MEASUREMENT UNCERTAINTY ESTIMATION OF ENVIRONMENTAL NOISE MEASUREMENTS

PACS REFERENCE:
Bezjak Mladen
Civil Engineering Institute of Croatia
Janka Rakuše 1
Zagreb
Croatia
+385 1 61 44 111
+385 1 61 44 786
mbezjak@zg.igh.hr

ABSTRACT
This work explaines the procedure for measurement uncertainty estimation of environmental noise measurements without regard to characteristics of noise (fluctuating or steady noise) and impulsiveness of sound. Measurement uncertainty shall be estimated independedly from the sort and quality of the equipment and independedly from the method used for environmental noise measurements ($L_{Aeq,T}$ could be measured directly or indirectly derived from measured values of A-weighted sound pressure level). The procedure of measurement uncertainty estimation shall be performed in accordance with the Guide of Uncertainty of Measurement - GUM [1].

1. INTRODUCTION:
Steady environmental noise is noise where levels do not vary more than 5 dB (for example heavy machine noise). If those levels do vary for 5 dB or more, it is the so-called fluctuating noise (for example aircraft noise). Furthermore, ISO 1996-2 [3], declares that impulsive sound is any kind of sound that occur less than 20 times per second (for example gunshot). The most important and the most representative parameter expressing environmental noise is equivalent continous A-weighteid sound pressure level ($L_{Aeq,T}$) during reference time interval (T). Reference time interval is a period established by the national standard or the local legislation. $L_{Aeq,T}$ shall be determined directly or indirectly. $L_{Aeq,T}$ could be directly measured by the equipment which is capable to measure, continuously integrate and average A-weighted sound pressure levels during the reference time interval. Indirectly determined $L_{Aeq,T}$ means to measure A-weighted sound pressure levels (L_{pA}) during reference time interval and from measurand (measured value) to calculate $L_{Aeq,T}$:

$$L_{Aeq,T} = 10 \cdot \log\left[\frac{1}{N}\sum_{i=1}^{N} 10^{0.1 \cdot L_{pAi}}\right] \quad \text{………. (1)}$$

$N = \frac{t_2 - t_1}{\Delta t}$ …. number of intervals,

Δt ……………. measurment interval, between two measured A-weighted sound pressure levels (determined by the measurer according to the national standard or the local legislative),

$t_2 - t_1$ ……….. reference time interval,

L_{pAi} …………... measured A-weighted sound pressure level of the i'th event (i'th measurment interval).

Now it can be said, regardless of that if environmental noise is steady or fluctuating, $L_{Aeq,T}$ is measured value - measurand.

2. DETERMINATION OF $L_{Aeq,T}$ AND STANDARD UNCERTAINTY ESTIMATION, $u(L_{Aeq,T})$:

According to GUM [1], standard uncertainty of directly or indirectly determined measurand ($L_{Aeq,T}$) must be estimated.

2.1 Measurement uncertainty estimation of the measuring system (equipment)

Measuring system consist of:

microphone with preamplifier,
calibrator of sound pressure levels,
sound level meters.

Well maintained measuring system must be periodically calibrated and maintained. Furthermore, for each part of the measuring system a document with clearly established measuring range and deviation of results issued by manufacturer must exist. If the measurement uncertainty of each part of measuring system is not explicitly declared by the manufacturer, it must be estimated by the measurer based on his/her measurement experience, and/or based on any kind of data from a manual or similar document delivered by that manufacturer (accuracy, errors, calibration charts, …).

Microphone with preamplifier

A microphone is a sound pressure sensor with a quality declaration by the manufacturer. It is certain that the manufacturer performs adequate testings to check whether the real deviations of the results are in accordance with declared values or not, in order to be sure that the real deviations of the results are grouped near the upper limit of declared values. Manufacturer intentions are having those real deviations of the results maximum allowed for declared class of microphone. According to the above, standard uncertainty of with microphone measured values could be classified [5] as type B (normal distribution): For level of confidence of 95 %, deviation of measurement results is:

$a = \pm 2 \cdot u(M)$. Standard uncertainty of microphone, $u(M)$ is than [5]:

$$u(M) = \frac{a}{2} \quad \text{.........} \ (2)$$

Calibrator of sound pressure levels

A calibrator is an instrument for adjustments of the measuring system before the beginning of measurements. Deviations of sound pressure levels at the referent frequentions are equal and continuous on the specific measuring range, so the standard uncertainty of sound pressure level adjustments with calibrator could be classified as type B (rectangular distribution), according to GUM. If the maximum deviation of adjustments with calibrator at the referent frequency is "*a*" dB, then associated standard uncertainty figure out [5]:

$$u(K) = \frac{1}{\sqrt{3}} a \quad \text{.........} \ (3)$$

Sound level meters (apparatus for measured data acquisition and analysis)

A sound level meter is an instrument of a declared type (according to IEC publication 651) by the manufacturer and quality. Since such instruments consist of several parts or elements, the general quality is determined by its worst part. The expectation that manufacturer shall compose its product from the components of similar quality is quite logical. Otherwise, the instruments would be more expensive than necessary. It could be presumed that the manufacturer of such instruments performed adequate testings to be sure that the general quality of the instrument would be maximum with the minimum costs. In addition, in the instrument documentation, deviations of the results at a specific measuring range must be declared. Just like in the case of a microphone, this is a normal distribution with standard uncertainty type B, and for level of confidence of 95 %, measured quantities deviated from $\pm 2 \cdot u(M)$. Standard uncertainty calculated by following formula:

$$u(A) = \frac{1}{2}a \text{ ………. (4)}$$

According to GUM, [1], standard uncertainty of such measuring system calculated from:

$$u(MS) = \sqrt{u^2(M) + u^2(K) + u^2(A)} \text{ ………. (5)}$$

2.2 Measurement uncertainty estimation of measurands

Measurand ($L_{Aeq,T}$) could be determined directly (by measure) or indirectly (by calculations from measured A-weighted sound pressure levels).

a) $L_{Aeq,T}$ is determined directly (by measure)

If $L_{Aeq,T}$ is directly measured, standard uncertainty is equal to standard uncertainty of the measuring system:

$$u(L_{Aeq,T}) = u(MS) = \sqrt{u^2(M) + u^2(K) + u^2(A)} \text{ ………. (6)}$$

b) $L_{Aeq,T}$ is determined indirectly (by calculations from measured A-weighted sound pressure levels)

If $L_{Aeq,T}$ is not directly measured but calculated from the measured A-*weighted* sound pressure levels (L_{PAi}), as shown by an equation (1), than in accordance to GUM [1], combined standard uncertainty must be calculated:

$$u_c(L_{Aeq,T}) = \sqrt{\left(\frac{\partial L_{Aeq,T}}{\partial L_{pAi}}\right)^2 \cdot u^2(L_{pAi}) + \left(\frac{\partial L_{Aeq,T}}{\partial N}\right)^2 \cdot u^2(N)} \text{ ………. (7)}$$

Combined standard uncertainty is a total differential of function which determines relationship between measurands (L_{pAi}) and the equivalent continuous A-weighted sound pressure level ($L_{Aeq,T}$) This function is shown by an equation (1).

$\left(\frac{\partial L_{Aeq,T}}{\partial L_{pAi}}\right) = \log e$ … partial derivation of $L_{Aeq,T}$ by A-weighted sound pressure level, L_{pAi}

$u(L_{pAi}) = u(MS) = \sqrt{u^2(M) + u^2(K) + u^2(A)}$ … standard uncertainty of directly measured values (measurands) L_{pAi} is equal to standard uncertainty of the measuring system.

$\left(\frac{\partial L_{Aeq,T}}{\partial N}\right) = -\frac{10 \cdot \log e}{N}$ … partial derivation of $L_{Aeq,T}$ by total number of intervals, N

$u(N)$ … standard uncertainty of number N, appears because of non-harmonized ratio between $t_2 - t_1$ i Δt. For example, if referent interval is 15 minute, ($t_2 - t_1$ = 15 min.), and measurement interval is 7 s (Δt = 7 s), than N = 128,6. As N must be an integer value, the deviation is: a = 0.6, and general conclusion in accordance with GUM is: rectangular distribution, with standard uncertainty type B:

$$u(N) = \frac{a}{\sqrt{3}} \text{ ………. (8)}$$

Now, the values of $L_{Aeq,T}$ and associated combined standard uncertainty $u_c(L_{Aeq,T})$ are known, without regard of the characteristics of noise (steady or fluctuating), and without regard of wether $L_{Aeq,T}$ is measured directly or is calculated from directly measured L_{pAi}.

3. DETERMINATION OF RATING NOISE LEVEL ($L_{Ar,T}$) AND ASSOCIATED COMBINED STANDARD UNCERTAINTY ESTIMATION, $u_c(L_{Ar,T})$

ISO 1996-2:2000 declares that with regard to tone and impulsive sound, adjustments on $L_{Aeq,T}$ are necessary.

3.1 Adjustments on $L_{Aeq,T}$ with regard to tone (K_T)

There are two cases of tone adjustments:

Case a)

If the tone component of the measured levels is predominant during the reference time interval and clearly heardable and could be determined by frequency analysis at the 1/3 octave spectra, than $L_{Aeq,T}$ could be adjusted as follows [3]:

$$K_T = \text{from 5 dB to 6 dB} \quad \text{………. (9A)}$$

Case b)
If the tone component of the measured levels is predominant during the reference time interval and not clearly heardable and could be determined by frequency analysis at the 1/3 octave spectra, than $L_{Aeq,T}$ could be adjusted as follows [3]:

$$K_T = \text{from 2 dB to 3 dB} \quad \text{………. (9B)}$$

If the tone adjustments would not be estimated, but by means of fast fouriere transformations (FFT) exactly determined, than much precisely value of K_T could be obtained. The exact value of K_T would lie between 5 dB and 6 dB (or 2 dB and 3 dB). If the mean value of the interval would be set as a tone adjustment (5,5 dB, or 2,5 dB), according to GUM, the maximum deviation from the exact value is then 0,5 dB. This is a rectangular distribution [5] with standard uncertainty:

$$u(K_T) = \frac{0.5}{\sqrt{3}} \quad \text{………. (10)}$$

3.2 Adjustments on $L_{Aeq,T}$ with regard to impulsive sound (K_I)
Case a)
If an impulsive sound could be recognized and measured as separate event from separate source during the reference time interval, than the impulsive sound should be measured directly. A-weighted sound exposure level (L_{AE})is the value that should be measured. Sound exposure level is then measured value used for discrete events such as impulsive sound. The procedure for standard uncertainty estimation of Sound exposure level is equal to the procedure as described in item 2: "standard uncertainty estimation of equivalent continous A-weighted sound pressure level". The rating noise level for this case is [3]:

$$L_{Ar,T} = 10 \cdot \log\left[10^{0.1\cdot(L_{Aeq,T}+K_T)} + 10^{0.1\cdot L_{ArKI,T}}\right] \quad \text{………. (11)}$$

$L_{Aeq,T}$ ……. equivalent continuous A-weighted sound pressure level during reference time interval T
K_T ………... tone adjustment, according to (9)
$L_{ArKI,T}$ ……. impulse adjusted A-weighted level of the impulsive sound during reference time interval T:

$$L_{ArKI,T} = 10 \cdot \log\left[\frac{1}{T}\sum_{i=1}^{N} 10^{0.1\cdot L_{AEri}}\right] \quad \text{………. (12)}$$

T ………… reference time interval
L_{AEri} …….. rating sound exposure level during the i'th time interval:

$$L_{AEri} = L_{AEi} + K_{Ii} \quad \text{………. (13)}$$

L_{AEi} ……... measured sound exposure level during the i'th reference time interval
K_{Ii} ………. impulse adjustment during the i'th reference time interval [3]:

K_{Ii} = 5 dB for ordinary impulsive sound (hammering) ………. (14A)
K_{Ii} = 12 dB for high-energy impulsive sound (explosive) ………. (14B)

CEC research shows that the impulse adjustment lies between 8 dB and 15 dB, for high-energy impulsive sound, or between 2 dB and 7dB, for ordinary impulsive sound. Since ISO 1996-2:1987 [3] explicitly determined values of K_I, and in accordance with (14) this is rectangular distribution with maximum deviation: a = 3 dB for ordinary impulsive sound, or a = 4 dB for high-energy impulsive sound. Standard uncertainty of the i'th impulse is:

$$u(K_{Ii}) = \frac{3}{\sqrt{3}} \quad \text{………. (15A), or}$$

$$u(K_{Ii}) = \frac{4}{\sqrt{3}} \quad \text{.........} \; (15B)$$

Estimated combined standard uncertainty of $L_{Ar,T}$, calculated from (11) and according to GUM:

$$u_c(L_{Ar,T}) = \sqrt{\left[\frac{\partial L_{Ar,T}}{\partial L_{Aeq,T}} \cdot u(L_{Aeq,T})\right]^2 + \left[\frac{\partial L_{Ar,T}}{\partial K_T} \cdot u(K_T)\right]^2 + \left[\frac{\partial L_{Ar,T}}{\partial L_{ArKI,T}} \cdot u(L_{ArKI,T})\right]^2} \quad \text{.......} \; (16)$$

$\frac{\partial L_{Ar,T}}{\partial K_T} = \log e \cdot \frac{10^x}{10^x + 10^y}$, $\quad \frac{\partial L_{Ar,T}}{\partial L_{Aeq,T}} = \log e \cdot \frac{10^x}{10^x + 10^y}$, $\quad$ za: $x = 0.1 \cdot (L_{Aeq,T} + K_T)$, and $y = 0.1 \cdot L_{ArKI,T}$, $u(L_{Aeq,T})$ ...... determined according to item 2.2

$u(K_T)$ .... determined according to (10)

$\frac{\partial L_{Ar,T}}{\partial L_{ArKI,T}} = \log e \cdot \frac{10^y}{10^x + 10^y}$, $\quad$ za: $x = 0.1 \cdot (L_{Aeq,T} + K_T)$, and $y = 0.1 \cdot L_{ArKI,T}$

Estimated combined standard uncertainty of $L_{ArKI,T}$, calculated from (12) and according to GUM:

$$u_c(L_{ArKI,T}) = \sqrt{\left[\frac{\partial L_{ArKI,T}}{\partial T} \cdot u(T)\right]^2 + \left[\frac{\partial L_{ArKI,T}}{\partial L_{AEri}} \cdot u(L_{AEri})\right]^2}, \quad \text{where: } \frac{\partial L_{ArKI,T}}{\partial T} = -\frac{10 \cdot \log e}{T}$$

$u(T)$ ...... standard uncertainty because of aberration of the integration time of the apparatus declared by manufacturer, and the real time. In this case, the declared aberration (*a*) should be considered as uncertainty (*u*).

$$\frac{\partial L_{ArKI,T}}{\partial L_{AEri}} = \log e$$

Estimated combined standard uncertainty of L_{Aeri}, calculated from (13) and according to GUM:

$$u_c(L_{AEri}) = \sqrt{\left[\frac{\partial L_{AEri}}{\partial L_{AEi}} \cdot u(L_{AEi})\right]^2 + \left[\frac{\partial L_{AEri}}{\partial K_{Ii}} \cdot u(K_{Ii})\right]^2},$$

$\frac{\partial L_{AEri}}{\partial L_{AEi}} = 1$, $\frac{\partial L_{AEri}}{\partial K_{Ii}} = 1$

$u(L_{AEi}) = u(MS) = \sqrt{u^2(M) + u^2(K) + u^2(A)}$ .... standard uncertainty of measurand (L_{AEi}) is equal to standard uncertainty of the measuring system.

$u(K_{Ii})$ .... determined in accordance with (15)

<u>*Case b)*</u>

When the impulsive sound could not be recognized and measured as separate event from separate source during reference time interval. For this case, rating noise level is:

$$L_{Ar,T} = L_{Aeq,T} + K_T + K_I \quad \text{..........} \; (17)$$

$L_{Aeq,T}$ is calculated according to (1) or directly measured while K_T and K_I are determined according to (9) and (15).

Estimated combined standard uncertainty of $L_{Ar,T}$, calculated according to GUM [1]:

$$u_c(L_{Ar,T}) = \sqrt{\left[\frac{\partial L_{Ar,T}}{\partial L_{Aeq,T}} \cdot u(L_{Aeq,T})\right]^2 + \left[\frac{\partial L_{Ar,T}}{\partial K_T} \cdot u(K_T)\right]^2 + \left[\frac{\partial L_{Ar,T}}{\partial K_I} \cdot u(K_I)\right]^2} \quad \text{..........} \; (18)$$

$$\frac{\partial L_{Ar,T}}{\partial L_{Aeq,T}} = 1, \quad \frac{\partial L_{Ar,T}}{\partial K_T} = 1, \quad \frac{\partial L_{Ar,T}}{\partial K_I} = 1$$

While $u(L_{Aeq,T})$, $u(K_T)$ and $u(K_I)$ are determined according to (6) or (7), (10) and (15), respectively.

Now, when the rating noise level ($L_{Ar,T}$) is known as well as the associated estimated combined standard uncertainty $u_c(L_{Ar,T})$, without regard of a possibility of recognition and without regard of a measurable impulsive sound, there is ordinary or high-energy impulsive sound. Also, ($L_{Ar,T}$) could be determined without regard if the tone components could be clearly heardable and defined. ($L_{Ar,T}$) is calculated in accordance with (11), or (17), while $u_c(L_{Ar,T})$ is calculated in accordance with (16), or (18).

4. DETERMINATION OF LONG TERM AVERAGE SOUND LEVEL ($L_{Aeq,LT}$) AND LONG TERM AVERAGE RATING LEVEL ($L_{Ar,LT}$) AND ASSOCIATED ESTIMATED COMBINED STANDARD UNCERTAINTIES, $u_c(L_{Aeq,LT})$ I $u_c(L_{Ar,LT})$

Long-term time intervals consist of several reference time intervals and they are used when embracement of all noise variation is necessary. Long-term average sound level is calculated according to:

$$L_{Aeq,LT} = 10 \cdot \log\left[\frac{1}{N}\sum_{i=1}^{N} 10^{0.1 \cdot L_{Aeq,T}}\right] \text{………. (19)}$$

While long term average rating level is calculated according to:

$$L_{Ar,LT} = 10 \cdot \log\left[\frac{1}{N}\sum_{i=1}^{N} 10^{0.1 \cdot L_{Ar,T}}\right] \text{………. (20)}$$

$N = \frac{t_2 - t_1}{\Delta t}$ ….. number of intervals, Δt …… reference time interval,

$t_2 - t_1$ …….. long-time interval.

As the similarity between the above expressions and equation (1) is obvious, estimated combined standard uncertainties, $u_c(L_{Aeq,LT})$ and $u_c(L_{Ar,LT})$, are calculated according to procedure described in item 2 (case b):

$$u(L_{Aeq,LT}) = \sqrt{\left(\frac{\partial L_{Aeq,LT}}{\partial L_{Aeq,T}}\right)^2 \cdot u^2(L_{Aeq,T}) + \left(\frac{\partial L_{Aeq,LT}}{\partial N}\right)^2 \cdot u^2(N)} \text{ ………. (21)}$$

$$u(L_{Ar,LT}) = \sqrt{\left(\frac{\partial L_{Ar,LT}}{\partial L_{Ar,T}}\right)^2 \cdot u^2(L_{Ar,T}) + \left(\frac{\partial L_{Ar,LT}}{\partial N}\right)^2 \cdot u^2(N)} \text{ ………. (22)}$$

$\left(\frac{\partial L_{Aeq,LT}}{\partial L_{Aeq,T}}\right) = \log e$ …. partial derivation of (19) by $L_{Aeq,T}$

$u(L_{Aeq,T}) = u(MS) = \sqrt{u^2(M) + u^2(K) + u^2(A)}$ …. standard uncertainty of measurand ($L_{Aeq,T}$), equal to standard uncertainty of measuring system.

$\left(\frac{\partial L_{Aeq,LT}}{\partial N}\right) = -\frac{10 \cdot \log e}{N}$ …. partial derivation of (19) by N

$u(N) = \frac{a}{\sqrt{3}}$ …. [5] standard uncertainty of number N, where a represents deviation because of the non-harmonisation between the long term and the reference time interval. For example, if the long time interval is 5 hours and 18 minutes ($t_2 - t_1$ = 318 min.) and the reference time interval is equal to

15 minutes (Δt = 15 min.), then N = 21.2. Since N must be an integer value, the deviation is: a = 0.2.

$\left(\frac{\partial L_{Ar,LT}}{\partial L_{Ar,T}}\right) = \log e$ …. partial derivation of (20) by $L_{Ar,T}$

$u(L_{Ar,T})$ …. combined standard uncertainty of $L_{Ar,T}$ – calculated in accordance with (16) ili (18)

$\left(\frac{\partial L_{Ar,LT}}{\partial N}\right) = -\frac{10 \cdot \log e}{N}$ …. partial derivation of (20) by N

$u(N) = \frac{a}{\sqrt{3}}$ …. same as above.

5. EXPRESSION OF MEASUREMENT RESULTS AND ASSOCIATED MEASUREMENT UNCERTAINTY

according to GUM [1], measurement result and associated measurement uncertainty should be express as follows:

Example: $L_{Aeq,LT}$ *= 51,4 dB(A) with estimated combined standard uncertainty* u_c *= 1,28 dB(A)*

For the expression of numerically values of measurement results and associated measurement uncertainty, a three significant digits value should be sufficient.

6. LITERATURE

1. Guide for Uncertainty of measurement, CIPM, 1993.
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