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Uncertainties associated with the use of a sound level meter

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ABSTRACT

During the years from 1997 to 2001 the National Physical Laboratory provided a sound level meter verification service, where measurements of various parameters regarding the performance of a sound level meter were compared to the requirements of BS 7580. These measurements were carried out on a wide range of sound level meter types and the results are suitable for use in an assessment of a practical value of measurement uncertainties associated with the use of a sound level meter.

A value for measurement uncertainty associated with A-weighted noise emission levels, based on these verification data, together with contributions based on practical consideration of the operation and calibration of a sound level meter is proposed. This value is directly related to the practical use of sound level meters and should be suitable for inclusion in uncertainty budgets concerned with sound power level determination. In addition, the following simple guidelines regarding the practical use of a sound level meter are proposed.

To reduce the magnitude of measurement uncertainty resulting from the operation of a sound level meter, effort should be concentrated on reducing contributions associated with the time weighting and with indicator range changing. It is recommended that the indicator range used for measurements is the same as that used for the sound calibrator, and the slow time weighting is used. To reduce the magnitude of measurement uncertainty resulting from the use of a sound level meter, effort should be concentrated on reducing the effect of the observer. It is recommended that the indication on the sound level meter is observed remotely via an ac output (a common feature on class 1 meters).

The actual estimated value of measurement uncertainty assuming a slow time weighting is 0.39 dB. This value is reduced to 0.33 dB if there is no range change and there is no observer present. The reported combined total standard uncertainty for measurements carried out using the "slow" time weighting (with or without an observer and with or without a range change) is 0.4 dB.

For the majority of ISO sound power standards the frequency range of interest is specified as covering one-third octave bands centre frequencies from 100 Hz to 10 kHz. In this case the reported final total combined uncertainty associated with band limited noise emission is the same as the A-weighted value.

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1. INTRODUCTION

When reporting the result of a measurement of a physical quantity, some quantitative indication of the quality of the result must be given. Without such an indication, measurement results cannot be compared either amongst themselves or with values given in a specification or standard. The generally accepted method is to evaluate and express its uncertainty.

A primary need for values of uncertainty is to demonstrate compliance with noise emission level declaration as required for numerous regulatory purposes, for example the European Directive 2000/14/EC(1) "*on the approximation of the laws of the Member States relating to the noise emission in the environment by equipment for use outdoors*". This Directive requires that machinery is labelled with a guaranteed A-weighted sound power level. Here, a guaranteed sound power level means a single-number noise emission value including the uncertainties due to production variation and measurement procedures.

Information on measurement reproducibility given in current International Standards relating to the determination of sound power level(2 to 8) can be helpful towards the derivation of measurement uncertainties, but it is incomplete. In particular, it does not give an analysis of the various components of measurement uncertainty and their magnitudes. The accepted format for expression of uncertainties generally associated with methods of measurement is that given in the *Guide to the Expression of Uncertainties in Measurement*(9). This format incorporates an uncertainty budget, in which all the various sources of uncertainty are identified and quantified, from which the combined total uncertainty can be obtained. The data necessary to enable such a format to be adopted in the case of the International Standards relating to sound power are not currently available. However, an indication, taken from ISO 3745:2003(6), is given below of the sources of uncertainty that are thought to be associated with the methods and equipment described in the standards. The general approach to calculation of uncertainties appropriate to International Standards, conforming to the Guide, is illustrated below for information.

The general expression for the calculation of the sound power level, L_W, is given by the following equation:

$$L_W = \overline{L_p} + 10\lg\left(\frac{S}{S_0}\right) + \delta_{slm} + \delta_{rep} + \delta_{boun} + \delta_{mic} + \delta_{met} + \delta_{angle} + \delta_{imp} \quad \text{dB} \qquad (1)$$

where,

$\overline{L_p}$ is the surface sound pressure level,

S is the area of the measurement surface, in square metres,

S_0 = 1 m^2,

δ_{slm} is an input quantity to allow for any error in the measuring instrumentation,

δ_{rep} is an input quantity to allow for any error in the operating conditions of the noise source under test,

δ_{boun} is an input quantity to allow for any error in the influence of the test room boundaries,

δ_{mic} is an input quantity to allow for any error in the finite number of microphone positions,

δ_{met} is an input quantity to allow for any error in the meteorological conditions,

δ_{angle} is an input quantity to allow for any difference of angle between the direction in which the sound is emitted by the source and the normal to the measurement surface,

δ_{imp} is an input quantity to allow for any error in the impedance of the surroundings into which the source is emitting sound energy.

The input quantities included in equation 1 to allow for errors are those thought to be applicable in the current state of knowledge, but further research could reveal that there are others.

A probability distribution (normal, rectangular or triangular) is associated with each of the input quantities to allow for errors. Its expectation (mean value) is the best estimate for the value of the input quantity and its standard deviation is a measure of the dispersion of values, termed uncertainty. It is presumed (in Reference 6) that the mean values of all of the input quantities for errors given in equation 1 are equal to zero. This presumption may not be valid for some input quantities and so an allowance has to be made to account for a potential bias in results. It is a requirement of Reference 9, that the errors considered in Equation 1 are relative to values that have been taken to represent "true" (or correct) values. Thus, when considering the input quantities listed above it may be necessary to take account not only of variations about mean values (quantified as standard deviations) but also the possibility that mean values may be different from the adopted "true" values. This is discussed later (see sub-section 3.1.1). However, in any particular determination of a sound power level or sound energy level of a noise source under test, the uncertainties do not vanish and they contribute to the combined uncertainty associated with values of the sound power level or sound energy level.

The contributions to the combined total standard uncertainty associated with the value of the surface sound pressure level depend on each of the input quantities to allow for errors, their respective probability distributions and sensitivity coefficients, c_i. The sensitivity coefficients are a measure of how the values of the surface sound pressure level are affected by changes in the values of the respective input quantities. In the model used in equation 1, all sensitivity coefficients have the value 1. The contributions of the respective input quantities to allow for errors to the overall uncertainty are then given by the products of the standard uncertainties, u_i and a factor corresponding to their probability distribution.

The combined total standard uncertainty of the determination of the sound power level, $u(L_W)$, from the n individual contributions is given by the following equation:

$$u(L_W) = \sqrt{\sum_{i=1}^{n} (c_i u_i)^2} \qquad (2)$$

where u_i is the ith uncertainty contribution.

The *Guide to the Expression of Uncertainties in Measurement* requires an expanded uncertainty, U, to be specified, such that the interval $[L_W-U, L_W+U]$ covers e.g. 95% of the values of L_W that might reasonably be attributed to L_W. To that purpose, a coverage factor, k, is used, such that $U=k.u$. The coverage factor depends on the probability distribution associated with the measurand.

The standard uncertainties from the various contributions for most noise sources remain to be established by research. There have been proposals for some contributions, in particular a value for δ_{slm}[10]. However, this value for δ_{slm} is based on the tolerances given in IEC 60651:2000[11], which, in the absence of any actual measured data relating to the performance of a sound level meter, is a reasonable first step in proposing a value for δ_{slm}. However, such a value will provide an upper limit for δ_{slm} but will not be strictly applicable to the use of a sound level meter in practice.

During the years from 1997 to 2001 the National Physical Laboratory provided a sound level meter verification service, where measurements of various parameters regarding the performance of a sound level meter were compared to the requirements of BS 7580[12]. These measurements were carried out on a wide range of sound level meter types and the results are suitable for use in an assessment of a practical value of δ_{slm}.

In this paper, a value for δ_{slm}, based on these data together with contribution based on practical considerations of the operation and calibration of a sound level meter is proposed. Such a value will be directly related to the practical use of sound level meters and should be suitable for inclusion in Equation 1.

2. UNCERTAINTY BUDGET FOR NOISE MEASUREMENTS WITH A SOUND LEVEL METER

There are many factors to be considered when assessing the measurement uncertainty associated with a sound level meter. In this paper it is proposed that the A-weighted sound pressure level, L_A, obtained by using a sound level meter, is given by the following equation:

$$L_A = L_{Ames} + \delta_{fr} + \delta_{lin} + \delta_{dl} + \delta_{rms} + \delta_{time} + \delta_{ad} + \delta_{cal} + \delta_{res} + \delta_{dir} + \delta_{obs} + \delta_{case} + \delta_{temp} + \delta_{pres} + \delta_{ws} + \delta_{mic} \quad (3)$$

where:

L_A is the unknown A-weighted sound pressure level

L_{Ames} is the measured A-weighted sound pressure level

δ_{fr} is the correction associated with the frequency-weighting network

δ_{lin} is the correction associated with the linearity on the sound level meter reference range

δ_{dl} is the correction associated with the linearity on other range settings of sound level meter

δ_{rms} is the correction associated with the detector characteristics

δ_{time} is the correction associated with the time weighting function (fast or slow)

δ_{ad} is the correction associated with the adjustment of the sound level meter during calibration with a sound calibrator

δ_{cal} is the correction associated with the calibration of the sound calibrator

δ_{res} is the correction associated with the resolution of the display

δ_{dir} is the correction associated with the directivity of the microphone

δ_{obs} is the correction associated with the influence of the observer

δ_{case} is the correction associated with the sound level meter case

δ_{temp} is the correction associated with variations in ambient temperature

δ_{pres} is the correction associated with variations in ambient pressure

δ_{ws} is the correction associated with a windshield

δ_{mic} is the correction associated with the calibration of the microphone

These corrections will be assessed in two groups:

(a) those associated with operation of the sound level meter;

δ_{ad} , δ_{cal} , δ_{fr} , δ_{lin} , δ_{dl} , δ_{rms} , δ_{res} , δ_{time} ,

(b) those associated with the sound level meter in use;

δ_{dir} , δ_{obs} , δ_{case} , δ_{temp} , δ_{pres} , δ_{ws} , δ_{mic}.

2.1 UNCERTAINTY ASSOCIATED WITH A-WEIGHTING MEASUREMENTS

A primary need for values of uncertainty is to demonstrate compliance with noise emission level declaration as required for numerous regulatory purposes, for example the European

Directive 2000/14/EC "*on the approximation of the laws of the Member States relating to the noise emission in the environment by equipment for use outdoors*". This Directive requires that machinery is labelled with a guaranteed A-weighted sound power level. Here, a guaranteed sound power level means a single-number noise emission value including the uncertainties due to production variation and measurement procedures. So, the main body of this paper is, therefore, primarily concerned with uncertainties associated with A-weighted noise emission values.

Values for each of these (A-weighted) contributions are assessed in sub-sections 3.1 and 3.3 for group (a) and group (b) respectively.

2.2 UNCERTAINTY ASSOCIATED WITH FREQUENCY BAND MEASUREMENTS

Although numerous regulatory bodies require A-weighted noise emission values, the g*uide to the expression of uncertainties in measurement* requires that any measured value should be accompanied by an associated measurement uncertainty. Several of the Standards in the ISO 3740 series include specifications for the determination of one-third-octave-band noise emission levels and so there is a need to assess measurement uncertainties associated with band limited values.

In group (a), the only uncertainty contribution for which there is information on any potential frequency dependence is δ_{fr}, the correction associated with the frequency-weighting network. In this case it will be the correction associated with a linear weighting. Values of uncertainties associated with a linear weighting are considered in sub-section 4.1.

In group (b), information regarding any potential frequency dependence is available for all contributions except δ_{obs}, the correction associated with the influence of an observer. Values for uncertainties associated with these six contributions are considered in sub-section 4.2.

3. VALUES OF INDIVIDUAL UNCERTAINTY CONTRIBUTIONS FOR A-WEIGHTED NOISE EMISSION LEVELS

As indicated in Section 2 the uncertainty contributions may be considered in two groups, one group, (a) associated with the operation of the sound level meter and the other, (b) associated with its use. In this Section both groups are considered, group (a) in sub-section 3.1 with a summary in sub-section 3.2 and group (b) in sub-section 3.3 with a summary in sub-section 3.4.

L_{Ames} is the measured A-weighted sound pressure level. No uncertainty contribution associated with this value is provided here, as it will be accounted for separately as the standard deviation of repeated determinations for a source under test.

3.1 VALUES OF INDIVIDUAL UNCERTAINTY ASSOCIATED WITH THE OPERATION OF A SOUND LEVEL METER

In this group a number of contributions have been assessed by using data obtained from measurements carried out as part of a sound level meter verification process on a range of instruments. These verification measurements were carried out according to the tests specified in BS 7580 : Part 1 : 1997. This Standard assesses a sound level meter with the requirements and tolerances for a Type 1 sound level meter given in BS EN 60651:1994[(13)] . The values of standard uncertainty contributions obtained in this way will represent practical values inherent with commonly used sound level meters and not related to the tolerances that are specified in the Standard. The five specific contributions that are obtained in this way are, δ_{fr} , δ_{lin} , δ_{dl} , δ_{rms} , and δ_{time} .

Data obtained over the period 1997 to 2001 from measurements during verification tests were examined and information relating to frequency weighting, reference range linearity, other ranges linearity, time weighting and detector characteristics were extracted. In all, data from 22 different sound level meter types involving nine different Manufacturers were used. The Manufacturer and type numbers are listed below in alphabetical order of Manufacturer:

- 01dB Symphony;
- 01dB Concerto;
- 01dB SIP95;
- B&K 2231B;
- B&K 2260;
- B&K 2239A;
- B&K 2238;
- B&K 2260B;
- B&K 2236A;
- B&K 2230;
- CEL 593;
- CEL 393;
- CEL 480;
- Cirrus CR831A;
- Larson-Davis 820;
- Norsonic 116;
- Norsonic SA110;
- Quest 1900E;
- Rion NL-14;
- Rion NL-15;
- Rion NL-31;
- Svantek 912A.

The data for each of the five uncertainty contributions is discussed in sub-sections 3.1.1 to 3.1.5.

The other three contributions δ_{ad} , δ_{cal} and δ_{res} are assessed from practical consideration of the operation and calibration of a sound level meter. The data for each of these three uncertainty contributions is discussed in sub-sections 3.1.6 to 3.1.8.

3.1.1 The contribution associated with the A-weighting network, δ_{fr} .

BS 7580: Part 1: 1997 requires that the A-weighting network is tested over the range 31.5 Hz to 12.5 kHz using a continuous sinusoidal signal at preferred octave-band centre frequencies. The signal level at 1 kHz was set as an indication of the reference sound pressure level. The response of the sound level meter was compared to that of tables IV and V of BS EN 60651:1994. Values of the A-weighted frequency response for each sound level meter are shown in Table A.1.1 in Annex 1 together with the ideal values.

It is acknowledged that the effect on A-weighted sound pressure levels of variations from the ideal A-weighted function will be dependent on the frequency distribution of the noise source. For the purposes of this examination, an A-weighted level has been calculated for each of the 22 sound level meters assuming five noise spectra, namely; flat, rising at 3 dB per octave falling at 3 dB per octave, rising at 6 dB per octave and falling at 6 dB per octave. In order to assess values of standard uncertainty the resultant means and standard deviations, σ_m of the data from the 22 sound level meters has been calculated for each of the five spectra. These data are shown in Table 1 together with maximum and minimum values. It can be seen that the mean values are not quite zero. This indicates that there may be some bias in the A-weighting assessment. In order to account for this in the standard uncertainty a value of standard deviation, σ_{zero} has been calculated by forcing a zero mean. These data are also shown in Table 1.

Table 1 Mean and standard deviations for A-weighted levels

Spectra	Mean (dB)	Maximum	Minimum	σ_m (dB)	σ_{zero} (dB)
Flat	-0.04	0.10	-0.13	0.05	0.07
- 3 dB	-0.06	0.01	-0.11	0.03	0.07
+ 3 dB	-0.03	0.22	-0.20	0.09	0.09
- 6 dB	-0.06	0.04	-0.23	0.06	0.11
+ 6 dB	-0.03	0.33	-0.24	0.12	0.12

It can be seen from Table 1 that values of σ_{zero} are slightly larger than those of σ_m and that there is a variation with spectra with values of σ_{zero} ranging from 0.07 dB to 0.12 dB. For the purposes of assessing contributions to the uncertainty budget for a sound level meter the value of standard deviation of σ_{zero} for a flat spectrum of 0.07 dB will be assumed.

It should be noted that the measurement uncertainties associated with the data obtained from the verification tests are of the same order as those values listed in Table 1. So, the values in Table 1 cannot be directly attributed to variations between sound level meters with any reasonable degree of statistical confidence. The values listed in Table 1 may, however, be assumed to be representative of a worst case.

3.1.2 The contribution associated with linearity on the reference range, δ_{lin}.

BS 7580:Part 1:1997 requires that the linearity of the sound level meter is tested relative to the reference sound pressure level as indicated on the reference range using a continuous sinusoidal signal of frequency 4 kHz. Measurements were made at the level intervals required by the standard and results were compared to the requirements of Table XII of BS EN 60651:1994. For the purposes of assessing a value of standard uncertainty for inclusion in a sound level meter uncertainty budget a flat spectrum is assumed and differences between measured values and those corresponding to a perfectly linear device recorded. Values of these differences for each sound level meter are shown in Table A.1.2 in Annex 1. The same analysis process as described in sub-section 3.1.1 was performed and the resultant values of mean, maximum, minimum, σ_m and σ_{zero} are shown in Table 2.

Table 2 Mean and standard deviations for reference range linearity.

Mean (dB)	maximum	Minimum	σ_m (dB)	σ_{zero} (dB)
-0.01	0.29	-0.24	0.10	0.10

It can be seen from Table 2 that the mean value is close to zero and so values of σ_m and σ_{zero} are, when rounded to the second place of decimals, the same. So, for the purposes of assessing contributions to the uncertainty budget for a sound level meter the value of standard deviation of 0.10 dB will be assumed.

It should be noted that the measurement uncertainties associated with the data obtained during the verification tests are estimated to be of the same order as the values listed in Table 2. So, the values in Table 2 cannot be directly attributed to variations between sound level meters with any reasonable degree of statistical confidence. However, the listed values of δ_{lin} may be assumed to be representative of a worst case.

3.1.3 The contribution associated with linearity on other ranges, δ_{dl}.

BS 7580 : Part 1 : 1997 requires that measurements are made for an indication of the reference sound pressure level on all other ranges which include it. For the purposes of assessing a value of standard uncertainty for inclusion in a sound level meter uncertainty budget a flat spectrum is assumed and differences between measured values and those corresponding to a perfectly linear device recorded. Values of these differences for each sound level meter are shown in Table A.1.2 in Annex 1. Some of the sound level meters tested had a very large dynamic range and so there was only a need for a single range. For these instruments a difference between measured values and those corresponding to a device that is perfectly linear on range switching is assumed to be zero. The same analysis process as described in sub-section 3.1.1 was performed and the resultant values of mean, maximum, minimum, σ_m and σ_{zero} are shown in Table 3.

Table 3 Mean and standard deviations for other ranges linearity.

Mean (dB)	Maximum	Minimum	σ_m (dB)	σ_{zero} (dB)
-0.02	0.41	-0.66	0.17	0.17

It can be seen from Table 3 that the mean value is close to zero and so values of σ_m and σ_{zero} are, when rounded to the second place of decimals, the same. So, for the purposes of assessing contributions to the uncertainty budget for a sound level meter the value of standard deviation of 0.17 dB will be assumed.

3.1.4 The contribution associated with the detector characteristics, δ_{rms}

BS 7580-Part 1:1997 requires that the rms accuracy shall be tested on the reference range for a crest factor of 3 by comparing the sound level meter indication for a sequence of tone bursts with that for a continuous sinusoidal signal. The frequency of the continuous signal is 2 kHz at an amplitude that produces an indication 2 dB below the upper limit of the sound level meter primary indicator range. Results of this test are compared to table VII of BS EN 60651:1994. Differences between measured data and those corresponding to a perfect rms detector were recorded. Values of these differences for each sound level meter are shown in Table A.1.2 in Annex 1. The resulting 22 values were analysed as described in sub-section 3.1.1. The resultant values of mean, maximum, minimum, σ_m and σ_{zero} are shown in Table 4.

Table 4 Mean and standard deviations for rms accuracy.

Mean (dB)	Maximum	Minimum	σ_m (dB)	σ_{zero} (dB)
0.00	0.3	-0.3	0.19	0.19

It can be seen from Table 4 that the mean value is zero and so values of σ_m and σ_{zero} are, therefore, the same. So, for the purposes of assessing contributions to the uncertainty budget for a sound level meter the value of standard deviation of 0.19 dB will be assumed.

3.1.5 The contribution associated with fast or slow time weighting function, δ_{time}.

BS 7580-Part 1:1997 requires that the time averaging be tested on the reference range by comparing the indication for a continuous sinusoidal signal with that for a sequence of tone bursts having the same equivalent continuous level. A continuous signal at a frequency of 4 kHz and an amplitude 30 dB below the upper limit of the linearity range is applied to the sound level meter. A sequence of tone bursts as specified by BS 7580 : Part 1 : 1997 are applied (see also Table III of BS EN 60804[(14)]) and the difference between the indication on the sound level meter with that for the continuous signal recorded. Values of these differences for each sound level meter are shown in Table A.1.2 in Annex 1. The resulting 22 values have been analysed as described in sub-section 3.1.1. The resultant values of mean, maximum, minimum, σ_m and σ_{zero} are shown in Table 5 for both fast and slow time weighting.

Table 5 Mean and standard deviations for time weighting.

Weighting	Mean (dB)	Maximum	Minimum	σ_m (dB)	σ_{zero} (dB)
Fast	-0.15	0.3	-0.7	0.22	0.27
Slow	-0.06	0.5	-0.7	0.19	0.19

It can be seen from Table 3 that for fast time weighting the mean is –0.15 dB and so the value of σ_{zero} of 0.27 dB is greater than the value of σ_m of 0.22 dB. For the slow time weighting, the mean value is close enough to zero for the values of σ_m and σ_{zero}, when rounded to the second place of decimals, to be the same at 0.19 dB. It is not clear from an inspection of the ISO standards relating to the determination of sound power, which time weighting should be used so, for the purposes of assessing contributions to the uncertainty budget for a sound level meter, both values of standard deviation, σ_{zero} will be used in calculating two values of the final combined total standard uncertainty one for "fast" and one for "slow" time weighting.

3.1.6 The contribution associated with the adjustment of the sound level meter during calibration with a sound calibrator, δ_{ad}

Before a noise emission measurement is carried out the sensitivity of the sound level meter must be checked using a calibrated sound calibrator or pistonphone and if necessary adjusted according to the sound level meter manufacturer's instructions and the data in the calibration certificate for the sound calibrator. The potential error here is dependent on the resolution of the sound level meter display. All the sound level meters that have been submitted to NPL for verification according to BS EN 7580 have had a display resolution of 0.1 dB. The contribution to an overall uncertainty budget will, therefore, be half of this resolution, which is ± 0.05 dB.

3.1.7 The contribution associated with the calibration of the sound calibrator, δ_{cal}

It is a requirement of the ISO standards relating to the determination of sound power that the sound calibrator shall be calibrated "periodically in a manner that is traceable to appropriate standards". This requirement includes the provision of an uncertainty in the calibration supplied by the authorised laboratory. This is dependent on the quality control system of the Laboratory or Test House carrying out the calibration. All the calibrators associated with sound level meters submitted for verification that were used in this study were calibrated at the National Physical Laboratory that provides calibrations with a measurement uncertainty of ± 0.05 dB. This reported uncertainty is based on a standard uncertainty multiplied by a coverage factor, k = 2. For the purposes of assessing a value of δ_{cal} suitable for inclusion in an overall uncertainty budget, it is assumed that the uncertainty supplied by the NPL is typical of that supplied by other calibration laboratories and so an uncertainty of ± 0.05 dB will be assumed.

3.1.8 The contribution associated with the resolution of the display, δ_{res}

The potential error here is dependent on the resolution of the sound level meter display. The contribution to an overall uncertainty budget will, therefore, be the same as that assumed for δ_{ad} (see sub-section 3.1.6 above) which is ± 0.05 dB.

3.2 SUMMARY OF INDIVIDUAL STANDARD UNCERTAINTY CONTRIBUTIONS ASSOCIATED WITH THE OPERATION OF A SOUND LEVEL METER

All values of standard uncertainty associated with the operation of a sound level meter as described in sub-sections 3.1.1 to 3.1.8 are summarised below together with an indication of their associated statistical distribution. These values are then listed in Table 6 together with their uncertainty contribution, u to the final combined total standard uncertainty, $u(L_W)$ to be associated with the operation of a sound level meter. The value of $u(L_W)$ is given by:

$$u(L_W) = \sqrt{\sum_{i=1}^{8} u_i^{\,2}} \tag{4}$$

where u_i is the ith uncertainty contribution.

Values of the eight contributions are listed below using the error notation from Section 2.

δ_{fr} This is dependent on the uncertainty associated with the application of the A-weighting function and the standard uncertainty is ± 0.07 dB (see sub-section 3.1.1) with a normal distribution.

δ_{lin} This is dependent on the linearity of the sound level meter when used on the reference range and the standard uncertainty is ± 0.10 dB (see sub-section 3.1.2) with a normal distribution.

δ_{dl} This is dependent on the linearity of the sound level meter when used on ranges other than the reference range and the standard uncertainty is ± 0.17 dB (see sub-section 3.1.3) with a normal distribution.

δ_{rms} This is an assessment of the ability of the sound level meter to provide a true rms indication and the standard uncertainty is ± 0.19 dB (see sub-section 3.1.4) with a normal distribution.

δ_{time} This is dependent on the ability of the sound level meter to provide time averaged data as required by the time weighting functions described as “fast” or “slow” in IEC 61672 part1:2002(15) and the standard uncertainty is ± 0.27 dB and ± 0.22dB (see sub-section 3.1.5) for fast and slow respectively with normal distributions.

δ_{ad} This is dependent on the resolution of the sound level meter display and the standard uncertainty is ± 0.05 dB (see sub-section 3.1.6) with a rectangular distribution.

δ_{cal} This is dependent on the uncertainty associated with the calibration of the sound calibrator, and the uncertainty is ± 0.05 dB, assuming a coverage factor k = 2 (see sub-section 3.1.7) with a normal distribution.

δ_{res} As for δ_{ad} above, this is dependent on the resolution of the sound level meter display and the standard uncertainty is ± 0.05 dB (see sub-section 3.1.8) with a rectangular distribution.

Table 6 Uncertainty associated with operation of the sound level meter

Quantity	standard uncertainty ± dB	probability distribution	distribution divisor	uncertainty contribution ± dB
δ_{ad}	0.05	Rectangular	√3	0.03
δ_{cal}	0.05	Normal	2	0.03
δ_{fr}	0.07	Normal	1	0.07
δ_{lin}	0.10	Normal	1	0.10
δ_{dl}	0.17	Normal	1	0.17
δ_{rms}	0.19	Normal	1	0.19
δ_{res}	0.05	Rectangular	√3	0.03
δ_{time} (fast)	0.27	Normal	1	0.27
δ_{time} (slow)	0.22	Normal	1	0.22
TOTAL(fast)				0.394
TOTAL(slow)				0.362

It can be seen from Table 6 that the value of the final combined total standard uncertainty for "fast" time weighting is 0.032 dB higher than for "slow" time weighting. The value to be used is discussed in Section 4. It is clear that in order to reduce the magnitude of the final combined total standard uncertainty effort should be concentrated on reducing δ_{time} , δ_{rms} and δ_{dl}. It is possible that more recent sound level meter design may have reduced these factors and certainly those sound level meters with a single large dynamic range will of course reduce δ_{dl} to zero. This will reduce the combined total standard uncertainties to 0.355 dB and 0.320 dB for "fast" and "slow" time weighting respectively. It should be noted that δ_{dl} would also be zero if the range that is used for the sound pressure level measurement were the same as that used when applying the sound calibrator.

3.3 VALUES OF INDIVIDUAL UNCERTAINTY ASSOCIATED WITH THE USE OF A SOUND LEVEL METER

In this group, uncertainty contributions are assessed from practical consideration of the sound level meter in use and from manufacturers data.

3.3.1 The contribution associated with microphone directivity, δ_{dir} .

For the purposes of estimating a value of combined total standard uncertainty for measuring instrumentation, a value for the uncertainty associated with errors resulting from sound incident at angles other than that for which the instrumentation has been calibrated should be included as part of δ_{angle} as described in Section 1. However, if this is not the case a value has been estimated for a hemispherical enveloping surface as described in ISO 3744:1994. In this simple estimation, it is assumed that the hemisphere radius is twice the largest source dimension and that the source is radiating equally from all positions on its surface. The angles of incidence on the microphone diaphragm resulting from this equal radiation has been calculated as ranging from zero degrees (normal incidence) to approximately 20° and the corresponding changes in microphone sensitivity at one-third-octave frequency intervals estimated from manufacturers data. A flat frequency spectrum has been assumed and an A-weighted sound pressure level calculated with these sensitivity changes applied and compared to the normal incidence case. A change in A-weighted level of up to 0.14 dB was observed.

3.3.2 The contribution associated with the effect of an observer, δ_{obs} .

This is very dependent on the frequency distribution of the source and the size and location of the observer. Ideally measurements will be made utilising remote data logging so the influence of an observer may be neglected. However, measurements carried out for this investigation using a reference sound source in a hemi-anechoic room, have indicated a value of uncertainty of up to ± 0.2 dB.

3.3.3 The contribution associated with the application of case corrections, δ_{case}

IEC 61672:2002(15) requires that corrections be applied to account for the effect of the presence of the sound level meter in the sound field. Whilst it is a requirement of IEC 61672 that these corrections are supplied, manufacturers do not provide any indication of the magnitude of associated uncertainties. For the purposes of providing a contribution to the combined total standard uncertainty, it is proposed that a value of 10% of the correction be assumed. (It is suggested that a value of uncertainty larger than about 10% would probably indicate poor statistical confidence in the correction). Values of corrections for the sound level meters presented for verification purposes (see sub-section 3.1) have been applied to a flat frequency spectrum and the difference in A-weighted sound pressure level due to the presence of the sound level meter in the sound field has been calculated as ranging from 0.04 dB to 0.11 dB. For the purposes of assessing a value of δ_{case} the worst-case figure of 0.11 dB has been assumed and so the value for inclusion in Equation 2 is therefore taken as 0.011 dB.

3.3.4 The contribution associated with variation in ambient temperature, δ_{temp}.

It is assumed here that variations in sound level meter output with changes in temperature result from changes in the sensitivity of the microphone. Microphones are calibrated at a temperature of 23 °C and their use at other temperatures will result in small errors because microphone sensitivity is a function of ambient temperature[16]. The magnitude of the error is dependent in the difference in temperature relative to 23 °C and on the rate of change of microphone sensitivity, which is in turn dependent on microphone type. There is a range of microphones used with sound level meters, but in this examination only those used with the 22 sound level meters discussed in sub-section 3.1 are considered. The rates of change of sensitivity with temperature for the various microphones used have been obtained[16, 17, 18] and range from 0.002 dB per K to 0.015 dB per K. The ISO series of standards relating to the determination of sound power level provide an expression to obtain a correction factor to account for changes in the sound power output of a noise source resulting from changes in temperature and atmospheric pressure. In Annex E of a draft revision of ISO 3744:2003[19] for instance, this expression is stated to be valid for a temperature range of from 15 °C to 30 °C. So, for the purposes of analysis this temperature range will be assumed. The range relative to the calibration temperature of 23 °C is from – 8 °C to + 7 °C. In this report, errors due to temperature changes are assessed assuming a range of ± 8 °C in conjunction with the rates of change above. This provides a potential error of up to between 0.016 dB and 0.12 dB depending on microphone type. For the purposes of supplying data for a sound level meter uncertainty budget the worst case of 0.12 dB is adopted.

3.3.5 The contribution associated with variation in ambient pressure, δ_{pres}.

As discussed in sub-section 3.3.4 above, it is assumed that variations in sound level meter output with changes in atmospheric pressure result from changes in the sensitivity of the microphone. Microphone calibrations are corrected to a standard atmospheric pressure of 101.3 kPa and their use at pressures removed from this will result in small errors because microphone sensitivity is a function of ambient atmospheric pressure[16]. The magnitude of the error is dependent in the difference in pressure relative to 101.3 kPa and on the rate of change of microphone sensitivity, which is in turn dependent on microphone type. There is a range of microphones used with sound level meters, but in this paper only those used with the 22 sound level meters discussed in sub-section 3.1 are considered. The rates of change of sensitivity with pressure for the various microphones used have been obtained [16, 17, 18] and range from 0.0015 dB per kPa to 0.019 dB per kPa. Unlike the case of temperature, the ISO standards do not provide an indication of a temperature range within which measurements should be made. However, the ISO series of standards relating to the determination of sound power level provide an expression to obtain a correction factor to account for changes in the sound power output of a noise source resulting from changes in temperature and atmospheric pressure. In order to provide an engineering grade accuracy without using this expression to correct for changes in pressure it is necessary to limit ambient atmospheric pressure to the range 97.5 kPa to 102.5 kPa. So, for the purposes of analysis this pressure range will be assumed. The range relative to the calibration pressure of 101.3 kPa is from – 3.8 kPa to + 1.2 kPa. In this report, errors due to pressure changes are assessed assuming a worst-case range of ± 3.8 kPa in conjunction with the rates of change above. This provides a potential error of up to between 0.0057 dB and 0.0722 dB depending on microphone type. For the purposes of supplying data for a sound level meter uncertainty budget the worst case of 0.0722 dB is adopted.

3.3.6 The contribution associated with the use of a windscreen, δws

If a windscreen is used corrections must be applied to account for the insertion loss due to the windscreen. Whilst the manufacturer supplies these corrections, they do not provide any indication of the magnitude of associated uncertainties. For the purposes of providing a contribution to the combined total standard uncertainty, it is proposed that a value of 10% of the correction be assumed. (As for δ_{case} above, it is suggested that a value of uncertainty larger than about 10% would probably indicate poor statistical confidence in the correction). Values of corrections for the sound level meters presented for verification purposes (see sub-section 3.1) have been applied to a flat frequency spectrum and the difference in A-weighted sound pressure level due to the presence of a wind screen has been calculated as ranging from 0.07 dB to 0.19 dB. For the purposes of assessing a value of δ_{case} the worst-case figure of 0.19 dB has been assumed and so the value for inclusion in Equation 2 is therefore taken as 0.019 dB.

3.3.7 The contribution associated with the calibration of the microphone, δmic.

The microphone associated with the sound level meter will have been calibrated and its sensitivity as a function of frequency will be available. It is assumed here that corrections to account for any variation of sensitivity with frequency will be applied to measured data. In this case, only an allowance for the uncertainty involved in the calibration of the microphone need be considered. The microphone calibration service at the National Physical Laboratory provides uncertainties that are dependent on both microphone type and on frequency. These uncertainties range from ± 0.03 dB to ± 0.1 dB and are based on a standard uncertainty multiplied by a coverage factor of k = 2. For the purposes of this paper the worst case of ± 0.1 dB will be assumed to apply to all microphones and frequencies between 50 Hz and 10 kHz.

3.4 SUMMARY OF INDIVIDUAL STANDARD UNCERTAINTY CONTRIBUTIONS ASSOCIATED WITH THE SOUND LEVEL METER IN USE

All values of standard uncertainty associated with the operation of a sound level meter as described in sub-sections 3.3.1 to 3.3.6 are summarised below together with an indication of their associated statistical distribution. These values are then listed in Table 7 together with their uncertainty contribution, *u* to the final combined total standard uncertainty, $u(L_W)$ to be associated with the operation of a sound level meter. The value of $u(L_W)$ is given by:

$$u(L_W) = \sqrt{\sum_{i=1}^{6} u_i^{\,2}} \qquad (5)$$

where, u_i is the *ith* uncertainty contribution.

Values of the seven contributions are listed below using the error notation from Section 2.

δ_{dir} A value of up to 0.14 dB has been estimated using a simple procedure for a hemispherical enveloping surface as described in sub-section 3.3.1. It is assumed that over the small range of angle of incidence considered, the change in microphone sensitivity is a linear function of angle of incidence and so the statistical distribution associated with δ_{dir} is assumed to be triangular.

δ_{obs} Some measurements carried out for this study (see sub-section 3.3.2) have indicated a value of uncertainty of up to ± 0.2 dB. The statistical distribution associated with δ_{obs} is assumed to be rectangular.

δ_{case} Using values of case correction supplied for sound level meter verification purposes, a value of 0.011 dB has been proposed. The statistical distribution associated with δ_{case} is assumed to be rectangular.

δ_{temp} The potential change in microphone sensitivity resulting from measurements being carried out at temperatures removed from the calibration temperature is assumed to be 0.12 dB (see sub-section 3.3.3). The change in sensitivity is a linear function of temperature and so the statistical distribution associated with δ_{temp} is assumed to be triangular.

δ_{pres} The potential change in microphone sensitivity resulting from measurements being carried out at pressures removed from the calibration value is assumed to be 0.0722 dB (see sub-section 3.3.4). The change in sensitivity is a linear function of pressure and so the statistical distribution associated with δ_{pres} is assumed to be triangular.

δ_{ws} Using values of windscreen correction supplied (from manufacturer's instruction manuals) for sound level meter verification purposes, a value of 0.019 dB has been proposed. The statistical distribution associated with δ_{WS} is assumed to be rectangular.

δ_{mic} This is dependent on the uncertainty associated with the calibration of the microphone and is taken as ± 0.1 dB, assuming a coverage factor of k = 2 (see sub-section 3.3.7) with a normal distribution

Table 7 Uncertainties associated with the sound level meter in use

Quantity	standard uncertainty ± dB	probability distribution	distribution divisor	Uncertainty contribution ± dB
δ_{dir}	0.14	Triangular	√6	0.06
δ_{obs}	0.20	Rectangular	√3	0.12
δ_{case}	0.011	Rectangular	√3	0.01
δ_{temp}	0.12	Triangular	√6	0.05
δ_{pres}	0.0722	Triangular	√6	0.03
δ_{ws}	0.019	Rectangular	√3	0.01
Δ_{mic}	0.10	Normal	2	0.05
TOTAL				0.155

It can be seen from Table 7 that the final combined total standard uncertainty of 0.155 dB is smaller than the corresponding result for group (a). It is clear that in order to reduce the magnitude of the final combined total standard uncertainty effort should be concentrated on reducing δ_{obs}. If the indication on the sound level meter was observed remotely via an ac output (a common feature on class 1 meters) then δ_{obs} will be reduced to zero and the value of the final combined total standard uncertainty will reduce to 0.098 dB.

4. VALUES OF INDIVIDUAL UNCERTAINTY CONTRIBUTIONS AS A FUNCTION OF FREQUENCY

Here values of uncertainty associated with the various contributions discussed in Section 2, are assessed as a function of frequency. Data is available for frequencies at preferred octave band centre frequencies from 31.5 Hz to 12.5 kHz.

In group (a), the only uncertainty contribution for which there is information on any potential frequency dependence is δ_{fr}, the correction associated with the frequency-weighting network. In this case it will be the correction associated with a linear weighting. Values of uncertainties associated with a linear weighting are considered in sub-section 4.1.

In group (b), information regarding any potential frequency dependence is available for all contributions except δ_{obs}, the correction associated with the influence of an observer. Values for uncertainties associated with the remaining six contributions, δ_{dir}, δ_{case}, δ_{temp}, δ_{pres}, δ_{ws} and δ_{mic} are considered in sub-section 4.2.

4.1 FREQUENCY DEPENDENT UNCERTAINTIES ASSOCIATED WITH THE OPERATION OF A SOUND LEVEL METER

The only frequency dependent uncertainty in group (a) is δ_{fr}, which in this sub-section will be the correction associated with a linear weighting. Data have been obtained from measurements made during sound level meter verification as described in sub-section 3.1.

BS 7580: Part 1: 1997 requires that the sound level meter, when operating in its linear mode, is tested over the range 31.5 Hz to 12.5 kHz using a continuous sinusoidal signal at preferred octave-band centre frequencies. The signal level at 1 kHz was set as an indication of the reference sound pressure level. The response of the sound level meter was compared to that of tables IV and V of BS EN 60651:1994.

The difference between an ideal flat response and that obtained for each of the 22 sound level meters (see sub-section 3.1) was noted and the standard deviation of these data about the mean value for the 22 meters for each frequency band calculated. These standard deviations (s.d.) are shown in Table 8.

Table 8 Standard deviations for δ_{fr} at octave-band centre frequencies

Freq (kHz)	0.0315	0.063	0.125	0.250	0.500	1	2	4	8	12.5
s.d. (dB)	0.21	0.16	0.11	0.08	0.06	0	0.07	0.10	0.13	0.12

The value of the standard deviation at 1 kHz is zero only because it is the datum to which the sound level meter response at other frequencies is compared. It is assumed that its true value is similar to the adjacent frequency bands. The value of standard deviation for the A-weighted network is 0.07 dB (see sub-section 3.1.1). It can be seen from Table 8 that a similar result is obtained for frequencies between 250 Hz and 2 kHz with an increase to about 0.12 dB above 2 kHz and gradually rising to 0.21 dB at lower frequencies.

4.2 FREQUENCY DEPENDENT UNCERTAINTIES ASSOCIATED WITH THE USE OF A SOUND LEVEL METER

Information on the frequency dependence of uncertainties in group (b) exist for all contributions except for δ_{obs}, the correction associated with the influence of an observer. Frequency dependent uncertainties associated with the remaining six contributions, δ_{dir}, δ_{case}, δ_{temp} , δ_{pres} , δ_{ws} and δ_{mic} are considered in sub-sections 4.2.1 to 4.2.6.

4.2.1 Frequency dependent uncertainties associated with δ_{dir}.

Values of δ_{dir} have been estimated for a hemispherical enveloping surface according to ISO 3744:1994, as described in sub-section 3.3.1. In this simple estimation, it is assumed that the hemisphere radius is twice the largest source dimension and that the source is radiating equally from all positions on its surface. The maximum angle of incidence on the microphone diaphragm is taken as 20° (zero degrees is normal incidence) and the corresponding changes in microphone sensitivity, from that at normal incidence, at octave-band frequency intervals estimated from manufacturers data. Values of δ_{dir} of 0.03 dB, 0.09 dB, 0.33 dB and 0.75 dB for frequencies of 2 kHz, 4 kHz, 8 kHz and 12.5 kHz are estimated. Below 2 kHz values are taken as zero. The corresponding A-weighted value assuming a flat frequency spectrum is 0.14 dB (see sub-section 3.1.1). The significance of this variation with frequency and differences from the A-weighted value is discussed in sub-section 5.2.

4.2.2 Frequency dependent uncertainties associated with δ_{case}.

As discussed in sub-section 3.3.3, IEC 61672 requires that corrections be applied to account for the effect of the presence of the sound level meter in the sound field and, for the purposes of providing a contribution to the combined total standard uncertainty, it is proposed that a value of 10% of the correction supplied by the manufacturer be assumed to be representative of δ_{case}. Values of corrections for the sound level meters presented for verification purposes (see sub-section 3.1) have been examined. These corrections varied from one sound level meter to another so, for the purposes of providing a value of δ_{case} the largest has been assumed for each octave-band frequency considered. Values below 125 Hz are zero, with those above 125 Hz shown in Table 10.

Table 10 Value of δ_{case} at octave-band centre frequencies

Freq (kHz)	0.125	0.250	0.500	1	2	4	8	12.5
δ_{case} (dB)	0.01	0.01	0.02	0.02	0.07	0.01	0.04	0.12

It can be seen that values of δ_{case} generally increase as frequency increases, although there is a "peak" at 2 kHz. The value of δ_{case} when considering A-weighted levels is 0.011 dB (see sub-section 3.3.3). So, generally values corresponding to particular frequencies are similar to those values corresponding to A-weighted levels, with the exception of the large increases at 2 kHz and at 12.5 kHz. The values of δ_{case} are based on correction data supplied by the manufacturers and the relatively large values of δ_{case} are generally common to all sound level meters. This generality is probably because most sound level meters are similar in physical shape and size. It is likely that if sound level meters were designed to have a different physical appearance then these large values of δ_{case} may reduce or perhaps reappear at different frequencies. However, if these large values of δ_{case} are a problem they may be reduced to zero by using a microphone on an extension lead. The significance of this variation with frequency and differences from the A-weighted value is discussed in sub-section 5.2.

4.2.3 Frequency dependent uncertainties associated with $\delta_{temp.}$

As discussed in sub-section 3.3.4, there are variations in sound level meter output with changes in ambient temperature resulting from changes in the sensitivity of the microphone. The rate of change of microphone sensitivity with temperature change is frequency dependent, with values increasing above approximately 1 kHz. Whilst this increase for some microphone types is quite significant (e.g. for a B&K type 4160 the increase is from 0.003 dB per K at 1 kHz to 0.0137 dB per K at 8 kHz) the values at the higher frequencies are still always less than the worst case values adopted in sub-section 3.3.4. Therefore, for the purposes of this paper it is assumed that the uncertainty contributions when considering frequency band limited data will be similar to (and certainly not greater than) the A-weighted value discussed in sub-section 3.3.4.

4.2.4 Frequency dependent uncertainties associated with $\delta_{pres.}$

As discussed in sub-section 3.3.5, it is assumed that variations in sound level meter output with changes in atmospheric pressure result from changes in the sensitivity of the microphone. Over the frequency range of interest here, the variations of the rate of change of microphone sensitivity with changes in ambient atmospheric pressure are generally independent of frequency. However, for some microphones there is some evidence of a slight decrease in the rate of change between 4 kHz and 8 kHz and a slight increase at 12.5 kHz. However, these changes are very small and are very much smaller than the values assumed for the A-weighted values discussed in sub-section 3.3.5. So, for the purposes of this paper it is assumed that the uncertainty contributions when considering frequency band limited data will be similar to (and certainly not greater than) the A-weighted value discussed in sub-section 3.3.5.

4.2.5 Frequency dependent uncertainties associated with $\delta_{WS.}$

As discussed in sub-section 3.3.6, if a windscreen is used corrections must be applied to account for the insertion loss due to the windscreen and, for the purposes of providing a contribution to the combined total standard uncertainty, it is proposed that a value of 10% of the correction supplied by the manufacturer be assumed. Values of corrections for the sound level meters presented for verification purposes (see sub-section 3.1) have been examined. These corrections varied from one sound level meter to another so, for the purposes of providing a value of δ_{WS} the largest has been assumed for each octave-band frequency considered. Values below 125 Hz are zero, others are shown in Table 11.

Table 11 Values of δ_{WS} at octave-band centre frequencies

Freq (kHz)	0.125	0.250	0.500	1	2	4	8	12.5
δ_{WS} (dB)	0.01	0.02	0.03	0.03	0.04	0.04	0.04	0.1

It can be seen that values of δ_{WS} generally increase as frequency increases. The value of δ_{WS} when considering A-weighted levels is 0.019 dB (see sub-section 3.3.3). So, generally values corresponding to particular frequencies are similar to those values corresponding to A-weighted levels, although there is a large increase at 12.5 kHz. The significance of this variation with frequency and differences from the A-weighted value is discussed in sub-section 5.2.

4.2.6 Frequency dependent uncertainties associated with $\delta_{mic.}$

As discussed in sub-section 3.3.7, it is assumed that corrections are applied to account for any variation in microphone sensitivity with frequency so, only uncertainties associated with the calibration of the microphone need to be considered. A worst-case value of ± 0.1 dB was assumed for A-weighted data. When worst case values are assumed as a function of frequency then this value of ± 0.1 dB is reduced to ± 0.07 dB for frequencies up to 4 kHz, to ± 0.09 dB for 8 kHz and remains at ± 0.1 dB for 12.5 kHz. The significance of this variation with frequency and differences from the A-weighted value is discussed in sub-section 5.2.

5. TOTAL COMBINED STANDARD UNCERTAINTY FOR USE IN ISO STANDARDS

5.1 A-WEIGHTED NOISE EMISSION LEVELS

The combined total standard uncertainties from Tables 6 and 7 are expressed as a standard deviation. A standard deviation is a measure of the spread of a set of sound power level determinations, describing how values typically differ from the average. It is possible using a set of statistical tables to estimate the possibility of a single sound power level determination being different from the average sound power level by a given amount. It is usual to express this as a percentage of sound power level determinations that are expected to be outside a given range of sound power level. This percentage is called a confidence level and is an indication of how confident you are of a sound power level determination not being outside this range. For the purposes of inclusion in ISO standards it is suggested that a confidence level of 95% is adopted. For the case where the number of sound power level determinations in a set were very large (which is assumed here) it can be stated that 95% of sound power level determinations will be within a range of the average sound power level plus 1.96 (this is usually approximated to 2.0) times the standard deviation. This constant, 2.0 is called the coverage factor. The coverage factor multiplied by the standard deviation is known as the expanded uncertainty. The *Guide to the Expression of Uncertainties in Measurement* requires a sound power level, L_W to have a value of expanded uncertainty, U, to be specified, such that the interval $[L_W-U,\ L_W+U]$ covers a range of the values (this usually expressed as a percentage and here it is assumed to be 95%) of L_W that might reasonably be attributed to L_W. To that purpose, a coverage factor, k, is used (here it is assumed that the coverage factor is 2), such that $U=k.u$ (see Equation 2).

Using the data from Table 6 and 7, values of expanded uncertainty associated with a sound level meter can be calculated and are shown in Table 12. In Table 12, the values listed for sound level meter, (slm), in use, are the results of combining all the uncertainty contributions from both group (a) and (b) described in Section 2.

Table 12 Values of expanded uncertainty associated with a sound level meter

	Time weighting	Combined uncertainty	Expanded uncertainty
Slm operation: Group (a)	Fast	0.394	0.788
	Slow	0.362	0.724
Slm in use: Group (a) and (b)	Fast	0.423 (0.406)	0.846
	Slow	0.394 (0.375)	0.788

It can be seen from Table 12 that with the contribution from group (b), *(the uncertainties associated with the use of a sound level meter)*, increase the combined total standard uncertainties obtained from group (a), *(the uncertainties associated with the operation of a sound level meter),* by only 0.029 dB and 0.032 dB for the “fast” and “slow” time weighting respectively. These differences are reduced to 0.012 dB and 0.013 dB if it is assumed that δ_{obs} is zero (using the values in parenthesis in Table 12). The difference between the combined total standard uncertainty obtained for "fast" time weighting with that using "slow" time weighting is about 0.03 dB for all combinations shown in Table 12. In order to reduce the magnitude of the combined total standard uncertainty the use of the "slow" time weighting is recommended, especially when the format for reporting uncertainty values is considered (see following paragraph). Thus the value of the combined total standard uncertainty for a sound level meter is 0.394 dB or 0.375 dB when there is no observer present. However, this may be further reduced assuming there is no range change to 0.355 dB and 0.334 dB when there is no observer present. However, these reductions are not significant when the format for reporting uncertainty values is considered (see following paragraph).

The number of significant figures in a reported uncertainty should always reflect practical measurement capability. For the purposes of supplying a value of δ_{slm}, for inclusion in Equation 1, it is proposed that the combined total standard uncertainty is expressed to one place of decimals. Furthermore it is generally accepted that uncertainties should be rounded up to the appropriate number of significant figures(20). Thus the reported combined total standard uncertainty for measurements carried out using the "slow" time weighting (with or without an observer and with or without a range change) is 0.4 dB. This is increased to 0.5 dB if there is an observer and "fast" time weighting is used.

Similarly the value of expanded uncertainty assuming a confidence level of 95% will be 0.8 dB for "slow" time weighting (with or without an observer and with or without a range change) and 0.9 dB for "fast" time weighting with an observer. However, for the purposes of inclusion in an ISO standard only the value of combined total standard uncertainty is required as the value of δ_{slm} will be included in the combined total standard uncertainty for a sound power measurement that will, in turn, be expressed as an expanded uncertainty.

As discussed in sub-sections 3.1.1 and 3.1.2 the values of δ_{fr} and δ_{lin} may not be directly attributable to variations between sound level meters. If these two input quantities were, therefore, assumed to be negligible, the final combined total standard uncertainty would be reduced to 0.344 dB (when δ_{dl} is zero) and to 0.312 dB (when δ_{dl} and δ_{obs} are zero). Never the less, the reported uncertainty according to Reference 20 will still be 0.4 dB. However, it may be that for the purposes of including a value for δ_{slm} in Equation 1 the unrounded values may be used and the requirements of Reference 19 only considered for the uncertainty associated with a sound power level determination.

5.2 BAND-LIMITED NOISE EMISSION LEVELS

Whilst the prime driver for uncertainty data is to demonstrate compliance with noise emission level declaration as required for numerous regulatory purposes (see Section 2) it is of interest to examine potential changes to the combined total uncertainty as applied to frequency band limited data. The effect of variations in the value of uncertainty contributions for group (a) is considered in sub-section 5.2.1 and for group (b) in sub-section 5.2.2.

5.2.1 The effect on the final total combined uncertainty of frequency variations in group (a)

Applying values of δ_{fr} from Table 8 in sub-section 4.1 to the data in Table 6 produces the values of the final combined total uncertainty for "fast" and "slow" time weightings shown in Table 13.

Table 13 Final combined total uncertainty at octave-band centre frequencies for group (a)

Freq (kHz)	0.0315	0.063	0.125	0.250	0.500	2	4	8	12.5
Fast	0.441	0.419	0.403	0.396	0.392	0.394	0.400	0.409	0.406
Slow	0.413	0.390	0.372	0.364	0.360	0.362	0.369	0.378	0.375

The value of the standard deviation at 1 kHz is not shown as the value of δ_{fr} is given as zero in Table 8 (because it is the datum to which the sound level meter response at other frequencies is compared) and so, it is assumed that its value is similar to the adjacent frequency bands. The value of the final combined total uncertainty for the A-weighted network is 0.394 dB for "fast" and 0.362 dB for "slow" time weighting (see Table 6). It can be seen from Table 13 that a similar result is obtained, for both "fast" and "slow" time weighting, for frequencies between 250 Hz and 2 kHz with an increase of up to 0.016 dB above 2 kHz and increases of approximately 0.01 dB, 0.03 dB and 0.05 dB at frequencies of 125 Hz, 63 Hz and 31.5 Hz respectively. Considering the slow time weighting data (as recommended in 5.1 above, the range of values of from 0.413 dB to 0.360 dB may be reduced to 0.376 dB to 0.317 dB if it is assumed that there is no range change.

It may be concluded therefore that the A-weighted value for the total final combined uncertainty calculated for contributions in group (a) may be assumed for frequency band limited data.

5.2.2 The effect on the final total combined uncertainty of frequency variations in group (b)

Values of uncertainty contributions for band limited data were considered in sub-sections 4.2.1 to 4.2.5. The values of their uncertainty contribution are summarised in Table 14 together with values of final total combined uncertainty (TOTAL).

The A-weighted final total uncertainty from Table 7 is 0.155 dB. It can be seen from Table 14 that for frequencies below 4 kHz the value of the final total combined uncertainty is similar to the A-weighted value but there is an increase to 0.192 dB at 8 kHz and to 0.364 dB at 12.5 kHz.

If the group (b) data from Table 14 is combined with the group (a) data from Table 13 for slow time weighting, values of the final total combined uncertainty suitable for inclusion in an ISO standard may be assessed. Values calculated using all contributions and then assuming there is no observer present (δ_{obs} = 0) and also assuming there is no range change (δ_{obs} = 0 and δ_{dl} = 0) are listed in Table 15.

Table 14 Values of uncertainty contribution for group (b)

	Uncertainty contribution							
Freq (kHz)	δ_{obs}	δ_{dir}	δ_{case}	δ_{temp}	δ_{pres}	δ_{WS}	δ_{mic}	TOTAL
0.0315	0.12	0.06	.01	0.05	0.03	0.01	0.04	0.151
0.063	0.12	0.06	.01	0.05	0.03	0.01	0.04	0.151
0.125	0.12	0.06	.01	0.05	0.03	0.01	0.04	0.151
0.25	0.12	0.06	.01	0.05	0.03	0.01	0.04	0.151
0.5	0.12	0.06	.01	0.05	0.03	0.02	0.04	0.152
1.0	0.12	0.06	.01	0.05	0.03	0.02	0.04	0.152
2.0	0.12	0.01	.04	0.05	0.03	0.02	0.04	0.157
4.0	0.12	0.04	.01	0.05	0.03	0.02	0.04	0.145
8.0	0.12	0.13	.02	0.05	0.03	0.02	0.04	0.192
12.5	0.12	0.31	.07	0.05	0.03	0.06	0.05	0.364

Table 15 Band limited values of final combined total uncertainty

Freq (kHz)	All contributions	$\delta_{obs} = 0$	$\delta_{obs} = 0$, $\delta_{dl} = 0$
0.0315	.440	.423	.387
0.063	.418	.400	.362
0.125	.401	.383	.343
0.250	.394	.375	.334
0.500	.391	.372	.331
1.0	.392	.373	.332
2.0	.395	.376	.335
4.0	.400	.382	.342
8.0	.424	.407	.370
12.5	.523	.509	.480

It can be seen that assuming there is no observer and no range change the reported value of the final total combined uncertainty is 0.4 dB for all frequencies except 12.5 kHz where the value is 0.5 dB.

For the majority of ISO sound power standards the frequency range of interest is specified as covering one-third octave bands centre frequencies from 100 Hz to 10 kHz. In this case the reported final total combined uncertainty for band limited noise will be 0.4 dB.

6. CONCLUSIONS AND RECOMMENDATIONS

For contributions associated with the operation of a sound level meter, it is clear that to reduce the magnitude of the final combined total standard uncertainty, effort should be concentrated on reducing δ_{time} , δ_{rms} and δ_{dl}. The value of δ_{time} for the "slow" time weighting is less than that for "fast". Sound level meters with a single large dynamic range will of course reduce δ_{dl} to zero. The value of δ_{dl} will also be zero if the indicator range that is used for the sound pressure level measurement is the same as that used when applying the sound calibrator.

To reduce the magnitude of the combined total standard uncertainty the use of the "slow" time weighting is recommended.

It is recommended that the indicator range used for measurements is the same as that used for the sound calibrator.

For contributions associated with the use of a sound level meter, it is clear that to reduce the magnitude of the final combined total standard uncertainty effort should be concentrated on reducing δ_{obs}. If the indication on the sound level meter was observed remotely via an ac output (a common feature on class 1 meters) then δ_{obs} would be reduced to zero.

It is recommended that the indication on the sound level meter is observed remotely via an ac output (a common feature on class 1 meters).

The contribution from uncertainties associated with the use of a sound level meter, increase the combined total standard uncertainties obtained from the uncertainties associated with the operation of a sound level meter, by approximately 0.03 dB.

The actual estimated value of δ_{slm} for A-weighted noise emission levels assuming a slow time weighting is 0.39 dB. This value is reduced to 0.33 dB if there is no range change and there is no observer present (δ_{dl} and δ_{obs} =0) and reduced further still if it assumed that δ_{fr} and δ_{dl} are assumed negligible.

The reported combined total standard uncertainty for measurements carried out using the "slow" time weighting (with or without an observer and with or without a range change) is 0.4 dB. This is increased to 0.5 dB if there is an observer and "fast" time weighting is used.

It is recommended that the value of δ_{slm} to be used when reporting a sound pressure level measurement is 0.4 dB but for an uncertainty budget in ISO sound power standards, a value of 0.33 dB should be used.

For the majority of ISO sound power standards the frequency range of interest is specified as covering one-third octave bands centre frequencies from 100 Hz to 10 kHz. In this case the reported final total combined uncertainty associated with band limited noise emission is the same as the A-weighted value.

7. ACKNOWLEDGEMENTS

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ANNEX A – MEASUREMENT DATA

Table A.1.1 Values of A-WEIGHTING factors from verification measurements

	A-weighting factor (dB)																						
	Sound level meter																						
Freq	Ideal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
31.5	-39.4	-39.6	-39.3	-39.5	-40.3	-39.2	-39.6	-39.4	-39.6	-39.5	-39.6	-39.4	-39.5	-39.9	-39.5	-39.9	-39.9	-39.5	-39.1	-39.7	-39.7	-39.5	-39.4
63	-26.2	-26.3	-26	-26.3	-26.6	-26	-26.3	-26.2	-26.3	-26.2	-26.4	-26.2	-26.1	-26.4	-26.2	-26.4	-26.6	-26.3	-26.1	-26.3	-26.3	-26.1	-26.1
125	-16.1	-16.3	-16	-16.3	-16.4	-16.1	-16.2	-16.1	-16.3	-16.2	-16.3	-16.2	-16.1	-16.3	-16.2	-16.4	-16.4	-16.3	-16.1	-16.2	-16.2	-16.1	-16.2
250	-8.6	-8.7	-8.5	-8.7	-8.7	-8.7	-8.7	-8.6	-8.8	-8.7	-8.8	-8.7	-8.7	-8.7	-8.7	-9.1	-8.9	-8.8	-8.7	-8.8	-8.7	-8.6	-8.7
500	-3.2	-3.3	-3.2	-3.3	-3.2	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.3	-3.4	-3.3	-3.3	-3.5	-3.3	-3.3	-3.3	-3.3	-3.3	-3.2	-3.3
1k	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2k	1.2	1.2	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.2	1.2	1.4	1.2	1.2	1.2	1.2	1.1	1.1	1.2
4k	1	1	0.8	0.9	0.9	1	0.9	1	0.9	0.9	0.9	0.8	0.9	0.9	1	1.2	1	1	1	1.1	0.9	0.8	0.9
8k	-1.1	-1.1	-1.4	-1.2	-1.2	-1	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1.2	-1	-1	-1.2	-1.2	-0.9	-1.1	-1.2	-1.5	-1.2
12.5k	-4.3	-4.2	-4.5	-4.2	-4.4	-4.1	-4.3	-4.3	-4.3	-4.4	-4.3	-4.3	-4.4	-4.3	-4.3	-4.4	-4.3	-4.3	-3.5	-4	-4.3	-4.5	-4.4

Table A.1.2 Factors relating to LINEARITY, TIME WEIGHTING and DETECTOR characteristics from verification measurements

		Factor (dB)																					
		Sound level meter																					
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Ref	-ve	0	-0.24	-0.02	0.04	-0.05	0	0.02	-0.08	-0.01	-0.16	-0.15	0.26	0.11	0.00	-0.09	0.08	0.04	-0.08	-0.02	0.01	0.29	0.03
range	+ve	0	0.04	0.01	0	-0.06	0.01	-0.16	0.11	0	0.15	0.03	0.2	-0.01	0.00	0.10	-0.03	0.03	0.01	0.00	-0.01	-0.08	-0.05
Other	-ve	0.06	-0.2	0	0	-0.02	-0.02	-0.22	-0.02	-0.01	0.03	-0.09	0	0.03	-0.66	0.32	0.03	0.05	-0.02	-0.55	-0.12	-0.05	-0.04
range	+ve	0.1	-0.01	0	-0.07	-0.06	0	0	0.11	0	0.16	-0.04	0	0.06	-0.08	0.41	0.08	0.03	0.07	-0.05	-0.12	-0.05	0.03
Time	Fast	-0.6	0.3	-0.1	0	-0.1	0	-0.1	-0.1	0	-0.10	-0.30	-0.5	-0.70	0.00	-0.10	-0.30	-0.10	-0.10	0.00	-0.10	-0.20	0.00
	Slow	-0.3	0.1	0	0.5	-0.2	0	-0.1	0	0	-0.20	0.00	-0.2	-0.20	0.00	0.10	-0.70	-0.10	0.10	0.00	0.00	-0.10	0.00
ave	Rms	-0.1	0.3	-0.3	-0.1	0.3	0.2	0.2	0.1	0.2	0.20	0.20	0.2	-0.10	-0.20	-0.20	-0.20	-0.10	-0.10	-0.10	-0.20	-0.20	0.10