An introductory guide to uncertainty in acoustic measurements

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1. Preamble

This paper has been prepared as part of a chapter on accuracy, uncertainties and errors in environmental and occupational noise measurement. It was prepared by the authors for use in the Massey University course notes for the 300-level course, 214.316 Biophysical Effects of Noise and Vibration.

2. Introduction

In 1977, some 40 years ago now, the 'Comité International des Poids et Mesures[1]' requested the Bureau International des Poids et Mesures[2] recognise a deficiency of international consensus on the expression of uncertainty in measurement and address this problem in conjunction with the then (inter)national standards laboratories and make a recommendation.

The 'Bureau International des Poids et Mesures[3]' then convened a meeting of experts from various countries around the world for the purpose of arriving at a uniform and generally acceptable procedure for the specification of uncertainty. This Working Group on the 'Statement of Uncertainties' developed Recommendation INC-1 (1980), Expression of Experimental Uncertainties [1]. The 'Comité International des Poids et Mesures' approved the Recommendation in 1981 [2] and re-affirmed it in 1986 [3]. The task of developing a detailed guide based on the Working Group Recommendation was referred by the 'Comité International des Poids et Mesures' to the 'International Organization for Standardization' (ISO) [4], as it was believed that ISO could better reflect the needs arising from the broad interests of industry and commerce at that time.

Since the original recommendations of the Working Group and their 'Statement of Uncertainties' on the topic, there has been a variety of international research papers and practice guides on the application of measurement accuracy, uncertainty and error in environmental and occupational acoustics. In New Zealand, however, the topics of measurement accuracy, uncertainty and error tend to be generally either overlooked or only given reference, if any, when being assessed and reported on.

This is not necessarily due to any valid attempt to evade the subject matter, but appears more to be related to the fact that uncertainties have not historically been required. Furthermore, it appears from anecdotal investigations on the issue, that the subject matter can be generally misunderstood and in some cases hard to comprehend. It is also understood that the topic of uncertainty although taught at basic Secondary School Science level, is not always covered, or covered to the required detail within courses on acoustics in New Zealand. Regardless, it is important that both experts and non-experts alike have a basic understanding of the topic and its concepts.

This paper has been prepared first and foremost as a guide to the accuracy, error and uncertainty in acoustic measurement and assessment. It is an introductory guide on the uncertainty of acoustic measurement, for acoustic engineers and students involved in the measurement, assessment and prediction of environmental and occupational noise. This paper explains some of the key concepts to enable the reader to have a better understanding of the subject matter. It covers environmental and occupational acoustics, with a comment on environmental noise modelling and standards. Building acoustics is outside the scope of the paper.

3. Acoustic measurement

A measurement tells us about a quantity of something such as how long or how heavy an object is, with the measurement presented as a number to that property. The term 'measurand' is a technical term often used in science, meaning a 'quantity intended to be measured'. Measurements are made using an instrument of some kind, including the sound level meter used in acoustics to measure sound pressure level or intensity. In the case

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[1] Comité International des Poids et Mesures from the French translation meaning 'The International Committee for Weights and Measures', Abbreviated CIPM

[2] Bureau International des Poids et Mesures from the French translation meaning 'The International Bureau of Weights and Measures', abbreviated BIPM

[3] New Zealand is a member of BIPM, see www.bipm.org/en/about-us/member-states/nz

of acoustic measurement, the result can be expressed in three parts, the quantity, the unit and the descriptor; for example, 50 dB LAeq,8h.

In the field of acoustics, the objective of any measurement is to determine the 'true' value, which in itself is an idealised concept as there is no such thing as a 'perfect measurement'. For example, an environmental measurement result is only an approximation or estimate of the 'true' value and thus is only complete when accompanied by a statement of the uncertainty. Any measurement will also have imperfections that give rise to an error in the measurement result.

Traditionally, an error is viewed as having two components; namely, a random component and a systematic component. In acoustics, the result of a measurement is generally determined on the basis of series of observations obtained under repeatable and/or reproducible, conditions. There will always be variations in repeated observations, and these are assumed to arise because of the many intervening variables that can influence results.

In real-life acoustical practice, the requirement to have accurate assessment is key, as the purpose of any acoustic measurement is to provide the best estimate of the true sound pressure level. This must include the consideration of inaccuracies as well as noting any known limitations, qualifications or errors in the overall measurement system or measurement chain. Therefore, any acoustic measurement begins with an appropriate specification of the quantity intended to be measured, the method of measurement and the measurement procedure itself.

3.1 Importance of uncertainty in acoustic measurement

Acoustic engineers will be interested in the uncertainty of measurement because they wish to undertake good quality and accurate measurements and to understand the results when undertaking any assessment. The aim is to be as accurate as possible, as an overestimation of uncertainties could also have undesirable repercussions. The flip side of any 'underestimate' of uncertainties may also cause too much conviction to be placed in the values reported. In both cases this could lead to unintended consequences. For example, financial implications may result if remedial work was required due to an underestimation of a true value. In all cases a "true" value, not a "safe" value, of the uncertainty of each of the results is the overall aim and one primary reason to employ a suitable qualified and experienced acoustical engineer.

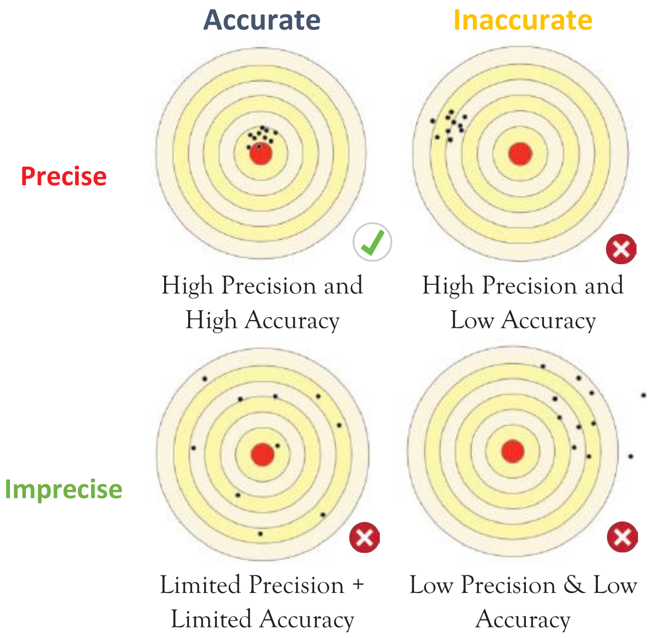
4. Key concepts in measurement

4.1 Accuracy and precision

When collecting measurement samples, any valid measurement, including acoustical measurements, will be made with the aim to be a 'true' representation, as well as being accurate and precise. The term 'precision' should not be confused with the term 'accuracy'. However, in many cases people often get the two concepts and terms confused.

The accuracy of measurement is the closeness of the agreement between the result of a measurement and a 'true value'. The term 'accuracy' is a qualitative concept, which relates to the quality of something rather than its quantity. In lay terms, accuracy is how close a measurement is to the 'true' or accepted value while precision can be thought of in terms of the repeatability, or reproducibility of the measurement. In other words, are the results consistent each time a measurement is taken? Thus, the more consistent the results the more precise the measurements.

It is possible to have precise measurements that are not accurate. It is also possible to have accurate measurements that are not precise. Figure 1 illustrates four concepts of accuracy and precision using a 'target analogy', where the aim is to be both accurate and precise in measurement.



High Precision and High Accuracy

High Precision and Low Accuracy

Limited Precision + Limited Accuracy

Low Precision & Low Accuracy

Figure 1: Accuracy and precision – the 'target analogy'

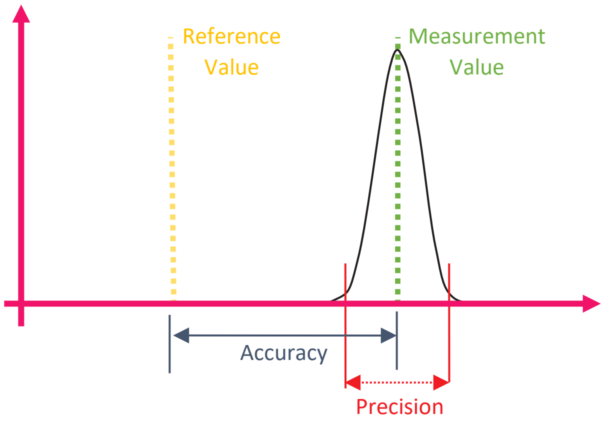


Figure 2: Accuracy and precision – A graphical representation

Figure 2 illustrates the same concepts using a graphical representation.

4.2 Repeatability and reproducibility

Repeatability and reproducibility are two components of precision. Reproducibility is one component of the precision of a measurement or method while the second component is repeatability. Figure 3 illustrates the concept of repeatability and reproducibility.

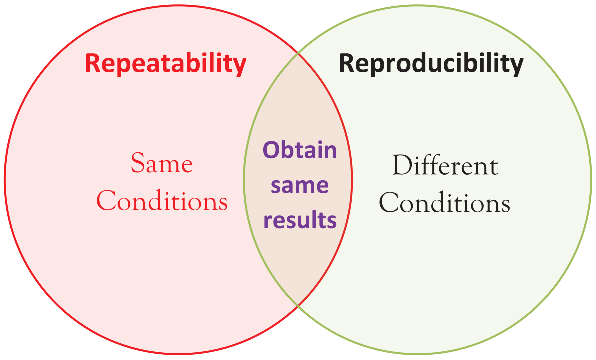


Figure 3: Repeatability and reproducibility

Repeatability is the ability of an acoustic engineer to consistently make the same measurement under the *same conditions*. That is, the closeness of the agreement between the results of successive measurements carried out under the *same conditions* of measurement. Repeatability conditions include (but are not limited to) the same measurement procedure, the same observer, the same measuring instrument (used under the same conditions) and at the same location.

Reproducibility is the ability of different acoustic engineers to consistently reproduce the same measurements under *changed conditions*, this is, the closeness of the agreement between the results of measurements carried out under changed conditions. A valid statement of reproducibility requires specification of the conditions changed. The changed conditions may include (but are not limited to): to the principle of measurement; method of measurement; measuring instrument; locations; time and reference standard.

4.3 Uncertainty

The concept of uncertainty in lay terms means doubt, and thus in its broadest sense "uncertainty of measurement" means doubt about the validity of the true value of a measurement. Although error and error analysis have long been a part of the practice of measurement science and acoustics, the concept of uncertainty as a quantifiable attribute (able to be expressed as a quantity) is relatively new in the history of measurement, as well as the history of modern acoustics in New Zealand.

It is widely recognised that even when all of the known or suspected components of error have been evaluated and the appropriate corrections have been applied, there still remains uncertainty about the stated result, that is, some doubt about how well the result of the measurement represents the value of the quantity being measured.

An example might be that the best produced sound level meter that is a well-known and trustworthy brand will 'give the right answers'. However, what any student needs to understand is that for every measurement there is always a margin of doubt or margin of error. The true value (of a quantity usually being decibels in acoustics) is the value attributed to a particular quantity and accepted, sometimes by convention, as having an uncertainty appropriate for a given purpose.

The uncertainty of measurement is a parameter, associated with the result of a measurement that characterises the dispersion of the values that could reasonably be attributed to the measurand. The uncertainty of measurement comprises, in general, many components. Thus, when given a measurement result and reviewing uncertainty, it is important to note that there is not one true value but an infinite number of values. These would be dispersed about the presented measured result that is consistent with all of the observations and data and that also has varying degrees of credibility attributed to the results.

Once we understand the concept of uncertainty means doubt, the next concept to understand is how 'big' is the margin or how 'sure' is the doubt. Thus, two further concepts are needed in order to quantify uncertainty. The first is the 'width' of the margin or more widely referred to as the 'confidence interval'. The second is the 'confidence level' which tells us how sure we are that the 'true' value is within the given margin.

An example is the length of a piece of a metal. The metal bar measures 100 ±1 mm at a 95% confidence level. These results can be interpreted in lay terms stating that we are 95% sure that the metal bar is between 99 mm and 101 mm in length. The ±1 mm in this example is the confidence interval (how big is the margin), and the 95% is the confidence level (how sure we are that the 'true' value is within the given margin).

5. Sources of uncertainty

In some publications, uncertainty components are categorised as "*random*" and "*systematic*" and are associated with errors arising from random effects and known systematic effects. This view is not entirely correct. The ideal method for evaluating and expressing the uncertainty of the result of a measurement should be universal. That is, the method should be applicable to all kinds of measurements and to all types of input data used in measurements.

The actual quantities used to express uncertainty should themselves be internally consistent, that is the measurements should be directly derivable from the components. Additionally, they should be independent of the component grouping, and of the decomposition of these components into sub-components.

The quantity used to express uncertainty should also be transferable, meaning that it should be possible to use directly, the uncertainty evaluated for one result, as a component in evaluating the uncertainty of another measurement, in which the first result is used. The uncertainty in the result of a measurement generally consists of several components which may be grouped into two categories according to the way in which their numerical value is estimated: those which are evaluated by statistical methods; and those which are evaluated by other means.

In practice, there are many possible sources of uncertainty in a measurement, including the incomplete definition of the actual quantity intended to be measured, the imperfect realisation of the definition of the quantity intended to be measured and non-representative sampling (the sample may not represent the defined quantity). Other possible sources of uncertainty include inadequate knowledge of the effects of environmental conditions on the measurement or imperfect measurement of environmental conditions, personal bias, approximations and assumptions incorporated in the measurement method and procedure and variations in repeated observations of the quantity being measured under apparently identical conditions.

These sources are not necessarily independent and an unrecognised systematic effect cannot be taken into account in the evaluation of the uncertainty of the result of a measurement, but contributes to its error.

5.1 Good practice to reduce uncertainty in noise measurements

The Salford University '*A good practice guide on the sources and magnitude of uncertainty arising in the practical measurement of environmental noise*' [5] summarises some of the more frequently encountered sources of measurement uncertainty. As shown in figure 4, the contributions to the uncertainty assessment are partitioned into three areas.

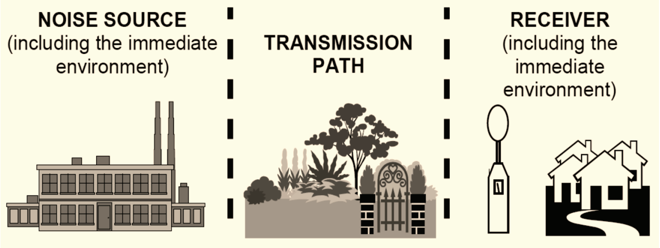


Figure 4: Partitioning of uncertainty assessment

The following list, summarised from the Salford University guide, is an ephemeral summary of some of the good practice measures to follow for the management of uncertainty.

1. The noise source and immediately surrounding environment

Spectral content of the noise emission: *Sources of uncertainty can include sound levels influenced by standing waves / interference patterns/beats and subjective assessment of tonality affected by standing waves/interference patterns]. Good practice includes determining the probability of standing waves and checking for the presence of standing waves, either subjectively by listening in several places around the measurement position, or by observing any change in level. If standing waves are present and cannot be avoided, take a spatial average, either by measuring at several fixed positions, or by slowly moving the microphone around the measurement position, whilst continually logging sound energy. Anticipate significant levels of uncertainty when measuring noise at the extremes of the audio frequency range, i.e. below 125 Hz or above 4 kHz.*

Nature of the noise source: point/line/area: *Sources of uncertainty can include the degree to which a single measurement is representative of a larger area. Good practice includes investigating all noise sources and determining their type, and the likely pattern of propagation plus the effect at the measurement position.*

Running condition, operator preference/machine load: *Sources of uncertainty can include variability in the running condition of the noise source for example operator preference and load. Good practice includes determining which variables may affect the noise emission and record the running condition at the time of measurement as well as considering how it fits in with all possible conditions. If necessary measure under different sets of conditions, the type and number of measurements will depend upon the nature of the task/reason for the measurement. Those conditions giving rise to average/ maximum noise levels may be considered a minimum. If no reliance can be placed on the word of the operator repeated measurements should be considered in critical situations.*

State of repair: *Sources of uncertainty can include variation in the noise emission due to wear and tear and subsequent maintenance. Good practice includes determining and recording the state of repair of the noise source(s) and enclosure(s) as well as carrying out additional checks to determine the likely variation in the level, before and after maintenance.*

Source height: *Sources of uncertainty can include variability in the measured sound pressure level due to the increasing influence of weather with source height or change in ground surface condition. Good practice includes anticipating greater uncertainty when measuring noise from elevated sources, repeat measurements under different propagation conditions if necessary.*

Movement of noise source (sources are stationary or moving): *Sources of uncertainty can include the unknown random pattern of a movable source or the number of moving sources. Good practice includes ddetermining and logging the movement and number of source(s) during the measurement. If the movement follows a routine, measure representative levels for one or more complete cycles.*

Enclosures and barriers close to the source: *Source of uncertainty may include changes to enclosures, buildings, openings in buildings or barriers surrounding the noise source. Good practice includes inspection of the noise source to determine the probable effect of and the possibility of changes occurring during the measurement. List possible changes and periodically check.*

Environmental conditions (weather): *Source of uncertainty include the ambient temperature which may affect the noise source for a number of reasons, including a change in the sound power of the noise source through to a change in the attenuation characteristics. Good practice includes determining the likely effect of changes in the prevailing weather conditions on the noise source as well as ensuring that the noise source is operating under conditions relevant to the purpose of the survey.*

Number of sources in operation and their positions relative to the measuring positions: *Source of uncertainty can include the mode of operation, particularly when concerned with outdoor activities. Good practice includes keeping a record and report the prevailing conditions at the time of measurement.*

2. The transmission path

Weather: *Source of uncertainty can include many things such as meteorological changes during measurements, meteorological conditions different from previous measurement period and meteorological conditions unrepresentative of conditions under which measurements should have been made. Good practice includes a review of the weather forecast when planning measurement sessions as well as keeping a good record of meteorological conditions for the duration of the measurement and avoiding measuring during extreme conditions unless specific conditions are required as part of the measurement or testing, otherwise only conduct measurements during favourable propagation conditions.*

Ground effects: *Source of uncertainty can include variability in the measured sound pressure level due to changes in the ground surface during or between measurement periods and excess attenuation due to the ground dip. Good practice includes avoiding noise measurement during or immediately after precipitation, accompany measurement results with a description of the ground surface between the noise source and measurement position and consider taking a spatial average when measuring tonal noise close to an acoustically hard surface. Good practice also means estimating the source and receiver heights/distance and fully reporting and logging all measurement results. By measuring under conditions favourable for propagation (downwind/temperature inversion), attenuation due to the ground dip will be minimised. Not only will the measurements represent the worst case, usually* *the cause of complaint, but a higher of repeatability will be achieved.*

Barriers: *Source of uncertainty can include variation in the depth of the acoustic shadow cast by a barrier due to changes in the weather and changes to a barrier due to man's activity or the season. Good practice includes noting the potential effect of changes in weather on barrier shadow and having regard for the effect of seasonal changes such as on foliage.*

3. The receiver and immediately surrounding environment

Microphone position: *Source of uncertainty can include not reporting the exact microphone orientation and position with respect to all other significant reflecting surfaces and not checking that small changes in location have minimal effect on measurements. Good practice includes following the standards for guidance as well as ensuring the microphone height and reason for choosing that height should be recorded.*

Instrumentation: *Source of uncertainty can include use of instrumentation with an unknown degree of precision in or as part of the measurement chain and uncertainty associated with the precision of the measurement. Good practice includes ensuring that the whole measurement chain (including field calibrator) meets the required degree of precision and that you report the type of meter and calibrator used with the measurement results together with details of all other instrumentation used. Good practice also means you follow the manufacturers' instructions and standards such as ensuring all noise measurements are conducted using a sound level meters and field calibrators whose conformance and calibration have been checked periodically against national standards.*

Choice of measurement position: *Source of uncertainty can include interpreting measurement results as representative of something other than that which was actually measured and comparing measurement results taken at different positions. Good practice includes ensuring all measurement positions should be selected to minimise the influence, on the measurement result, of all factors other than the subject of the measurement. To enable repeatably, and therefore comparable measurements, the exact location should be reported such as in a diagram or with GPS co-ordinates including distances to all significant reflecting surfaces and other features. When assessing community noise complaints, it is useful to measure at a number of positions around the noise source to build up an understanding of the noise environment.*

Background noise level: *Source of uncertainty can include variable and complex patterns in the noise emission along with large variations in the measured level due to changes in the weather. Good practice includes considering how the weather will affect the measurement result as well as consider how long-term patterns in the noise emission will affect the measurement result.*

4. Key Players

The Assessor (the person carrying out the measurements)

The Complainant (if applicable)

The Client: The Source Owner

Source of uncertainty across these areas can include incorrect measurement planning generally caused by lack or incorrect knowledge of the problem/site/surrounds/source etc. Good practice includes the use of a check-list and a custom before measurement plan before commencing measurements.

6. Calculating uncertainty

To calculate the uncertainty of a measurement, including in acoustics, firstly you must identify the sources of uncertainty in the measurement chain. Then you must estimate the size of the uncertainty from each source and ensure the same units are used for all quantities. Finally, the individual uncertainties are combined to give an overall figure.

There are clear rules to follow for assessing the contribution from each uncertainty, and for combining the overall uncertainties together.

No matter what are the sources of your uncertainties, there are usually two accepted approaches to estimating uncertainty; many text books describe these as 'Type A' and 'Type B' uncertainty evaluations. In most measurement situations, uncertainty evaluations of both types are needed or can be applied.

Type A Evaluation

Type A evaluations are uncertainty estimates using *statistics* (usually from actual repeated measurements). Type A measurement of uncertainty for data is where the distribution of values is spread around the mean (of a normal distribution) and the magnitude of the standard uncertainty can be calculated from repeated measurements. Type A assessments can be for a set of 'n' measurement data with the standard uncertainty associated with the *mean* of that data or the estimated standard uncertainty of any one measurement.

- Standard uncertainty (see Section 6.1) for one measurement is: $u = s$
- Standard uncertainty of the mean (more than one measurement) is given by: $u = s/\sqrt{n}$, where s is the estimated standard deviation (σ_{n-1}) of a set of n data, based on a measure of the spread of results of a limited sample.

When calculating standard uncertainty for each factor or magnitude, Type A evaluation is done with a set of repeated readings enabling the mean and estimated standard deviation to be calculated for the data set.

For example, the height of a microphone on a tripod is measured four times: 1.52 m, 1.50 m, 1.52 m and 1.58 m. The mean height is calculated: x = 1.53 m; and the standard deviation, sd = 3.5 mm. Thus the standard uncertainty of the mean is: $u = sd/\sqrt{n} = 3.5/\sqrt{4} = 1.7$ mm. Therefore, the height of the microphone is 1.53 m with a standard uncertainty of 1.7 mm.

Using the same method, equipment and operator, a second microphone is measured once at 1.51 m. The uncertainty associated with a single measurement may be calculated from the measurements of the first microphone. Standard uncertainty $u = sd = 3.5$ mm. Therefore, the height of the second microphone is 1.51 m with a standard uncertainty of 3.5 mm.

Type B Evaluation

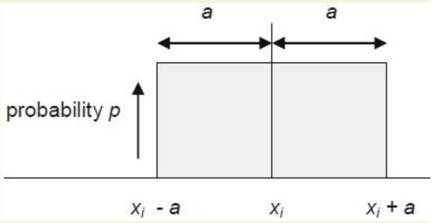
Most other evaluations are Type B evaluations where there is only an *estimate* of the upper and lower limits (± x) of uncertainty and we have to assume that the value can fall anywhere between the limits, with equal probability (rectangular distribution).

Type B assessments are generally based on estimates or literature from published data or manufacturers' data for example, as opposed to actual measurements.

Type B Evaluation

Rectangular/Uniform Distribution

Standard uncertainty with equal probability: $u = a/\sqrt{3}$



An estimate of the upper and lower limits (± x) of uncertainty

Figure 5: Type B evaluation of uncertainty

For data with estimated upper and lower limits ($x \pm a$) of uncertainty, you assume that the value can fall anywhere between with equal probability (rectangular distribution), the standard uncertainty is: $u = x/\sqrt{3}$.

For example, a sound level meter displays the measurement result of 55.5 dB. There is equal probability that the true value lies at any point in the range 54.5 dB to 56.5 dB; that is, the true measurement result is 55.5 ±1.0 dB.

The standard uncertainty is: $u = 1.0/\sqrt{3} = 0.6$ dB (to 1 decimal place). Therefore, it may be stated that the sound level meter has displayed a result of 55.5 dB with a standard uncertainty of 0.6 dB. For most practical measurements this would be regarded as small.

It should also be noted at this point that there is often a mistake made to describe 'Type A' evaluations as 'random' and 'Type B' evaluations as 'systematic', but this is not necessarily true in all cases, and should be treated with caution (see Section 10.0 for more detail).

There are different classification methods of evaluating uncertainty components. The different terms are discussed in the following sections.

6.1 Standard uncertainty

Standard uncertainty in environmental and occupational noise measurement is the result of a measurement expressed as a standard deviation. The standard uncertainty is denoted by *u*. The standard uncertainty of the mean has historically also been called the standard deviation (*sd*) of the mean, or the standard error of the mean. The standard uncertainty tells us about the uncertainty of an average (not just about the spread of values). The intended purpose of *u* is to provide an interval about the result of a measurement.

In terms of acoustic engineering, an example of standard uncertainty could be the standard uncertainty due to the variation of weather estimated as 2.7 dB. When assessing standard uncertainty, you will always need to know the source of the uncertainty. For the example above, the source is the weather. Other sources of uncertainty include the receiver, sound path and noise source(s).

Standardisation of confidence level

Standard uncertainty equates to a 68% level of confidence (see Section 6.4 for more detail) in the measurement. All sources of uncertainty need to be expressed at the same confidence level so they can be combined together later on.

For example, a source of literature states that the total estimated accuracy of a Class 1 sound level meter is ± 1.6 dB at a 95% level of confidence (± 2 *sd*). The standard uncertainty equates to a 68% level of confidence (± 1 *sd*). Therefore, the standard uncertainty for the Class 1 sound level meter is: $u = 1.6/2 = 0.8$ dB.

Convert to same units

All standard uncertainty values must be expressed in the same units, so they can be combined together. So if the final value is expected to be stated in dB, then all the standard uncertainty values must be converted to dB.

For example, a source-to-receiver distance has been measured as 30 m with a standard uncertainty of ±1 m. This may be converted to dB using the inverse square law:

+1 m equates to: $10 \log_{10}(((30+1)/30)2) = +0.28$ dB

-1 m equates to: $10 \log_{10}(((30-1)/30)2) = -0.29$ dB

Because of the log scale, it produces a slightly asymmetric uncertainty interval. So approximate by taking the larger value, hence the uncertainty of ±1 m in 30 m may be considered to be the equivalent of ±0.29 dB.

6.2 Combined uncertainty

Combined standard uncertainty is the standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, that is, the combination of the individual standard uncertainties. The combined standard uncertainty is denoted by u_c. In acoustic engineering, the standard uncertainty could be the result of a measurement, when that result is obtained from the values of a number of other quantities, for example, the standard uncertainty from source, receiver and transmission path. Individual standard uncertainties ($u_1, u_2, \ldots, u_n$) calculated by Type A or Type B evaluations can be combined validly by 'summation in quadrature' (also known as 'root sum of the squares'). The combined standard uncertainty for a normal distribution is:

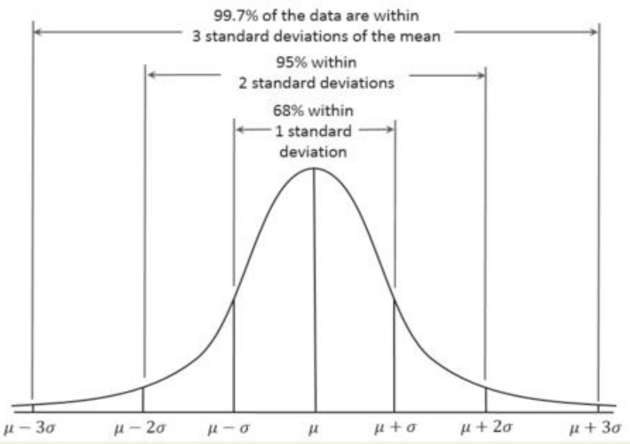
$$u_c = \sqrt{(u_1^2 + u_2^2 + u_3^2 + \ldots)}$$

6.3 Coverage factor

The *coverage factor*, *k*, is a numerical factor used as a *multiplier* of the combined standard uncertainty in order to obtain an expanded uncertainty. The coverage factor is stated so that the standard uncertainty of the measured quantity can be used in calculating the combined standard uncertainty of other measurement results that may depend on that quantity. The value of the coverage factor is chosen on the basis of the level of confidence (confidence level) required of the interval.

If uncertainty values are normally distributed, one standard deviation about the mean ($k = 1$) corresponds to a 68% confidence interval (see Figure 6 below). This is the default for all the standard uncertainty calculations so they can be pooled to produce the combined uncertainty.

Normal Distribution – "Bell Curve"



±1 standard deviation ≈ 68% confidence

±2 standard deviations ≈ 95% confidence; and

±3 standard deviations ≈ 99% confidence

Figure 6: Normal distribution and percentage confidence

One way to review the coverage factor is that once the combined standard uncertainty is calculated (which is based on one standard deviation about the mean) we can then re-scale the result to have the overall uncertainty stated at another level of confidence. Normal practice is to re-scale the combined standard uncertainty to a level of confidence of 95%.

Wherever an expanded uncertainty is quoted with a given coverage factor, you can find the standard uncertainty by the reverse process, that is, by dividing by the coverage factor.

Table 1: Different percentage confidence levels and their corresponding coverage factor

Confidence level, p (expressed as a %)	Coverage factor, k
68%	1
90%	1.645
95%	1.960
95.5%	2
99%	2.576
99.7%	3

The value of the coverage factor is chosen on the basis of the percentage of confidence (confidence level) that is required. The relationship between the coverage factor and the percentage confidence level (for a normal distribution) is shown in Table 1.

6.4 Expanded uncertainty

The expanded uncertainty is a quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values. It is simply the combined uncertainty multiplied by a coverage factor and produces a new confidence interval for the measurement.

Expanded uncertainty U, is given by multiplying the combined standard uncertainty u_c, by the chosen coverage factor, k:

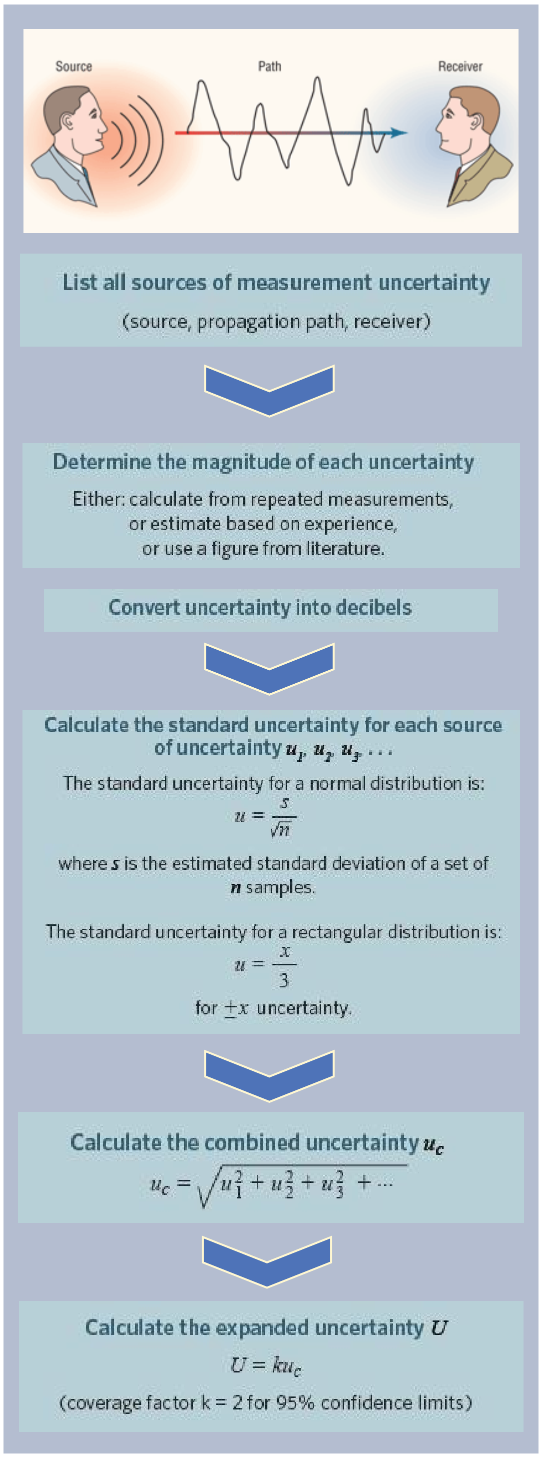
$$U = k\,u_c$$

7. Expression of uncertainty in acoustic measurement

Correct use of noise conventions is important in acoustics so that persons using the current notation are clear on which particular noise descriptors are being used. The standard final notation for expressing uncertainty is then expressed as (value) ± U with a confidence level of 95%. For example, 50 ± 3 dB, with a confidence level of 95%. However, in acoustics, a host of noise descriptors are also used such as L_{A10}, L_{Aeq} and L_{AFmax} for example, which must also be factored into the notation. Thus, in acoustics, the format should be '*value-uncertainty-unit-descriptor-confidence level*'. For example, 50 ± 3 dB $L_{Aeq,15min}$ with a confidence of 95%. Note, in this example, the measurement result would normally be expressed to the nearest whole value and the confidence level to one decimal place.

8. Overview of the uncertainty process

For the purpose of acoustic measurements, the following flow chart (Figure 7) provides the general steps to evaluating the overall uncertainty of a measurement.



List all sources of measurement uncertainty

(source, propagation path, receiver)

Determine the magnitude of each uncertainty

Either: calculate from repeated measurements, or estimate based on experience, or use a figure from literature.

Convert uncertainty into decibels

Calculate the standard uncertainty for each source of uncertainty $u_1, u_2, u_3, \ldots$

The standard uncertainty for a normal distribution is:

$$u = \frac{s}{\sqrt{n}}$$

where s is the estimated standard deviation of a set of n samples.

The standard uncertainty for a rectangular distribution is:

$$u = \frac{x}{3}$$

for $\pm x$ uncertainty.

Calculate the combined uncertainty u_c

$$u_c = \sqrt{u_1^2 + u_2^2 + u_3^2 + \cdots}$$

Calculate the expanded uncertainty U

$$U = ku_c$$

(coverage factor k = 2 for 95% confidence limits)

Figure 7: Flow chart of overall uncetainty evaluation

9. The Uncertainty Budget

The following two examples illustrate uncertainty budgets for the source, receiver and transmission path. The first one in Table 2 is a simple controlled scenario using a Class 1 sound level meter.

As can be seen from the table above, the greatest contribution to the uncertainty budget is the transmission path with 1.5 dB of standard uncertainty. The sound source was very stable, contributing only 0.7 dB, with a similar level of contribution from the calibrated Class 1 sound level meter. Yet overall, the expanded uncertainty is over 3 dB for this controlled scenario. If the measured value was 55 dB $L_{Aeq,15min}$, then the final expression of the result is 55 ± 3.6 dB $L_{Aeq,15min}$ with a confidence of 95%.

Table 2: Simple uncertainty budget for a controlled scenario

Source of Uncertainty	Standard uncertainty (dB)	Notes
Source	0.7	Rectangular Distribution
Transmission Path	1.5	
Receiver	0.8	Class 1 SLM
Combined uncertainty (u_c)	1.84	√(Source^2+Path^2+Receiver^2)
Expanded uncertainty (U)	3.6	u_c x 1.96 (for 95% confidence)
±3.6 dB (at 95% confidence)		

The second scenario corresponds to a short-term environmental noise assessment using $L_{Aeq,1h}$, under favourable conditions. The uncertainty budget is shown in Table 3. The most significant contribution to the budget is the weather, and it is unlikely this can be reduced. The measured value was 52 dB $L_{Aeq,1h}$, so the final expression of the result is 52 ± 4.6 dB $L_{Aeq,1h}$ with a confidence of 95%.

It is worth noting that this level of uncertainty is the same as that reported in a number of studies involving experienced practitioners measuring the same environmental noise using their own equipment, under favourable conditions. In practice, the uncertainty may be larger for inexperienced operators and under less favourable conditions.

Without an uncertainty budget and a significant number of repeated measurements, it is not unreasonable to assume that the level of uncertainty in environmental noise measurement may be at in the order of ± 5 dB L_{Aeq}.

10. Random and systematic error

The influences that give rise to uncertainty are recognised as either random or systematic. The concept of error is an idealised concept and errors cannot be known exactly. Figure 9 illustrates the two concepts of systematic error and random error using a 'target analogy'.

Systematic errors, are reproducible inaccuracies that are consistently in the same direction.

10.1 Random Error

A random error in measurement is caused by variability factors which vary from one measurement to another, thus a random error as the name suggests is random in

Table 3: Uncertainty budget for a more complex scenario under favourable conditions

Source of Uncertainty	Notes	Value (half-width)	Conversion of uncertainty (dB)	Distribution (divisor)	Standard Uncertainty (dB)
Source					
Location/Position	Stationary, stable	1 dB	NA	Normal (1)	1.0
Directionality	Omni-directional				
Transmission Path					
Weather	Wind direction and temperature (stable)	3 dB	NA	Rectangular (√3)	1.73
Ground	Not a major concern				
Topography	Flat – no change	none			
Receiver					
Location/Position	Uncertainty in height	0.7 dB	NA	Normal (1)	0.7
	Uncertainty in distance from source	1 in 100 m	0.09	Rectangular (√3)	0.05
Instrumentation	Class 1 with windshield	1.7 dB		Rectangular (√3)	0.98
Background	Depends on the standard		NA		
Façade effects / Reflective Surfaces	Need to make assumptions – check with small change in SLM placement			Normal (1)	
Combined uncertainty (root sum of squares)					2.3 dB
Expanded uncertainty (95% confidence [k = 2])					4.6 dB

nature and very difficult to predict. A good way to view random errors is to think of them as errors caused by errors that are not obvious and are variable due to chance.

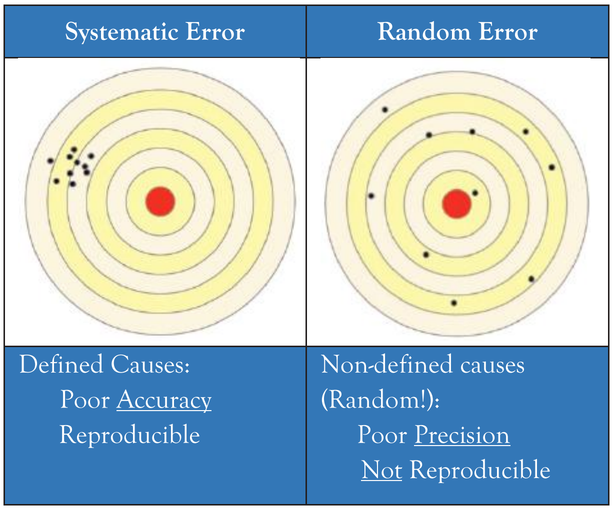


Figure 9: Systematic and random error

In acoustics, an example of a random error in measurement is the difference in noise levels due to variations in the environment. Examples include effects on the transmission path due to temperature and wind changes, or variation in the source, if it is traffic, due to varying speed and vehicle type. Also, random errors exist as a result of the instrument, even if using a Class 1 / Type 1 sound level meter, although this is very small with modern instrumentation.

Although it is not possible to compensate for the random error of a measurement result, it can usually be reduced by taking a number of repeated measurements and averaging the result.

This should have the effect of reducing the standard error of the mean. This is based on the assumption that random errors have what is referred to as 'an expected zero value', which means the errors are truly random and scattered around the mean value.

Although we expect that averaging over a large number of measurements should minimise the error, the estimate may still be imprecise, but not necessarily inaccurate. Averaging various measurements of the same quantity can help offset and reduce random errors, but can never eliminate them altogether.

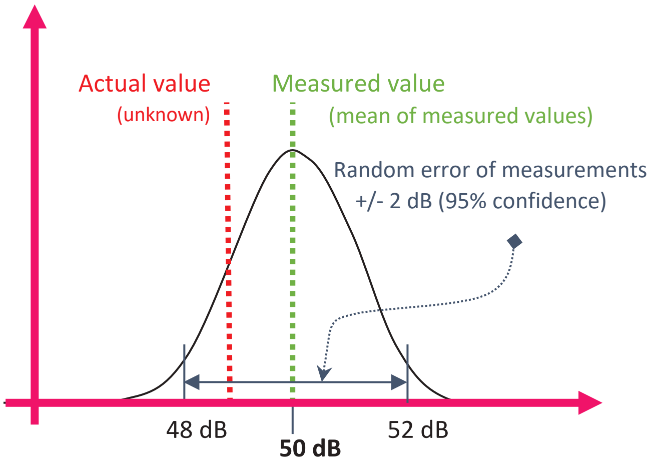


Figure 10: Random error in noise measurements

Figure 10 illustrates random error in noise measurement. For this example, the error is assumed to be randomly distributed about the mean value with an uncertainty of ±2 dB at the 95% confidence level.

10.2 Systematic Error

Systematic errors are reproducible inaccuracies that are consistently in the same direction. They are often due to a problem which persists throughout the entire measurement process. For sound level measurement, this may simply be due to the sound level meter being out of calibration by a fixed amount.

Systematic error is also referred to as '*systematic bias*'. This is errors that cannot be reduced by averaging over a large data set of measurements. A systematic error cannot be detected by analysis of the measurement data alone; some prior knowledge or observation is necessary for detection.

Figure 11 illustrates systematic error in noise measurement. For this example, the systematic error is assumed to be +1.5 dB introduced from 'drift' from the calibration levels. Thus the measured level will always be 1.5 higher than what it should be.

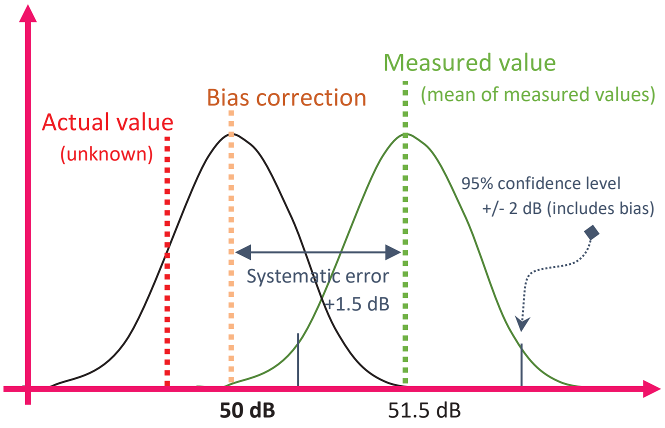


Figure 11: Systematic error in noise measurements

If this error is not accounted for by the acoustic engineer, a wrong conclusion may be drawn. Although often a very hard task, if the systematic bias can be identified and the amount determined, it can be corrected by simple subtraction of the bias.

11. The National measurement system and standards

In New Zealand, the Minster of 'Ministry of Business Innovation and Employment' (MBIE) has the primary responsibility to provide measurement standards in accordance with the International System (SI) of units. The *Measurement Standards Act* 1992 is administered by MBIE and requires the Minister to provide uniform units of measurement of physical quantities for use throughout New Zealand. The method by which this is achieved is prescribed in the *National Standards Regulations* 1976 (with relevant amendment), which requires the Chief Meteorologist of the Measurement Standards Laboratory, to be a "verifying authority" in respect of units of measurement. The New Zealand base units of measurement are required to be of the same magnitude as the standard of measurement for the time being accepted by nations adhering to the Metre Convention. A schedule of units is given in the Regulations themselves.

The value of a quantity is expressed as the product of a number and a unit. The International System of Units, the SI, is the internationally agreed basis for expressing measurements at all levels of precision and in all areas of science, technology, and human endeavour. For each kind of quantity, there is only one SI unit. The unit of sound pressure is the Pascal (Pa), which is equivalent to a Newton per square metre (N/m^2). This unit has been adopted by The General Conference on Weights and Measures CGPM and International Bureau of Weights and Measures (of which New Zealand is a member). This provides the internationally agreed reference in terms of which all other units are now defined.

There are other standards and organisations that provide information on definition and terms such as '*ISO/TR 25417:2007 Acoustics - Definitions of basic quantities and terms*'. This specifies definitions of acoustical quantities and terms used in noise measurement, including the symbols and units to be used in documentation. It was prepared by ISO Technical Committee TC 43, Acoustics, subcommittee SC 1, Noise; with the principal aim of harmonising the terminology.

12. New Zealand standards and measurement

Standards New Zealand (SNZ) is the national standards business unit within MBIE, who specialises in managing the development of standards, including acoustic standards units of measurement standards, including 'NZS 6501:1982 Units of Measurement', which provides lists of the agreed international symbols and names for the coherent units of the International System of Units, known as SI.

12.1 Current practice in New Zealand - Uncertainty and compliance assessment for environmental noise

In New Zealand, the current environmental noise standards for the measurement and assessment of environmental sound are *NZS 6801:2008 Acoustics – Measurement of Environmental Sound* (NZS6801:2008) and *NZS 6802:2008 Acoustics – Environmental Noise* (NZS6802:2008). These two standards are the corner stone of the wide-range of day-to-day environmental noise measurement and assessment in New Zealand.

The first commentary on confidence limits of measurements that is part of a NZS680X standard can be found as far back as in the 1991 version of NZS6801. In Section 6 of NZS6802:1991, *Information to be included in reports*, it states:

> **C6.1**
>
> A report should be objective and impartial. The report should attempt to describe the sound environment or sound scape at the time of measurement. The variation of measurements should be reported and confidence limits specified where appropriate.

However, compliance with the last part of this statement, was in the authors' experience, uncommon in noise reports of the time.

The 1999 version of this standard in Section 9 Information to be included in reports, has a similar statement, that talks about reporting variation, but not confidence limits:

> **C9**
>
> A report should be objective and impartial. The report should attempt to describe the soundscape at the time of measurement. Sources controlling the key descriptors should be identified. The variation in sound levels should be reported.

The 2008 version of NZS6801 and NZS6801 include some commentary on uncertainty. In the forward of NZS6801:2008, it states this topic "*would be a new issue for many users*" and that the standard "*does not require the documentation of uncertainty for all environmental sound measurements but simply encourages users to familiarise themselves with the topic through refer to a good practice guide*".

Section 9.6 of NZS6801:2008 provides a paragraph on sound measurement uncertainty, stating that "*it is recommended to record an estimate of the measurement uncertainty along with the level of confidence*" and then refers to Appendix A. However, this appendix is only *informative* meaning that it is not a technical (normative) part of the standard, and therefore does not contain any necessary requirements for conformance to the standard.

It is noted that this standard has other statements on uncertainty, in particular with respect to location information. In clause C9.4.2, it states "*Dimension uncertainty should be stated, for example ± 10 m*".

The bulk of the information on measurement uncertainty in the New Zealand standard Series NZS680X, including NZS6801 and NZS6802, appears to be from the University of Salford Good Practice Guide [5]. *Appendix A – Uncertainty*, of NZS6801:2008 provides three paragraphs on the topic, referring the reader to the University of Salford Good Practice Guide [5].

The final paragraph of Appendix A provides a key comment in regard to compliance measurements. This paragraph is reproduced in part below from the Standard.

> When comparing a sound level with an applicable noise limit, the sound level should be deemed to comply if the sound level is equal to or less than the noise limit. It should be deemed not to comply if the sound level is greater than the noise limit, regardless of the uncertainty. Where compliance or non-compliance is marginal and contested, steps should be taken to reduce the uncertainty, where possible.

Section 6.6 of NZS6802:2008 refers to Appendix A of NZS6801:2008. Other references are made, such as taking three sound level measurements to reduce measurement uncertainty (see Table A3 of NZS6802:2008).

In addition to NZS6801:2008 and NZS6802:2008, the traffic noise standard, *NZS 6806:2010 Acoustics – Road traffic noise – New and altered Roads* and the wind turbine noise standard, *NZS6808:2010 Acoustics – Wind Farm Noise*, both discuss uncertainty. Section 5.4 of NZS6806:2010 provides details of uncertainty. Section 5.4.4 of NZS6806:2010 states:

> When comparing a sound level with the applicable noise criteria, the sound level should be deemed to comply if the sound level is equal to or less than the noise criteria. It should be deemed not to comply if the sound level is greater than the noise criteria regardless of the uncertainty. Where compliance or non-compliance is marginal and disputed, steps should be taken to reduce the uncertainty, where possible

NZ 6806:2010 makes reference to the University of Salford Good Practice Guide. There are no supporting Appendices for uncertainty in NZS6806:2010. Like NZS6801:2008, it has an informative Appendix C on uncertainty. The Appendix C is a reproduction based directly on Appendix A of NZS6801:2008. Section 5.7 of NZS6808:2010 contains a paragraph on uncertainty stating:

> Prediction and measurement of sound levels from wind farms involve values of a range of parameters that can be known or predicted only within a certain tolerance. The sizes of such uncertainties determine the level of confidence in the overall results. Information on uncertainties is provided in Appendix C.

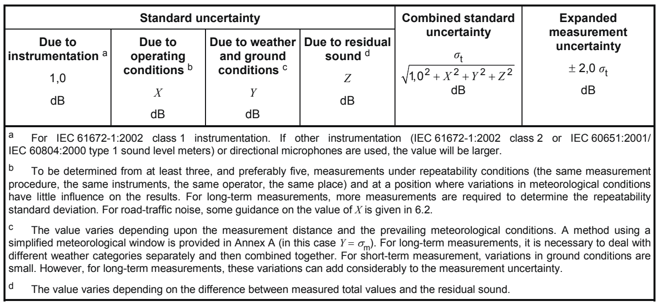
Unlike NZS6801:2008 and NZS6808:2010, no specific comment appears to be made discussing how to deal with compliance and uncertainty. Although there are brief comments in the other NZS680X series standards, at best these are all basic operations, such as NZS6801:1999 which states under 'Section 7.2 General' that measurement uncertainty is always a factor with outdoor sound measurement and can be better quantified when sound propagation influences are defined.

13. International standards – Environmental noise

There is a host of international environmental noise standards that include addressing uncertainty in environmental noise measurement and assessment.

One such example is Chapter 4 of '*ISO 1996-2:2007 Acoustics - Description, measurement and assessment of environmental noise - Part 2: Determination of environmental noise levels*' which describes how sound pressure levels can be determined by direct measurement, by extrapolation of measurement results by means of calculation, or exclusively by calculation. Recommendations are given regarding measurement uncertainty. The standard provides the following table, which is only summarised in part as follows:

Table 1 — Overview of the measurement uncertainty for L_{Aeq}



Standard uncertainty				Combined standard uncertainty	Expanded measurement uncertainty
Due to instrumentation [a]	Due to operating conditions [b]	Due to weather and ground conditions [c]	Due to residual sound [d]		
1,0 dB	X dB	Y dB	Z dB	σ_t $\sqrt{1{,}0^2 + X^2 + Y^2 + Z^2}$ dB	$\pm 2{,}0\ \sigma_t$ dB

[a] For IEC 61672-1:2002 class 1 instrumentation. If other instrumentation (IEC 61672-1:2002 class 2 or IEC 60651:2001/IEC 60804:2000 type 1 sound level meters) or directional microphones are used, the value will be larger.

[b] To be determined from at least three, and preferably five, measurements under repeatability conditions (the same measurement procedure, the same instruments, the same operator, the same place) and at a position where variations in meteorological conditions have little influence on the results. For long-term measurements, more measurements are required to determine the repeatability standard deviation. For road-traffic noise, some guidance on the value of X is given in 6.2.

[c] The value varies depending upon the measurement distance and the prevailing meteorological conditions. A method using a simplified meteorological window is provided in Annex A (in this case $Y = \sigma_m$). For long-term measurements, it is necessary to deal with different weather categories separately and then combined together. For short-term measurement, variations in ground conditions are small. However, for long-term measurements, these variations can add considerably to the measurement uncertainty.

[d] The value varies depending on the difference between measured total values and the residual sound.

ISO 1996-2:2007 notes that the above table is not complete as when preparing this part of the standard, insufficient information was available. What is important to note is that in most cases it will likely be appropriate to add more uncertainty contributions, thus caution is noted when applying the table. It should be noted that the 2017 3rd edition of the standard includes well over 100 mentions of the term uncertainty.

From 2015, all International Organization for Standardization (ISO) standards involving measurement (not just those to do with acoustics and noise) must include comprehensive coverage of estimating and assessing uncertainty.

14. New Zealand standards – Occupational noise

The Australian Standard AS1269 started out in 1989 with a single part titled 'Acoustics - Hearing conservation'. It was withdrawn in 1998 and replaced by a far more comprehensive five-part (0 to 4) standard on occupational noise management, which was jointly adopted by both Australia and New Zealand as AS/NZS 1269:1998. All parts of the standard were updated in 2005 and Part 4 on 'Auditory assessment' again was updated in 2014. Thus, the current five standards are:

1. AS/NZS 1269.0:2005 Occupational noise management - Overview;
2. AS/NZS 1269.1:2005 Occupational noise management - Measurement and assessment of noise immission and exposure;
3. AS/NZS 1269.2:2005 Occupational noise management - Noise control management;
4. AS/NZS 1269.3:2005 Occupational noise management - Hearing protector program;
5. AS/NZS 1269.4:2014 Occupational noise management - Auditory assessment.

All of the AS/NZS 1269 standards are generally reaffirmed by Standards New Zealand each year as the current standards. As with the NZS6801 and NZS6802, the environmental noise standards, the occupational noise standards also make reference to uncertainty but in the case of the AS/NZS 1269 standards series only very briefly. For example, AS/NZS 1269.1:2005 states in Section 8.1 that there is always uncertainty in the measurements made but does not explicitly state how this should or could be addressed.

15. International standards – Occupational noise

'*ISO 9612:2009 Acoustics - Determination of occupational noise exposure- Engineering method*', is the international standard that specifies an engineering method for measuring workers' exposure to noise in an occupational environment and the calculation of the noise exposure.

This standard provides a stepwise approach to the determination of occupational noise exposure from sound level measurements. The procedure contains steps to deal with work analysis, selection of measurement strategy, measurements, error handling and uncertainty evaluations plus calculations, and presentation of results.

The aim is to be able to compare results performed in different countries using the same method. One of the issues around uncertainty was whether or not to include this, as regulations vary across countries.

Accompanying ISO 9612:2009 are helpful tools for the end user to deal with uncertainty. These tools are included in the body of the standard and in an Appendix (normative) as well as a handy spreadsheet file. The standard states that the main sources of uncertainties and errors in the occupational noise measurement result from:

a) uncertainty due to microphone position, instrumentation and calibration – this depends on where the microphone is fixed and what class of instrumentation and calibrator is used;
b) uncertainty due to variations in the daily work, and operational conditions. Typically, this depends on the complexity of the work situation. These variations are expected to be the highest for a mobile worker among non-constant noise sources;
c) errors due to false contributions, for instance from wind or impact on microphones;
d) errors due to lacking or faulty work analysis; and
e) contributions from non-typical noise sources, speech, music (radio), public address systems, alarm signals and non-typical behaviour.

Note: c), d) and e) should be reduced by following good practice, as specified in the standard. Whereas, b) can be reduced by taking repeated measurements and averaging.

16. Acoustic modelling

The topic of accuracy in noise modelling is important as acoustic modelling is an influential tool used by acoustic engineers on a daily basis. Given the complexity of modelling and related algorithms, most modelling is done by propriety software packages. Environmental noise modelling predictions are generally used in decision making applications. The most common application of noise modelling is for noise assessments where a decision is to be made regarding some future development.

Acoustic models for environmental sound are based on statistical approximations of the real world and as such, some deviation between the predicted values and measured values may occur. Acoustic models are generally based on standards with input data being based around algorithms. However, every model has a number of uncertainties, such as meteorological conditions and path geometry, which have to be specified as modelling inputs.

There is a host of proprietary acoustic modelling software available, allowing selection of specific standards models, such as *ISO 9613-2: Acoustics – Attenuation of sound during propagation outdoors - Part 2 General method of calculation*, which is a commonly used standard for prediction software. Three popular software examples of environmental (noise) prediction software include Predictor-LimA, SoundPlan and CadnaA. Figure 12 shows an example output of sound pressure level contours from CadnaA for an industrial site.

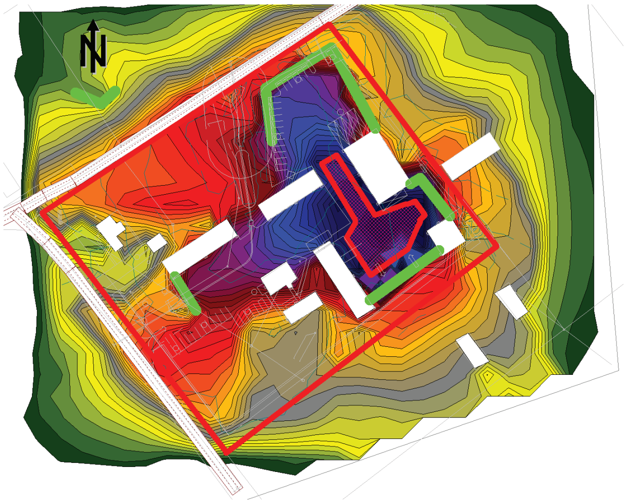


Figure 12: Example output from CadnaA

Clause 9 of ISO 9613-2:1996 provides a discussion on the accuracy and limitations of the method. It states that limiting attenuation to moderate downwind conditions of propagation will limit the effect of variable meteorological conditions to what it describes as 'reasonable values'. The standard provides an estimated accuracy of calculation of ±3 dB for distances up to 1000 m from the source. The uncertainties and challenges involved in large scale noise modelling and methodology, as opposed to modelling for smaller commercial or industrial; sites should not go unnoticed.

One of the limitations of modelling is the source to receiver distance, for example, CONCAWE [6] which was developed for receivers located between 100 m to 2000 m.

One area of noise modelling which can create significant uncertainty is whether a predicted noise level will represent the actual levels of the final development. If unknown variability or uncertainty overlap some threshold value at which different assessment outcomes are triggered, there is a significant risk of an incorrect assessment being made. Other inaccuracies relate to the limitations of the input data and to the ability of the chosen sound propagation algorithm to represent actual transmission conditions.

In summary, noise modelling is very useful and a powerful tool that should continue to be used as part of the acoustic engineers 'tool kit'. However, the question that should be asked very time, is how reliable is the noise model or more importantly, what are the qualifications and limitations of the model? This leads to the key question: what is the likely correlation between predicted levels and actual measured values

A noise model, as a tool to help decision making, represents an estimation, thus there needs to be judgement of the model's reliability and the resulting outputs. In other words, *a reliable model is one fit for purpose and the user needs to be aware of its relative benefits and limitations.* In many cases, the judgement of modelling inputs and results comes from the acoustic engineer's own experience of using the model and undertaking past field work and assessments.

17. Summary

The following sets out a summary of some issues regarding uncertainty that may be useful when undertaking future noise measurement and assessment:

- The uncertainty estimation process is not straightforward. However, even a basic appreciation of uncertainty in measurement and assessment will lead to a better understanding and confidence of reported findings;
- The area of uncertainty has become increasingly important internationally in all standards involving measurement;
- The estimation of uncertainty in acoustic measurement, assessment, modelling, analysis and reporting is an expert area. This should be carried out by an appropriately qualified and experienced person.
- A measurement or assessment result is part of a range and not a single value;
- The level of uncertainty is associated with a number of complex factors which include, but are not limited to, measurement techniques, weather conditions, instrumentation and even the experience of the person conducting the measurement;
- It is important to obtain sufficient data to properly understand and assess the effects on the measurement

...Continued on Page 24

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of source variability. For example, a highly variable noise source may have greater uncertainty and require a longer measurement period;

- All measurements and assessments will always have limitations and uncertainty components. However, the overall purpose is to minimise uncertainty as well as to avoid introducing additional uncertainty (or errors) when conducting assessments;
- Uncertainty may be insignificant and inconsequential for a very clear assessment outcome, but, it may also significantly affect the assessment outcome if marginal or borderline;
- All reasonably practicable steps must be taken to reduce the level of uncertainty (and errors) by following validated assessment methods such as acoustic standards.
- If an alternative method is used or there is deviation from the validated assessment methods, such as those set out in New Zealand Acoustic Standards, state the reasons for using this method(s) and explain how this could potentially affect the assessment or findings.

18. Conclusion

It is inevitable that the next revision of various New Zealand acoustics standards will incorporate the best practice and methodology of the international standards. Since the majority of these international standards now include comprehensive coverage of estimating, handling and reporting of uncertainty, it is only a matter of time before it will become a requirement in New Zealand.

When the assessment and reporting of uncertainty becomes a requirement in New Zealand, there must be clarity about what is required in the measurement, assessment and reporting process so that technical compliance can be verified. This would, among other things, likely involve producing detailed guidelines to promote and educate a full understanding on uncertainty statements. As seen with some international standards already the development of a spreadsheet is just one such example of a possible tool to assist end users, others may include websites with step by step guidance of the user.

Qualification this review

This paper review is intended as a guide only; it is not intended to be a surrogate for any expert advice from a professional acoustic engineer. The reader and users should further understand that the information within this review does not attempt to cover all areas and applications and therefore there will be omissions. While all care has been taken in the preparation of this work and the information which is included is believed to be correct at the time of preparation, users of this paper should apply discretion and rely on their own judgment regarding the use of the above information.

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L. Hannah, W. Page (2017), *An introductory guide to uncertainty in acoustic measurements*. New Zealand Acoustics. Vol. 30, No 3. Retrieved from www.acoustics.org.nz

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Appendix - Ontology

Metrology is defined by the International Bureau of Weights and Measures (BIPM) as "*the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology*", in lay terms meaning the scientific study of measurement.

The ontological formal naming and definition of the types, properties, and interrelationships and international vocabulary of metrology (VIM) is maintained by the Joint Committee for Guides in Metrology (JCGM), a group made up of eight international organisations (including but not limited to) International Bureau of Weights and

Measures, International Electrotechnical Commission (EC), International Organization for Standardization (ISO). In addition to the VIM vocabulary, there are definitions given in ISO and IEC standards, for example.

The following provides some basic definitions for terms used in this review.

Measurand: Quantity intended to be measured.

Uncertainty (VIM - the vocabulary of metrology definition): Non-negative parameter characterising the dispersion of the quantity values being attributed to a measurand, based on the information used. This VIM definition remains very similar to the definition of the standard deviation. This is why the GUM (ISO, 2008a) provides a more specific definition, with 3 notes

Uncertainty (GUM - Guide to the Expression of Uncertainty in Measurement definition): Parameter, associated with the result of a measurement, that characterises the dispersion of the values that could reasonably be attributed to the measurand.

Note 1: The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.

Note 2: Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of series of measurements and can be characterized by experimental standard deviations. The other components, which also can be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information.

Note 3: It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion.

True value: Quantity value consistent with the definition of a quantity. A true value is usually unknown.

Measurement Accuracy: Closeness of agreement between a measured quantity value and a "true" quantity value of a measurand.

Measurement Precision: Closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions.

Measurement Error: Measured quantity value minus a reference quantity value.

Systematic Error: Component of measurement error that in replicate measurements remains constant or varies in a predictable manner.

Random Error: Component of measurement error that in replicate measurements varies in an unpredictable manner.

Repeatability: Condition of measurement, out of a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time.

Reproducibility: Condition of measurement, out of a set of conditions that includes different locations, operators, measuring systems, and replicate measurements on the same or similar objects. Measurement reproducibility is measurement precision under reproducibility conditions of measurement.

Standard uncertainty: Measurement uncertainty expressed as a standard deviation.

Combined uncertainty: Standard measurement uncertainty that is obtained using the individual standard measurement uncertainties associated with the input quantities in a measurement model.

Expanded uncertainty: Expanded uncertainty product of a combined standard measurement uncertainty and a factor larger than the number one.

Coverage Interval: Interval containing the set of true quantity values of a measurand with a stated probability, based on the information available.

Coverage Factor: Number larger than one by which a combined standard measurement uncertainty is multiplied to obtain an expanded measurement uncertainty.