details of their sound calibrator measurements for review. The estimates of measurement uncertainty submitted are likely to vary widely because of differences between the laboratories in measurement methods, equipment and consideration of uncertainty contributions.

The Danish Accreditation Service conducted an interlaboratory comparison of calibrations of sound calibrators in 1998 - 1999 on behalf of the European Cooperation for Accreditation[4]. The European ‘loop’ within the comparison involved the circulation of two sound calibrators to primary and secondary measurement laboratories in nine countries. The sound pressure levels of the calibrators were determined and the participants supplied estimates of the

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[*] This Report uses the terms *calibrator* or *sound calibrator* to cover all the devices covered by IEC 60942:1997, including pistonphones and multi-frequency calibrators.

expanded uncertainty of their measurements. The estimated uncertainties varied widely, even between laboratories that used similar measurement techniques, and the uncertainty quoted by a small proportion of the participants exceeded the maximum permitted uncertainty for periodic tests of the calibrators that is specified in IEC 60942:1997.

2.2 TREATMENT OF MEASUREMENT UNCERTAINTIES

When reporting the result of a measurement of a physical quantity, some quantitative indication of the result has to be given to assess its reliability and to allow comparisons to be made. The ISO Publication *Guide to the expression of uncertainty in measurement* (known as "the GUM") establishes general rules for evaluating and expressing uncertainty in measurement that can be followed at many levels of accuracy and in many fields[5]. IEC 60942:1997 specifies that uncertainties of measurements shall be calculated according to the GUM.

The GUM was written to fulfil the need for an international consensus on the expression of uncertainty in measurement, and is intended to supply full information about how uncertainty statements are created and to provide a basis for the international comparison of measurement results. It defines the concept of uncertainty of measurement and the terms that are to be used to determine the quantity that best expresses the uncertainty of a measurement: the expanded uncertainty. The expanded uncertainty is computed from an assessment of the effects of all the possible sources of uncertainty in a measurement. The GUM groups the uncertainty components into two categories (A and B), both of which are based on probability distributions and are quantified by variances or standard deviations.

The standard uncertainty of a measurement result that is obtained from the values of a number of other quantities is termed combined standard uncertainty and is the estimated standard deviation associated with the result. The GUM specifies that the combined standard uncertainty be calculated as the root sum of squares of the standard uncertainties. This means that uncertainty components whose magnitude is an order smaller than that of the greatest component will have a minor contribution to the combined standard uncertainty.

It is generally held that it is useful to present, with the result of a measurement, an interval about the result that is expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the quantity to be measured. The GUM specifies the expanded uncertainty, calculated by multiplying the combined standard uncertainty by a coverage factor that depends on the coverage probability or level of confidence required of the interval. The most commonly used level of confidence is approximately 95 %, which under most conditions requires a coverage factor of 2 to be used. The GUM provides information and guidance on the evaluation and reporting of standard uncertainty, combined standard uncertainty and expanded uncertainty, and some examples of practical applications.

2.3 EUROMET PROJECT 576

A EUROMET project to compare the measurement uncertainties of calibration of sound calibrators was proposed in 2000. The comparison was intended to assist in obtaining better agreement between laboratories and to enhance mutual confidence in the services provided by the laboratories, and to provide IEC/TC29/WG17 with information for its revision of IEC 60942:1997. At the meeting of EUROMET acoustics contacts in Bratislava in 2000, NPL (GB) volunteered to act as the pilot laboratory and 13 other laboratories volunteered to participate. VNIIFTRI (Russia) were eventually unable to take part. Details of the participants are given in Appendix 1.

The protocol for the project agreed between the participants is reproduced in Appendix 2. The participants were asked to submit to the pilot laboratory a statement of their uncertainty budget(s) for measurement of the sound pressure level of sound calibrators, including the following information:

- purpose of the measurement (calibration, periodic verification, pattern evaluation)
- categorization of the measurement method(s) employed (insert voltage or comparison technique)
- details of the reference device(s) employed (microphone or sound calibrator, model number, calibration status)
- description of the measurement (all relevant details, for example number of replications, limits on environmental conditions and environmental corrections applied)
- sources of measurement uncertainty included in uncertainty budget (description)
- magnitude, distribution, Type (A or B) of individual measurement uncertainty contributions
- method of combining contributions
- final uncertainty quoted

The pilot laboratory proposed to compare each of the above aspects of the budgets and to compare the methods of assessing and combining uncertainty contributions with those outlined in the GUM. The causes of the differences in claimed measurement uncertainties will be identified and, where applicable, the suitability of the measurements for use with IEC 60942:1997 and the latest draft version of IEC 60942:200x[6] will be investigated.

The project was not intended to act as an audit of the services provided by the laboratory, but rather to result in co-operation through sharing of information and to enable the participants to compare their practices in the light of the work of their colleagues.

3. CALIBRATION CAPABILITIES OF EACH PARTICIPANT

This section summarises the reported capabilities for calibration of sound calibrators of the 13 participants. The laboratories are not identified by name in this report, and are numbered in random order. Twelve laboratories use the insert voltage technique and provided the associated uncertainty budgets, and four laboratories provided uncertainty budgets for their calibrations by the comparison method.

3.1 LABORATORY 1

Laboratory 1 provided uncertainty information for calibration of pistonphones by the insert voltage technique using three IEC type LS1P microphones as reference standards. The laboratory also performs pattern evaluations of sound calibrators.

Calibrations are performed at environmental conditions of 101.325 ± 4 kPa, 23 ± 1 °C, and 50 ± 15 % RH. Corrections to the measured sound pressure level (SPL) are applied for the effects of static pressure, air temperature, polarizing voltage and microphone equivalent load volume.

3.2 LABORATORY 2

Laboratory 2 performs calibrations of pistonphones and 1 kHz sound calibrators by the insert voltage technique in its role as the national primary laboratory. Calibrations of these devices are also made by the comparison method at other levels within the organisation, but have not been considered in this report.

The calibrations are performed using three different IEC type LS1P microphones as reference standards. Calibrations are performed at environmental conditions of 101.325 ± 3 kPa, 23 ± 2 °C, and 50 ± 30 % RH. Corrections to the measured SPL are applied for the effects of static pressure, air temperature, relative humidity, polarizing voltage and microphone equivalent load volume.

3.3 LABORATORY 3

Laboratory 3 provided uncertainty budgets for calibrations by the insert voltage technique of pistonphones and sound calibrators with SPLs of 94 dB or more and frequencies in the range 250 Hz – 1000 Hz. An IEC type WS1P reference microphone is normally used, and an LS2P microphone is used for calibrations for mechanical configuration 2.

Three replications of each measurement are made. Calibrations are performed at environmental conditions of 23 ± 3 °C and 40 ± 20 % RH. Corrections to the measured SPL of pistonphones are applied for the effects of static pressure, air temperature, relative humidty and microphone equivalent load volume, while for other sound calibrators the results are valid for the environmental conditions prevailing at the time of measurement, which in practice means over a range of static pressures of 101.325 ± 5 kPa.

3.4 LABORATORY 4

Laboratory 4 performs calibrations of pistonphones and 1 kHz calibrators using either the insert voltage technique or the comparison method. The calibrations by insert voltage technique use two replications with each of two or three IEC type LS1P reference microphones. The calibrations by comparison require at least five measurements, with at least one comparison with each of the two pistonphones that are used as the reference standards.

Corrections to the measured SPL are applied for the effects of static pressure, air temperature and relative humidity.

3.5 LABORATORY 5

Laboratory 5 performs calibration, periodic verification and pattern evaluation of sound calibrators. Where a microphone is used as the reference standard, the measurement may performed by one of:

- the insert voltage technique
- a compensation method in which an additive amplifier is used to cancel out the measured attenuation of the loaded microphone preamplifier
- the use of a special microphone preamplifier which has an input impedance of the order of TΩ

The laboratory also uses a comparison method for calibration of class 1 and class 2 calibrators.

For this project, the laboratory submitted an uncertainty budget for calibration of a class 0 sound calibrator where a calibrated IEC type LS1P microphone was used as the reference standard. At least five replications are performed. Corrections to the measured SPL are applied for the effects of static pressure, air temperature, relative humidity, adiabatic expansion factor, and microphone equivalent load volume.

3.6 LABORATORY 6

Laboratory 6 performs calibration and pattern evaluation of sound calibrators. Calibrations of pistonphones and 1 kHz calibrators are performed by the insert voltage technique, using reference microphones of IEC types LS1P, WS1P, LS2P and WS2P. The laboratory submitted uncertainty budgets to cover all the combinations of reference microphone and device under test.

Five replications are performed in each case. Measurements are performed at environmental conditions of 97 kPa – 105 kPa, 23 ± 1 °C, and 50 ± 15 % RH. Corrections to the measured SPL are applied for the effects of static pressure, ratio of specific heats, and microphone equivalent load volume. A working standard sound calibrator is measured before each calibration in order to ensure that the system is functioning correctly.

3.7 LABORATORY 7

Laboratory 7 calibrates pistonphones and 1 kHz calibrators both by the insert voltage technique (using an LS1P reference microphone) and by comparison with a calibrated pistonphone. At least 10 replications are performed for each calibration.

3.8 LABORATORY 8

Laboratory 8 submitted an uncertainty budget for calibration of sound calibrators by a comparison method over the frequency range 63 Hz – 1000 Hz.

3.9 LABORATORY 9

Laboratory 9 submitted uncertainty budgets for calibrations using the insert voltage technique. Calibrations of calibrators with SPLs in the range 70 dB – 130 dB at frequencies from 31.5 Hz – 12.5 kHz may be performed. The laboratory submitted uncertainty budgets for all these combinations of reference microphone and sound calibrator.

The insert voltage technique uses reference standard microphones of IEC types LS1, LS2 and WS2. Five replications of each measurement are made, and the measurements are interleaved with measurements of a working standard sound calibrator whose calibration history is known. Three replications of a 'check' measurement with a different example of the model of reference microphone are performed to ensure that the measurement system is performing satisfactorily. Measurements are performed at environmental conditions of 101.3 ± 3.6 kPa and 23.0 ± 3.5 °C. Corrections to the measured SPL are applied for the effects of static pressure and polarizing voltage.

3.10 LABORATORY 10

Laboratory 10 provides calibration or periodic verification of pistonphones and other sound calibrators, as the customers require. The measurements are made using the insert voltage technique, using IEC type LS1P or WS2P microphones as the reference standard. The laboratory also offers pattern evaluation testing.

Three replications are performed for each calibration. Calibrations are performed at environmental conditions of 101.3 ± 2.0 kPa, 19 °C - 26 °C, and 25 % - 70 % RH. Corrections to the measured SPL are applied for the effects of static pressure, air temperature and microphone capacitance.

3.11 LABORATORY 11

Laboratory 11 offers calibration and periodic verification of sound calibrators using the insert voltage technique. Measurements of pistonphones and 1 kHz calibrators are made using an IEC type LS1P microphone as the reference standard, while measurements of multi-frequency calibrators are made using an IEC type LS2P microphone as the reference standard. The laboratory submitted uncertainty budgets for all these combinations of reference microphone and device under test.

At least four replications of each measurement are made. Calibrations are performed at environmental conditions where static pressure is at least 90 kPa, air temperature 23 ± 1 °C, and relative humidity 50 ± 10 % RH. Corrections to the measured SPL are applied for the effects of static pressure, air temperature, polarizing voltage and microphone equivalent load volume.

3.12 LABORATORY 12

Laboratory 12 offers two accredited calibration services for sound calibrators, one using the insert voltage technique and one using the comparison method. Calibrations of calibrators with SPLs in the range 70 dB – 130 dB at frequencies from 31.5 Hz – 12.5 kHz may be performed. The laboratory submitted uncertainty budgets for all these combinations of reference microphone and device under test.

The insert voltage technique uses reference standard microphones of IEC types LS1, WS1, LS2 and WS2. Five replications of each measurement are made, and the measurements are interleaved with measurements of a working standard sound calibrator whose calibration history is known. Three replications of a 'check' measurement with a different example of the model of reference microphone are performed to ensure that the measurement system is performing satisfactorily. Measurements are performed at environmental conditions of 101.3 ± 3.6 kPa and 20.0 ± 0.5 °C. Corrections to the measured SPL are applied for the effects of static pressure and polarizing voltage.

The comparison method uses a calibrated pistonphone or 1 kHz calibrator as the reference standard. Only models that are closely equivalent to the reference standards are currently calibrated, so that corrections are not required. Measurements are performed at environmental conditions of 99.5 kPa – 103.0 kPa and 19.5 °C – 23.5 °C, and at least three replications are made. By comparing the output of a pistonphone coupled to an IEC type WS3 microphone when fitted with its usual grid and with a modified WS2 grid, the pistonphone can also be calibrated in its WS3 configuration.

3.13 LABORATORY 13

Laboratory 13 performs calibrations of sound calibrators using the insert voltage technique. Calibrations of calibrators with SPLs in the range 70 dB – 130 dB at frequencies from 30 Hz – 16 kHz may be performed using reference microphones of IEC types LS1, LS2, WS1 and WS2. The laboratory submitted uncertainty data for frequencies in the range 50 Hz – 10 kHz for LS1 and WS1 microphones and for 50 Hz – 16 kHz for LS2 and WS2 microphones.

Five replications of the measurement are carried out in each case. Calibrations are performed at environmental conditions of 101.325 ± 3 kPa and 23 ± 3 °C. Corrections to the measured SPL are applied for the effects of static pressure and air temperature.

4. COMPONENTS OF UNCERTAINTY

This section describes the reported components of uncertainty for each aspect of the measurements performed. The discussion is mostly based on the reported uncertainty budgets for pistonphone devices coupled to IEC type LS1P microphones, as this is the commonest configuration in which the national measurement laboratories calibrate, but other measurements are considered where there may be different magnitudes and different sources of uncertainty. Unless otherwise stated, the magnitudes of the uncertainty contributions are expressed as standard uncertainties (equal to standard deviations).

The discussion is divided by the three major elements of the calibration. For each element, there is a summary table in Appendix 3 that includes:

- Numeric values of standard uncertainties for pistonphone calibration
- A '✓' (tick) where the source of uncertainty has been considered but is included elsewhere in the analysis
- A '-' (dash) where the source of uncertainty has been considered but either assumed to be negligibly small or not reported
- A '×' (cross) where the source of uncertainty has not been considered.

4.1 INSERT VOLTAGE TECHNIQUE

4.1.1 Reference device

For the insert voltage (or similar) techniques, the reference device is a measurement microphone whose open-circuit sensitivity (or sensitivity level) is known. The associated uncertainties are discussed below and the standard uncertainties for measurements with IEC type LS1P microphone are listed in Table 2.

Calibration of reference microphone

The uncertainty in the calibration of the measurement microphone must be considered, and all the laboratories include this contribution in their budgets. The participants generally use IEC type LS1P and LS2P microphones as the reference standards, and the microphones are calibrated by the pressure reciprocity method. Laboratory 3 uses IEC type WS1P and LS2P reference microphones. For all participants except laboratory 4 and laboratory 13, this uncertainty is the greatest contribution to the budgets. The standard uncertainties range from 0.01 dB (laboratory 13) to 0.046 dB (laboratory 10).

Drift in sensitivity level between calibrations

The sensitivity levels of the microphones will be seen to drift by a small amount between calibrations, but only six participants considered its effect. Laboratory 1 performs measurements with three different reference microphones in order to detect drift in any of the microphones. Five participants include a term for this drift: laboratory 3 gives this contribution a triangular distribution, while laboratories 2, 4, 11 and 13 assess it as a rectangular distribution: the standard uncertainties are 0.008 dB (for intervals between calibrations of the reference standard of six months), 0.003 dB (one year), 0.012 dB (one or two years), 0.005 dB (three months) and 0.017 dB (two years) respectively.

Difference in sensitivity level between calibration frequencies

The sensitivity level of the reference microphone may differ between the frequency at which it is calibrated and the frequency of the calibrator under test. Only four participants considered its effect, making it the most widespread omission of all the uncertainty components. Laboratories 4, 5, and 13 reported that the associated uncertainty contribution for this difference is sufficiently small to be considered negligible. Laboratory 12 considers the contribution to be negligible at low frequencies but increased at frequencies above 1 kHz to a maximum of 0.0462 dB when calibrating using an IEC type WS2F microphone at 8 kHz.

Influence of environmental conditions (static pressure, air temperature, relative humidity)
The sensitivity of the reference microphone varies with the environmental conditions of static pressure, air temperature and relative humidity. While the influence of environmental conditions on sensitivity of Laboratory Standard microphones are fairly well understood[7], the performance of Working Standard microphones is less well known. The majority of laboratories perform the measurements in enclosures where the air temperature is maintained within ± 3 ºC or less of the reference temperature (which is 23 ºC for all except laboratory 12, which maintains 20 ºC); some are also able to control the humidity, while pressure-controlled areas are not generally used for calibrations of sound calibrators.

All the participants that use IEC type LS1P microphones correct the sensitivity level for the influence of static pressure using data from IEC 61094-2, published information[7] or the manufacturer of the microphones. Laboratories 5 and 6 do not include an uncertainty term for error in the correction, while the other participants calculate uncertainty contributions either according to the pressure at the time of the measurement or as a ‘blanket’ term to cover the full range of conditions encountered. The contributions are calculated from a proportion (usually about 10 %) of the pressure coefficient and from the range of static pressures within which measurements are performed. As laboratory 3 uses a WS1P reference microphone over a wide range of static pressures, this uncertainty provides its greatest contribution to the budget other than calibration of the reference microphone.

All participants except laboratories 3, 6, 9 and 12 make corrections for influence of air temperature on microphone sensitivity, and all except laboratories 5 and 6 include an uncertainty term for this influence. Where corrections are made the standard uncertainty is typically about 0.001 dB, but where corrections are not made the standard uncertainty increases to 0.0042 dB for LS1P. The uncertainty reported by laboratory 12 for this effect is its greatest contribution to the budget other than calibration of the reference microphone, because the reference microphone is calibrated at 23 ºC while the calibrations of calibrators are performed at 20 ºC. Where Working Standard microphone types (whose performance is not as well known) are used the uncertainty can be much greater, up to 0.0387 dB reported for IEC type WS2P microphones at 12.5 kHz by laboratory 12.

The influence of relative humidity on the sensitivity of LS1P microphones is so small that only laboratories 2, 4 and 7 estimate an associated uncertainty, which is in each case no greater than 10^{-4} dB.

Polarizing voltage
Where the polarizing voltage applied to the microphone strays from the nominal value, an error in the sensitivity level of the microphone is introduced. The participants measure polarizing voltage at the microphone power supply continuously or at the preamplifier terminals between measurements, and adjust the polarizing voltage supply if it strays outside a defined limit. Laboratories 9, 11 and 12 make a correction for the error, and laboratories 1, 2, 3, 7, 9, 11, 12 and 13 evaluate the uncertainty associated with the error. The uncertainty varies from 0.0002 dB (where corrections are made) to about 0.01 dB.

Capacitance of microphone cartridge
A term for error in the insert voltage measurement for the influence of the capacitance of the

microphone cartridge (where the magnitude of cartridge capacitance of microphone and preamplifier input capacitance are nearly equal) is included by laboratory 10 only. The contribution is negligible for LS1P microphones but there is a typical standard uncertainty of 0.0005 dB for the model of WS2P microphone used by the laboratory.

Effective load volume of microphone

The sound pressure level of the calibrator is measured at the diaphragm of a microphone that is coupled to the calibrator. Therefore, the measured sound pressure level is dependent on the geometry of the microphone and the susceptibility of the calibrator to changes in the effective load volume of the microphone. For convenience, the influence of these effects is discussed in this section.

The difference in the level of a pistonphone coupled to microphones of different effective load volumes is well known. Most of the participants present results for the nominal effective load volume of the pistonphone: laboratories 1, 3, 5, 6 and 11 make a correction for the difference between the actual effective load volume of the microphone and the nominal value for the pistonphone, and all except laboratories 9, 10 and 12 include an uncertainty term for the effect, which varied between 0.0011 dB and 0.0105 dB.

Laboratories 5 and 6 measure the actual effective load volume of at least their LS1P microphones prior to calibration of pistonphones. Laboratories 1 and 4 report the mean result of measurements with three and two LS1P microphones respectively. Laboratories 9 and 12 report the SPL when coupled to each model of microphone to be used by the customer, and therefore make a measurement using a second calibrated microphone of the same model to check that the calibration is not unduly affected by using another microphone of slightly different load volume. These two participants include an uncertainty contribution of 0.0035 dB for influence of differing load volumes of the individual microphones.

4.1.2 Device under test

The devices that are calibrated by the participants are generally pistonphones and 1 kHz calibrators whose characteristics are well known. Laboratories 9, 11 and 12 also provided uncertainty budgets for the calibration of multi-frequency calibrators. All these devices are susceptible to changes in environmental conditions. The associated uncertainties are discussed below and the standard uncertainties for measurements of pistonphones are listed in Table 3.

Influence of environmental conditions (static pressure, air temperature, relative humidity)

The influence of any deviation from the reference static pressure on the sound pressure level of pistonphone devices is well established, and all participants apply a correction to the measured sound pressure level for this effect. Laboratories 1, 3, 4, 7, 9, 10, 12 and 13 also allow an uncertainty (of up to 0.0088 dB, depending on range of static pressures) for any error in the applied correction, while laboratories 2, 5, 6 and 11 estimate only the uncertainty (0.001 dB or less) arising from estimates of error in the reading of the actual static pressure.

Modern models of electronic sound calibrator generally have very small sensitivities to changes in static pressure, while some models may show widely varying changes in sound pressure level. Of the participants who submitted uncertainty budgets for calibration of calibrators other than pistonphones, laboratories 2, 7, 9, 10 and 12 include an uncertainty term, which varies from 0.0001 dB to 0.0173 dB depending on the range of static pressures and manufacturers' information about, or laboratories' experience of, sensitivity to static pressure of the calibrator.

Many of the participants perform their calibrations in rooms that provide control of temperature to within ± 1 °C of the reference temperature of 23 °C, and so the associated uncertainties are generally small or negligible. Laboratory 12 performs the measurements at 20 °C, as a relic of the reference temperature of IEC 60942:1988. Although the response of pistonphone devices to air temperature is well established, only laboratories 2, 3 and 4 actually correct the measurement results to the reference temperature. Laboratories 1, 2, 4, 7 and 10 include uncertainty contributions of between 0.0001 dB and 0.0012 dB depending on temperature control and whether a correction is made, while laboratories 3, 5, 9 and 12 treat the uncertainty contribution as negligible.

Relative humidity may also be controlled, or the range within which measurements are performed may be limited. Laboratories 2, 3, 4, 5 and 6 perform a correction for the influence of humidity. Laboratories 1, 4, 6, 7 and 11 calculate an uncertainty contribution for the influence of humidity on the reference device that varies between 0.0001 dB and 0.0017 dB, while laboratories 2, 3, 5, 9 and 12 find such a contribution to be negligible.

Effective volume of sound calibrator

Laboratory 11 alone estimates an uncertainty term for the influence of any difference in the effective volume of pistonphones based on likely tolerances in construction. The standard uncertainty is estimated at 0.0003 dB.

4.1.3 Measurement method

The associated uncertainties are discussed below and the standard uncertainties for measurements of pistonphones with IEC type LS1P microphone are listed in Table 4.

Insert voltage measurement

Assessment and reporting of uncertainties in the measurement of insert voltage vary widely between the participants, because of the different implementations of the insert voltage technique and different measurement equipment. Some laboratories report a single contribution (shown in the top row of Table 4), while others identify components arising from the method itself and the calibration of individual items of equipment (listed individually in Table 4).

Laboratories 1, 4, 6 and 10 report a single uncertainty contribution for the measurement of insert voltage. The magnitude of this contribution varies from 0.0035 dB to 0.0086 dB, except for laboratory 4 where the magnitude is 0.0371 dB. This contribution, which is reported in the form of a standard deviation of the six replications, is the greatest for laboratory 4 and is significantly greater than the uncertainty in calibration of the reference microphone reported by laboratory 4.

The other participants provided details of individual contributions, with root-sum-of-squares subtotals of these components varying from 0.0011 dB to 0.0095 dB. Laboratory 2 includes uncertainty contributions for voltmeter AC calibration, and Type A and Type B components for measurement of microphone output voltage and measurement of insert voltage gain. Laboratory 3 includes the error in the calibration of the voltmeter reading the insert voltage and the error in setting the insert voltage. Laboratory 5 includes the error in the voltmeter reading of the insert voltage and considers all other contributions to be negligibly small. Laboratory 7 uses an expanded-scale meter and includes uncertainty contributions for the uncertainty in calibration of the voltmeter, the maximum error of the expanded-scale meter at full-scale deflection, and the reading error of the expanded meter.

Laboratories 9, 11, 12 and 13 provided details of the insert voltage apparatus: in each case, they use a function generator to generate a measured sinusoidal signal, which passes through a calibrated attenuator into the insert line of an insert voltage microphone preamplifier. Laboratories 9 and 12 include uncertainty contributions for the calibration of the voltmeter and attenuator, the errors in the readings of the two instruments, and the error in setting the insert voltage that arises from the resolution (0.01 dB) of the attenuator. Laboratory 11 includes the calibration of the voltmeter and considers all other contributions to be negligibly small. Laboratory 13 includes contributions for the calibration of the voltmeter and attenuator and the differential linearity of the voltmeter when setting the insert voltage, and assumes that the error in the voltage and attenuation are negligible.

Repeatability of SPL
Every laboratory performs between three and ten replications of the measurements in order to establish the repeatability of the test. Laboratories 1, 2 and 4 perform the calibration with three examples of the microphone model and laboratories 9 and 12 check the calibration results by performing a measurement with another example of the same model. Laboratories 2, 4 and 10 do not include an uncertainty term to account for the distribution of the replicated results, while the other participants calculate a Type A uncertainty contribution, based on either the actual results or previous tests of the repeatability, whose magnitude varies from 0.000 dB to 0.01 dB.

Resolution of reported SPL
All except laboratories 1, 5 and 10 report the sound pressure level to two decimal places of decibels and therefore include an uncertainty term of magnitude 0.0029 dB for the error introduced by the rounding.

4.2 COMPARISON METHOD

4.2.1 Reference device

For the comparison method, the reference device is a previously calibrated sound calibrator. Laboratories 4, 7 and 8 use a calibrated pistonphone, while laboratory 12 uses a pistonphone or 1 kHz calibrator to match as closely as possible the calibrator under test. The associated uncertainties are discussed below and the uncertainties for calibration of pistonphones coupled to IEC type LS1P microphones are listed in Table 5.

Calibration of reference calibrator
Where the reference calibrator is a pistonphone and the microphone coupled to it is of IEC type LS1P, the participants reported standard uncertainties in the range 0.025 dB to 0.035 dB.

Drift in SPL of reference calibrator
The SPL of the reference calibrator may drift between calibrations. Three participants include a term for this drift: laboratories 4, 8 and 12 reported standard uncertainties of 0.029 dB (for an interval between calibrations of the reference standard of one or two years), 0.006 dB (no interval stated) and 0.017 dB (four months) respectively.

Error due to harmonic distortion of reference calibrator
In the comparison measurements, differences in the distortions of the outputs of the reference calibrator and the calibrator under test result in errors in the measured SPL, if the appropriate correction is not known. Laboratories 4 and 7 included uncertainty contributions for this error of 0.006 dB and 0.0029 dB respectively. Laboratory 12 estimates this contribution to be negligibly small.

4.2.2 Device under test

The devices that are calibrated by the participants are pistonphones and 1 kHz calibrators whose characteristics are well known. The associated uncertainties are discussed below and the standard uncertainties for measurements of pistonphones are listed in Table 6.

Influence of environmental conditions (static pressure, air temperature, relative humidity)
The influence of any deviation from reference environmental conditions on the sound pressure level is well established for most models of sound calibrator. In a comparison calibration, the effect of such influences is likely to be small where the reference and the device under test are of a similar model. Therefore, only laboratory 8 includes a contribution, of 0.006 dB, for calibration of all calibrators against the reference pistonphone.

4.2.3 Measurement method

The associated uncertainties are discussed below and the standard uncertainties for measurements of pistonphones coupled to IEC type LS1P microphones are listed in Table 7.

Comparison measurements and equipment
The reported uncertainties vary because of the different implementations of the comparison method and different measurement equipment. Where the device under test and the reference device are of similar fundamental frequency and SPL, uncertainties due to frequency response and level linearity of the measurement systems are usually negligible. For calibration of a pistonphone, the root-sum-of-squares subtotals of components of this type vary from 0.0068 dB to 0.0147 dB, while the equivalent subtotal for calibration of calibrators at other frequencies increases to a maximum of 0.0611 dB.

Laboratory 12 reports the SPL when coupled to each model of microphone to be used by the customer, and includes an uncertainty contribution of 0.0035 dB for the influence of differing load volumes of the individual microphones.

Repeatability of SPL
All four laboratories perform between three and ten replications of the measurements in order to establish the repeatability of the test. Laboratory 4 includes measurements with more than one reference calibrator. All four calculate a Type A uncertainty contribution, based on either the actual results or previous tests of the repeatability, whose magnitude varies from 0.001 dB to 0.01 dB.

Resolution of reported SPL
Laboratories 4 and 12 report the SPL to two decimal places of decibels and therefore include an uncertainty term for the error introduced by the rounding of magnitude 0.0029 dB. Laboratories 7 and 8 do not report any rounding of the result or associated uncertainty.

5. EXPANDED UNCERTAINTIES

5.1 CALCULATION

The participants generally follow the recommendations of the GUM. The arithmetic calculations for a small selection of the budgets were checked and no errors were found. Some participants use a form of presentation of the calculation of the expanded uncertainty that predates the GUM. Laboratory 5 evaluates the Type B components as percentages before converting to a Type B subtotal in decibels. Presentation of the results varies slightly between the participants, with some giving full derivations of the uncertainty contributions and others supplying a simple table to show the calculation of the expanded uncertainty.

For the majority of the participants, a coverage factor of k = 2 suffices to provide an expanded uncertainty with a level of confidence of about 95%. In the budget provided by laboratory 4, for calibrations by the insert voltage technique, the standard deviation of replicated measurements of insert voltage is the largest component of uncertainty, and a coverage factor of k = 2.37 is reported in order to maintain a level of confidence of about 95%. Laboratory 11 also uses k > 2 for sound calibrators other than pistonphones.

The reported expanded uncertainties for calibration of pistonphones are listed in Table 1. Most laboratories round the expanded uncertainty in the SPL up to the next 0.01 dB, while laboratory 3 rounds up the results for 1 kHz calibrators to the next 0.02 dB, and laboratory 1 rounds down from 0.0414 dB to 0.04 dB. For laboratory 4, the expanded uncertainty for calibration by comparison is less than that for the insert voltage technique because the reference pistonphones used for the comparison calibration are calibrated by another laboratory.

Table 1: Expanded uncertainties for calibration of pistonphone by each participant

	Reported expanded uncertainty (dB)	
Laboratory	Insert voltage technique	Comparison method
1	0.04	-
2	0.04	-
3	0.08	-
4	0.10	0.09
5	0.07	-
6	0.04	-
7	0.07	0.08
8	-	0.14
9	0.05	-
10	0.10	-
11	0.06	-
12	0.05	0.07
13	0.05	-

5.2 COMPARISON WITH INTERNATIONAL STANDARD

The maximum permitted uncertainty of IEC 60942:1997 for determination of the sound pressure level of a class 0 sound calibrator is 0.07 dB for pattern evaluation and 0.10 dB for periodic verification. All the participants that perform periodic verifications, and all except laboratory 10 that perform pattern evaluation, reported an expanded uncertainty that meets the requirement of IEC 60942:1997 for the class 0 sound calibrator.

IEC 60942:200x (currently at the stage of CDV) gives a maximum permitted uncertainty for a class LS sound calibrator at reference environmental conditions of 0.10 dB for both pattern evaluation and periodic verification. All the participants that perform periodic verifications or pattern evaluations report expanded uncertainties that meet the requirement of IEC 60942:200x for the class LS sound calibrator.

6. CONCLUSIONS

Inspection of the uncertainty budgets submitted by the 13 participating laboratories shows that the budgets are numerically correct, and generally follow the recommendations of the GUM. Laboratory 5 performs the majority of its calculations in per cent, while the other participants calculate their budgets in decibels. Although the various participants supplied different degrees of detail, no obvious errors were seen. However, it was impossible to check the calculation of individual uncertainty contributions.

In order to compare the reports of the various participants, this report concentrates on the calibration of pistonphones coupled to IEC type LS1P microphones. The greatest contribution to the expanded uncertainty is almost always the uncertainty in calibration of the reference device, which demonstrates the importance of maintaining and improving calibration facilities for measurement microphones. The differences in expanded uncertainties reported by the participants can be attributed partly to the differing uncertainties in calibration for the reference devices. Differences also arise from the environmental conditions at which the measurements are performed, and whether corrections are made to reduce the uncertainties associated with the effects of environmental conditions. Some other significant contributions that are particular to individual laboratories were identified.

Few omissions of significant sources of uncertainty were identified. The two most widespread omissions were contributions for the drift in sensitivity level of reference microphones between calibrations and for difference in the sensitivity level of a reference microphone between calibration frequencies.

It is recommended that each participant review the tables in Appendix 3 of this report in order to determine which sources of uncertainty are not included in their budgets, evaluate the contribution that may arise from each source and consider its inclusion if found to be significant. Sub-clause 7.1.4 of the GUM provides helpful assistance. The GUM may also be studied for examples of presentation of uncertainty budgets in a consistent format.

When the expanded uncertainties were compared with the maximum permitted uncertainties that are specified in IEC 60942:1997, the only laboratory failing to meet the requirements for pistonphones (i.e. class 0 calibrators) was laboratory 10 for pattern evaluation. All the participants that perform periodic verifications or pattern evaluations reported an expanded uncertainty that meets the requirement of IEC 60942:200x for the class LS sound calibrator.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

[1] International Electrotechnical Commission, IEC 60942:1997, Electroacoustics - Sound calibrators
[2] International Electrotechnical Commission, IEC 61094-2:1992, Measurement microphones part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique
[3] Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes, CIPM, Paris, 14 October 1999
[4] RASMUSSEN, K. Measurement of sound calibrators. *EA interlaboratory comparison Ac1*, DANAK/DPLA, December 1999.
[5] ISO Publication: 1995, ISBN 92-67-10188-9. Guide to the expression of uncertainty in measurement
[6] International Electrotechnical Commission, IEC 60942:200x, Electroacoustics – Sound calibrators (at present at the stage of CDV)
[7] RASMUSSEN, K. The static pressure and temperature coefficients of laboratory standard microphones. *Metrologia*, 1999, **36**, 265-273.

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APPENDIX 2. PROTOCOL FOR PROJECT

Background

IEC 60942:1997 specifies maximum permissible uncertainties of measurement for sound pressure level of sound calibrators when performing periodic or pattern evaluation tests. The maximum permissible uncertainties vary with the performance class for which conformance is claimed by the manufacturer. The standard specifies that measurement uncertainties shall be calculated according to the ISO Publication "Guide to the expression of uncertainty in measurement" (known as "the GUM"), yet there are many laboratories in which the requirements of the GUM are not well-known, or not yet enacted.

An EA interlaboratory comparison Ac1 'Measurement of sound calibrators' was conducted by DANAK (in cooperation with DPLA as the reference laboratory) from January 1998 to May 1999. The final report was published in December 1999. The European 'loop' within the comparison involved the circulation of two sound calibrators (one of which was a pistonphone) to measurement laboratories in 9 countries.

The sound pressure levels of the calibrators were determined by using a calibrated microphone or by comparison with a calibrated reference calibrator. The participants supplied estimates of the expanded uncertainty of their measurements. The estimated uncertainties varied widely, even between laboratories that used similar measurement techniques, and the uncertainty quoted by some of the participants exceeded the maximum permitted uncertainty for periodic tests of the calibrators specified in IEC 60942:1997.

Results of measurements of frequency and the associated estimated uncertainties were found to be satisfactory in all cases. It was found that the distortion results obtained varied because of different definitions and different measurement methods employed by the participants considerably, although the estimated uncertainties were satisfactory. However, sound calibrators are not intended to be used as transfer standards for frequency and distortion: the calibrator's sound pressure level is its most important characteristic.

The process of gathering Calibration and Measurement Capabilities for Acoustics, Ultrasound and Vibration for laboratories in the Euromet area is well advanced. In the course of this exercise, many national measurement laboratories have submitted details of their sound calibrator measurements for inclusion. The estimates of measurement uncertainty submitted vary widely, with some of the estimates being subject to review.

Comparison of the measurement uncertainty budgets of the national measurement laboratories would be instructive in obtaining better agreement between laboratories and enhance mutual confidence in the services provided by the laboratories. The results may be in time to inform drafts of the next edition of IEC 60942.

NB 'sound calibrator' here includes devices with pistonphone or electronic mechanisms, and the sound pressure level functions of multifunction acoustical calibrators.

Requirements of participants

The method requires no circulation of sound calibrators or measurements by the participants. The only requirement of the participants is that they submit to the pilot laboratory a full statement of their uncertainty budget(s) for measurement of the sound pressure level of sound calibrators. It is expected that nearly all laboratories will have this information readily available, and no great commitment of resources will be required. Therefore it is hoped that a large number of laboratories will be able to participate.

The following information is required to be submitted by the participants:

purpose of the measurement (calibration, periodic verification, pattern evaluation)
categorization of the measurement method(s) employed (insert-voltage or comparison technique)
details of the reference device(s) employed (microphone or sound calibrator, model number, calibration status)
description of the measurement (all relevant details, for example number of replications, limits on environmental conditions and environmental corrections applied)
sources of measurement uncertainty included in uncertainty budget (description)
magnitude, distribution, Type (A or B) of individual measurement uncertainty contributions
method of combining contributions
final uncertainty quoted

The participants may already have uncertainty budgets in electronic formats (such as spreadsheets), and submission of information in such formats is preferred.

Comparison of submitted information

The pilot laboratory will compare each of the above aspects of the budgets. The methods of assessing and combining uncertainty contributions will be compared with those outlined in the GUM. The causes of the differences in claimed measurement uncertainties will be identified and, where applicable, the suitability of the measurements for use with IEC 60942:1997 and the latest draft version of IEC 60942:200x will be investigated.

The project is not intended to act as an audit of the services provided by the laboratory; rather, it is intended to provide a forum for shared information and to assist the participants in comparing their practices in the light of the work of their colleagues.

NPL will volunteer to act as the pilot laboratory for this project.

APPENDIX 3. COMPARISON OF UNCERTAINTY CONTRIBUTIONS

This Appendix provides tabular comparisons of the standard uncertainties for each source of uncertainty reported by the participants. The contributions are for measurement of a pistonphone coupled to an IEC type LS1P microphone, except for laboratory 3, which uses IEC type WS1P reference microphones for measurements by the insert voltage technique.

The tables for the two measurement methods are divided by the three major elements of the calibration. The entries in the tables are:

- Numeric values of standard uncertainties
- A '✓' (tick) where the source of uncertainty has been considered but is included elsewhere in the analysis
- A '-' (dash) where the source of uncertainty has been considered but either assumed to be negligibly small or not reported
- A '×' (cross) where the source of uncertainty has not been considered.

A3.1. INSERT VOLTAGE TECHNIQUE

Table 2: Standard uncertainties (dB) for each laboratory arising from reference microphone

Source of uncertainty	1	2	3	4	5	6	7	9	10	11	12	13
Calibration of reference microphone	0.0173	0.013	0.025	0.015	0.03	0.015	0.03	0.015	0.046	0.025	0.015	0.01
Drift in sensitivity level between calibrations	-	0.003	0.008	0.012	-	×	×	×	×	0.005	×	0.017
Difference in sensitivity level between calibration frequencies	×	×	×	-	-	×	×	×	×	×	-	-
Influence of static pressure	0.0017	0.0012	0.016	0.0009	-	×	0.0009	0.0017	0.0019	0.0011	0.0017	0.0042
Influence of air temperature	0.0006	0.001	0.006	0.0009	-	×	0.0003	0.0098	0.0013	0.001	0.0098	0.0042
Influence of relative humidity	×	-	-	-	-	×	-	-	×	×	-	×
Polarising voltage	0.0029	0.0015	0.0104	×	-	×	0.0023	0.0004	×	0.0001	0.0004	0.004
Capacitance of microphone cartridge	×	×	×	×	×	×	×	×	-	×	×	×
Effective load volume of microphone	0.0029	0.0015	0.008	0.0026	0.0023	0.0011	0.0029	0.0035	×	0.0105	0.0035	-

Table 3: Standard uncertainties (dB) for each laboratory arising from calibrator under test

Source of uncertainty	1	2	3	4	5	6	7	9	10	11	12	13
Influence of static pressure	0.0058	0.0005	0.008	0.005	0.0005	0.0013	0.0088	0.0058	0.0043	0.001	0.0058	0.005
Influence of air temperature	0.0012	0.0003	-	0.0001	-	×	0.0003	-	0.0012	×	-	×
Influence of relative humidity	0.0012	-	-	0.0001	-	0.001	0.0012	-	×	0.0017	-	×
Effective volume of sound calibrator	×	×	×	×	×	×	×	×	0.0003	×	×	×

Table 4: Standard uncertainties (dB) for each laboratory arising from measurement method

Source of uncertainty	1	2	3	4	5	6	7	9	10	11	12	13
Insert voltage measurement (all contributions)	0.0086	✓	✓	0.0371	✓	0.0044	✓	✓	0.0035	✓	✓	✓
Calibration of voltmeter	✓	0.005	✓	✓	-	✓	0.0007	0.0022	✓	0.0011	0.0022	0.002
Error of voltmeter reading	✓	0.006	0.007	✓	0.0025	✓	0.0087	0.0015	✓	-	0.0015	-
Calibration of attenuator	✓	-	-	✓	-	✓	✓	0.0050	✓	-	0.0050	0.006
Error of attenuator reading	✓	-	-	✓	-	✓	✓	0.0012	✓	-	0.0012	-
Error in setting insert voltage	✓	0.0054	0.002	✓	-	✓	0.0029	0.0029	✓	-	0.0029	0.005
Repeatability of SPL	✓	×	0.005	×	-	0.01	0.005	0.0045	×	0.01	0.0045	-
Resolution of reported SPL	×	0.0029	0.0029	0.0029	×	0.0029	0.0029	0.0029	×	0.0029	0.0029	0.0029

A3.2. COMPARISON METHOD

Table 5: Standard uncertainties (dB) for each laboratory arising from reference calibrator

Source of uncertainty	4	7	8	12
Calibration of reference calibrator	0.027	0.035	0.031	0.025
Drift in SPL of reference calibrator	0.029	×	0.006	0.0173
Error due to harmonic distortion of reference calibrator	0.006	0.0029	×	-

Table 6: Standard uncertainties (dB) for each laboratory arising from calibrator under test

Source of uncertainty	4	7	8	12
Influence of static pressure	-	×	0.006	-
Influence of temperature	-	×	×	-
Influence of relative humidity	-	×	×	-

Table 7: Standard uncertainties (dB) for each laboratory arising from measurement method

Source of uncertainty	4	7	8	12
Meter maximum error at FSD	0.012	0.0087	0.005	✓
Error of meter reading	0.006	0.0058	0.003	✓
Measuring amplifier frequency response	-	✓	0.0050	-
Transducer assembly loading volume maximum error	-	-	0.006	-
Transducer assembly frequency response	-	-	0.006	-
Error due to drift in measurement system	0.006	0.0058	0.06	✓
Level linearity of measuring amplifier	-	✓	✓	0.0058
Uncertainty of microphone volume correction difference	-	-	-	0.0035
Repeatability of SPL	0.001	0.01	0.006	0.0046
Resolution of reported SPL	0.0029	×	×	0.0029