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Estimation of uncertainty in environmental noise measurement

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It is well known that environmental noise levels can vary over a wide range as a result of the diversity of site conditions and activities occurring during field measurements. Environmental noise very often occurs in the form of randomly fluctuating sound signals. To quantitatively describe this phenomenon, noise index such as equivalent pressure level Leq is widely used. The measured value of Leq based on the sound pressure level measurements by sound level meter will probably differ from the true one due to the effects of the errors throughout the experiment chain and in the physical phenomenon under study.

SRPS EN ISO 1996-2 (2010) contains guidelines on assessing the uncertainties of the determined sound pressure levels. This depends on the sound source, measurement time interval, weather conditions, distance from the source, measurement method and instrumentation.

Guidelines on estimating the measurement uncertainty in compliance with the ISO Guide to Uncertainty in Measurements (GUM) will be given in this paper. Five main sources of uncertainty (measurement chain, operating conditions, meteorological conditions, receiver location and residual noise) are combined to determine the overall uncertainty.

Keywords: environmental noise, measurement, uncertainty

0 INTRODUCTION

Noise can be define as an unwanted or undesired sound whereas environmental noise is any unwanted or harmful outdoor sound created by human activities that is detrimental to the quality of life of individuals.

Worldwide, 130 million of people are exposed to environemtal noise levels above 65 dB(A), while another 300 million live in uncomfortable environmental noise levels (55 dB(A)-65 dB(A)) [1].

Although by listening we detect noise with a great sensitivity, we have often difficulties to describe it and we certainly cannot define it in technical terms - we usually know when noise is excessive, but we cannot predict the required noise reduction and, more important, we cannot determine how to effectively reduce the excessive noise.

The proper environemtnal noise pollution assessment and design of effective noise control measures require noise measurement.

Noise measurement is an important diagnostic tool in noise control technology and noise pollution assessment. The objective of noise measurement is to make accurate measurement which gives us a purposeful act of comparing noises under different conditions for assessment of adverse impacts of noise and adopting suitable control techniques for noise reduction.

It is well known that environmental noise levels can vary over a wide range as a result of the diversity of site conditions and activities occurring during field measurements. Environmental noise very often occurs in the form of randomly fluctuating sound signals. To quantitatively describe this phenomenon, noise index such as equivalent pressure level L_{eq} is widely used. The measured value of L_{eq} based on the sound pressure level measurements by sound level meter will probably differ from the true one due to the effects of the errors throughout the experiment chain and in the physical phenomenon under study. In most physical experiments there will be a random component affecting to environmental noise measurement uncertainty.

A number of authors have already made significant contributions in the field of environmental noise measurement uncertainty determination [2,3].

Guidelines on estimating the measurement uncertainty in compliance with the ISO Guide to Uncertainty in Measurements (GUM) explained in a series of JCGM ("Joint Committee for

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Guides in Metrology") documents [4-6] and SRPS ISO 1996-2 [7] will be given in this paper.

In this method the separate uncertainties associated with each of the variables affecting the measured noise level are added together to derive a combined overall uncertainty. Because of limited time and resources, each component of the overall uncertainty must normally be estimated based on scientific judgment or practical experience rather than be determined from the results of a large set of repeated measurements.

2 MEASUREMENT UNCERTAINTY CLASIFFICATION

The word "uncertainty" means doubt, and therefore in its broadest sense "uncertainty of a measurement" means a "doubt about the validity of the result of that measurement". The concept of "uncertainty" as a quantifiable attribute is relatively new in the history of measurement.

GUM classifies uncertainties into three categories: standard Uncertainty, Combined Uncertainty, and Expanded Uncertainty.

The standard uncertainty with the symbol "u" is represented by an estimated standard deviation and equals to the positive square root of the estimated variance. The standard uncertainty of the result of a measurement consists of several components, which can be grouped into two types [4]. They are:

- Type A - Uncertainty components obtained using a method based on statistical analysis of a series of measurement.
- Type B - Uncertainty component obtained by means other than repeated observations. Prior experience and professional judgments are part of type B uncertainties.

Combined standard uncertainty of the result of a measurement is obtained from the uncertainties of a number of other quantities. The combined uncertainty is computed via the law of propagation of uncertainty. The result is different if the quantities are correlated or uncorrelated (independent).

Mathematically, expanded uncertainty is calculated as the combined uncertainty multiplied by a coverage factor, k. The coverage factor, k, includes an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

Thus, the numerical value for the coverage factor k should be chosen so that it would provide an interval $Y = y \pm U$ corresponding to a particular level of confidence.

3 ESTIMATION OF ENVIRONMENTAL NOISE MEASUREMENT UNCERTAINTY

SRPS ISO 1996-2 [7] contains guidelines on assessing and reporting the uncertainties of the determined sound pressure levels. This depends on the sound source and the measurement time interval, the meteorological conditions, the distance from the source and the measurement method and instrumentation. Some guidelines on how to estimate the measurement uncertainty are given, with focus on A-weighted equivalent-continuous sound pressure levels only. Five main sources of uncertainty (measurement chain, operating conditions, meteorological conditions, receiver location and residual sound) are used and combined to determine the overall uncertainty.

The measurement uncertainty shall be determined in compliance with the ISO Guide to Uncertainty in Measurements (GUM).

According to GUM each significant source of error has to be identified and corrected for. If the quantity to be measured is $L_{Aeq,\mathrm{m}}$, which is a function of the quantities x_{j} the equation becomes:

$$L_{Aeq,m} = f(x_j) \tag{1}$$

If each quantity has the standard uncertainty u_j the combined uncertainty u is given by

$$u(L_{Aeq,m}) = \sqrt{\sum_{j=1}^{n} (c_j u_j)^2} \tag{2}$$

where the sensitivity coefficient c_{j} is given by

$$c_j = \frac{\partial f}{\partial x_j} \tag{3}$$

The measurement uncertainty is the combined measurement uncertainty associated with a chosen coverage probability. By convention, a coverage probability of 95% is usually chosen, with an associated coverage factor of 2. This means that the true value during the specified conditions $L_{Aeq,true}$ is:

$$L_{Aeq,true} = L_{Aeq,m} \pm 2u \quad (4)$$

Other levels of confidence may be set. A coverage factor of 1.3 will, e.g., provide a level of confidence of 80 % and one of 2 a level of confidence of 95 %.

For environmental noise measurements $f(x_j)$ is extremely complicated and it is hardly feasible to put up exact equations for the function f. Following the principles given in ISO 3745 [8] and ISO 1996-2, some important sources of error can be identified and wrote as

$$L_{Aeq,true} = L_{Aeq,m} + \delta_{slm} + \delta_{sou} + \delta_{met} + \\ + \delta_{loc} + \delta_{res} \quad (5)$$

where δ_{slm} is the error due to the measurement chain (sound level meter in the simplest case), δ_{sou} is the error due to deviations from the ideal operating conditions of the source, δ_{met} is the error due to meteorological conditions and ground conditions deviating from the ideal conditions, δ_{loc} is the error due to the selection of receiver position and δ_{res} is the error due to residual noise. Often δ_{sou} + δ_{met} is determined directly from measurements.

Equation (5) is very simplified and each source of error is a function of several other sources of error. In principle equation (5) could be applied on any measurement lasting from seconds to years. The measurements are divided into long and short term measurements respectively in SRPS ISO 1996-1 [9]. A short term measurement may typically range between 10 minutes and a few hours whereas a typical long term measurement may range between a month and a year.

In according to equation (5) and identified sources of error equation (2) can be rewritten as:

$$u^2(L_{Aeq,m}) = (c_{slm}u_{slm})^2 + (c_{sou}u_{sou})^2 + \\ + (c_{met}u_{met})^2 + (c_{loc}u_{loc})^2 + (c_{res}u_{res})^2 \quad (6)$$

All the sensitive coefficients have been estimated to 1.0 except for the residual noise.

Table 1 of SRPS ISO 1996-2 [7] contains overview of the measurement uncertainty for the A-equivalent noise level. Higher uncertainties are to be expected on maximum levels, frequency band levels and levels of tonal components in noise.

3.1 Uncertainty due to measurement chain

The uncertainty due to measurement chain has been estimated to 1.0 dB. This value concerns the use of Class 1 instrumentation. However, the standard permits the use of instrumentation systems, including the microphone, cable and recorders if any, that conform to the requirements for a class 1 or class 2 instruments laid down in IEC 61672-1 [10]. If class 2 sound level meters or directional microphones are used the value will be larger. Studies carried out at Brüel & Kjær [11] have shown these to be double those of Class 1 instrumentation.

The values of measurement uncertainty include influence of the following factors:

- Directional response
- Frequency weighting
- Level linearity
- Tone burst response
- Power supply voltage
- Static pressure
- Air temperature
- Humidity
- Calibrator
- Windscreen

3.2 Uncertainty due to operating condition

Uncertainty due to operating conditions is determined from at least 3, and preferably 5, 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.

3.2.1 Road traffic

When measuring the equivalent noise level the number of vehicle pass-bys shall be counted during the measurement time interval. If the measurement result shall be converted to other traffic conditions distinction shall be made between at least the three categories of vehicles „passenger cars" and „medium heavy (2 axles)" and „heavy (> 3 axles)". To determine if the traffic conditions are representative, the average traffic speed shall be measured and the type of road surface noted.

For the road traffic noise the uncertainty can be calculated by

$$u_{sou} \cong \frac{C}{\sqrt{n}} \tag{7}$$

where n is the number of pass-bys. For mixed traffic C=10, for heavy vehicles only C= 5 and for passenger cars only C = 2.5.

3.2.2 Rail traffic

When measuring the equivalent noise level the number of train pass-bys, the speeds and the train lengths shall be determined during the measurement time interval. If the measurement result shall be converted to other traffic conditions distinction shall be made between at least the following categories: High speed trains, inter-city trains, regional trains and freight trains.

For the rail traffic noise the uncertainty can be also calculated by means equation (7) where C=10 if the sampling was made regardless of the operating conditions and C=5 if the sampling takes into account the relative occurrence of the different train classes (freight, passenger, etc).

3.2.3 Industrial sources

The source operating conditions shall be divided into classes: For each class the time variation of the sound emission from the source shall be reasonably stationary in a stochastical sense. The variation shall be less than the variation in transmission path attenuation due to varying weather conditions. If 5 minute to 10 minute L_{eq}-values measured at a distance long enough to include noise contributions from all major sources and short enough to minimize meteorological effects during a certain operating condition, a new categorization of the operating conditions shall be made.

In order to be able to estimate the uncertainty of the operating conditions for industrial sources it is necessary to repeat the measurements at a distance sufficiently close to the source to make the sound pressure level variations independent of the meteorological conditions. The equation for this is

$$u_{sou} = \sqrt{\sum_{i=1}^{n} \frac{(L_{Aeq,m,i} - \overline{L}_{Aeq,m})^2}{n-1}} \tag{8}$$

$L_{Aeq,m,i}$ is the measured value representing a typical cycle of operation, $\overline{L}_{Aeq,m}$ is the arithmetic average of all $L_{Aeq,m,i}$ and n is the total number of all independent measurements.

In order two measurements to be independent the requirements of table 1 have to be met. “Sou” in table 1 indicates that the minimum time is influenced by the operating conditions of the source.

Table 1. *Minimum time between two measurements to be independent*

distance	<100 m		100÷300 m		>300 m	
	day	night	day	night	day	night
Road	24		48	48	72	72
Rail	24	24/sou	24	48	72	72
Industry	sou	sou	48	48	72	72
Aircraft	sou	sou	sou	sou	sou	sou

The equivalent noise level shall be measured during each class of operating condition and the resulting the equivalent noise level shall be calculated taking the frequency and duration of each class of operating condition into account in according to equation:

$$L_{Aeq,m} = 10 \log \sum_{i=1}^{n} p_i \cdot 10^{0.1 \cdot L_{Aeq,m,i}} \tag{9}$$

where $L_{Aeq,m}$ is the total equivalent noise level for the whole time interval and $L_{Aeq,m,i}$ is equivalent noise level for class of operating condition i, which lasts for p_i of the total time.

The total measured equivalent noise level is a function of equivalent noise level for each class of operating condition and duration of each class of operating condition, so that the sensitivity coefficient can be given by

$$c_{L_{Aeq,m,i}} = \frac{\partial L_{Aeq,m}}{\partial L_{Aeq,m,i}} = \frac{p_i \cdot 10^{0.1 \cdot L_{Aeq,m,i}}}{\sum_{i=1}^{n} p_i \cdot 10^{0.1 \cdot L_{Aeq,m,i}}} \tag{10}$$

$$c_{L_{Aeq,m,i}} = \frac{\partial L_{Aeq,m}}{\partial p_i} = \frac{10^{0.1 \cdot L_{Aeq,m,i}}}{\sum_{i=1}^{n} p_i \cdot 10^{0.1 \cdot L_{Aeq,m,i}}} \tag{11}$$

If $L_{Aeq,m,i}$ is determined with the uncertainty u_{Li} and p_i with the standard uncertainty u_{pi}, then the uncertainty of $L_{Aeq,m}$ is then given by

$$u_{sou} = \sqrt{\sum_{i=1}^{n} c_{p_i}^2 \cdot u_{p_i}^2 + \sum_{i=1}^{n} c_{L_{Aeq,m,i}}^2 \cdot u_{L_i}^2} \tag{12}$$

3.3 Uncertainty due to meteorogical conditions

The variability of noise levels during measurements is influenced by the meteorological conditions. The noise levels must be measured during favourable propagation conditions.

If only one or a few short term measurements are carried out they should be taken during favourable conditions. For the soft ground favourable conditions are assumed to be valid for downward propagation if

$$\frac{h_s + h_r}{d} \geq 0.1 \quad (13)$$

where h_s is source height, h_r is receiver height and d is distance between the source and receiver.

If the ground is hard larger distances may be acceptable.

The favourable sound propagation conditions can be determined based on the radius of curvature, R, which depends on the gradient of wind speed and temperature. Positive values of R correspond to downward sound ray curvature (e.g. during downwind or temperature inversion). Such sound propagation conditions are often referred to as “favourable”, that is the sound pressure levels are high. $1/R = 0$ corresponds to straight-line sound propagation (homogeneous atmosphere, „no-wind“); negative values of R correspond to upward sound propagation (e.g. during upwind or on a calm summer day).

The radius of curvature can be calculated from measured meteorological parameters according to Annex A of SRPS ISO 1996-2 [7].

In the case of measurements during favourable conditions the uncertainty is

$$u_{met} = 2 \quad (14)$$

In other conditions the uncertainty can be determined from Figure A.1 [7].

3.4 Uncertainty due to selection of reciever position

The location of receiver position is critical in obtaining accurate and useful sound data. The selection of receiver position should be carefully considered early in the development of a measurement plan, once the objectives for the measurement system have been clearly identified. In order to analyze to what extent a proposed receiver location influences the uncertainty of the results at that site, it is necessary to examine carefully the relation between the residual sound and the sound pressure levels to be measured. For accurate measurements, the level difference should exceed 15 dB.

For the most common cases default values for the standard uncertainties using different receiver positions are given in table 2 for traffic noise. For industrial noise and other positions the uncertainties have to be determined for each individual case based on the repeated measurements and equation (8).

Table 2. *Uncertainty of different reciver location*

Reciver location	u_{oc}
Traffic noise incident from all angles	
Microphone in free field	0.5
Microphone directly on the surface	0.4
Microphone near reflecting surface	0.4
Traffic noise with predominantly grazing incidence	
Microphone directly on the surface	2.0
Microphone near reflecting surface	1.0

2.4 Uncertainty due to residual noise

The uncertainty due to residual sound is dependent on the following primary factors:

- the parameter measured
- the difference between measured total values and the residual sound
- the uncertainty of the assessments of the total values and the residual sound.

The uncertainty due to residual sound varies depending on the difference between measured total values and the residual sound (including self-generating noise in the instrumentation). It is well-known how the residual sound level influences measurement of the specific sound level. At 10dB below, the influence has traditionally been accepted to be insignificant.

In order to determine the uncertainty for the specific sound level, the actual measured overall level, the residual noise level during the measurement and the residual noise used for correction are combined.

The specific noise level is then the overall noise level (the specific noise level $L_{ss,m}$ and the residual noise level during the measurement $L_{res,m}$) corrected for the residual sound level $L_{res,c}$ measured with specific noise source off:

$$L_{ss,m} = 10\log((10^{0.1 \cdot L_{ss,m}} + 10^{0.1 \cdot L_{res,m}}) - \\ - 10^{0.1 \cdot L_{res,c}}) \quad (15)$$

The sensitivity coefficients are

$$c_{res,m} = \frac{\partial L_{ss,m}}{\partial L_{res,m}} \approx 10^{0.1\cdot(L_{res,m} - L_{ss,m})} \quad (16)$$

$$c_{res,c} = \frac{\partial L_{ss,m}}{\partial L_{res,c}} \approx -10^{0.1\cdot(L_{res,c} - L_{ss,m})} \quad (17)$$

The total uncertainty is given by

$$u_{ss} = \sqrt{(c_{res,m}\cdot u_{res,m})^2 + (c_{res,c}\cdot u_{res,c})^2} \approx \sqrt{2}c_{res}\cdot u_{res} = \sqrt{2}\cdot 10^{0.1\cdot(L_{res,m} - L_{ss,m})}\cdot u_{res} \quad (18)$$

In equations (16) to (18) it is assumed that there is little difference between the residual noise during the measurement and the residual noise used for correction. If the residual noise level is much smaller than the noise level from the source to be measured the sensitivity coefficient for residual coefficient is:

$$c_{res} \approx 10^{0.1\cdot(L_{res} - L_m)} \quad (19)$$

The uncertainty associated with the residual noise u_{res} is determined in according equation (6) except the last term.

4 CONCLUSION

It is well known that environmental noise levels can vary over a wide range as a result of the diversity of site conditions and activities occurring during field measurements. Environmental noise very often occurs in the form of randomly fluctuating sound signals.

The uncertainty estimation in environmental noise measurement is not an easy procedure, since it is difficult to identify all sources of uncertainty related to the equivalent noise level and determine its contributions to the combined measurement uncertainty. Also, there is not a completely established procedure used on a broad scale to estimate the uncertainty in environmental noise measurement.

This paper is an attempt to provide guidelines on estimating the measurement uncertainty in compliance with the ISO Guide to Uncertainty in Measurements (GUM) and SRPS ISO 1996-2. Five main sources of uncertainty (measurement chain, operating conditions, meteorological conditions, receiver location and residual noise) are combined to determine the overall uncertainty.

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