Long-term Leq Errors Expected and how long to Measure (Uncertainty and Noise Monitoring)

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During the Harmonoise-Projcet of the European Union [1] a large number of systematic measurements were performed by deBAKOM over time periods of up to 12 weeks at 5 distances from roads, rail lines and loud speakers. Wind speed, wind direction, atmospheric stability, temperature and humidity have been measured simultaneously at these sites. Using these data one can demonstrate how a long term equivalent level as defined by the European Noise Directive can be measured and how the uncertainties of such measurements can be expressed. Based on the autocorrelation function derived from these results, different measurement approaches are discussed. It is demonstrated that for a distance of 1200 m from a large motor way the uncertainty can be reduced to ±0.4 dB. This is achieved using a stratified data evaluation scheme. It is demonstrated that the observed difference of 0.6 dB between measurements taken in August and March may be the changing of ground impedance or similar effects.

1 Introduction

The European Noise Directive [2] has introduced two basic quantities the L_{den} (day evening and night) and L_n (night) to describe the reception noise level. These quantities are understood to be yearly averages as regards emission of sound and an average year as regards meteorological circumstances.

The evaluation of these quantities from measured data has to be done in such a way that the influencing parameters are weighted according to their long term occurrence. This approach is called representative sampling. To apply this, additional information is needed, which allows to reduce the variance.

Road traffic changes from hour to hour. During the day, sound propagation is governed by different meteorological situations. Ground impedance and ground roughness [1] may change depending on seasonal changes of vegetation. All these parameters influence the variance of the L_{den} and L_n in an “average year”.

In the following we will demonstrate this concept using measured data obtained during two 8 weeks measurement campaigns.

2 Average

The equivalent levels over the measurement periods may be obtained using

$$L_{den} = 10\lg \cdot \frac{1}{n}\sum_{i=1}^{n} 10^{0.1(L_i + D_i)} \quad (1)$$

whereas L_i is the hourly L_{eq} and D_i the addition for the different periods of the day and n the number of measured hours. The night time level is obtained accordingly without addition for the night hours. These averages may be assumed to be long term averages if during the measurement all influencing parameters, such as wind direction, atmospheric stability etc. have occurred with frequencies equal to those in the long term.

To check this, the Ladenburg Harmonoise Project data are used. The data were taken in 2002 (period I) and 2003 (period II). To keep the description short, only the L_{den} and L_n for the site 1 (25 m distance to a super highway) and site 5 (1200 m distance to a super highway) were used (see [1]). If the assumption is correct that in both 8 week periods the same meteorological situations have occurred, with identical frequencies, the averages should be equal for both periods. The results measured are shown in table 1.

Table 1: Comparison of average L_{den} and L_n at Ladenburg in 2002 (period I) and 2003 (period II) including uncertainties

	I		II	
Site	1	5	1	5
L_{den}	78.0	52.6	77.4	54.2
Uncertainty	±0.2	±0.3	±0.2	±0.4
N	1208	1014	1066	878
L_n	70.3	45.8	69.6	47.0
Uncertainty	±0.2	±0.3	±0.2	±0.5
N	394	343	360	335

The uncertainties were calculated by assuming that the sound pressure squared is normally distributed.

The average sound pressure square is given by:

$$p^2{}_m = 10^{0.1 \cdot L_{den}} \cdot p_o{}^2 , \qquad (2)$$

whereas $p_o = 2 \cdot 10^{-5}$ N/m².

The standard deviation is given by:

$$S^2 = \frac{1}{N} \sum_{i=1}^{n} 10^{0.2(Li+D)} \cdot p_o{}^2 - (p^2{}_m)^2 \qquad (3)$$

The above given uncertainties are described by the upper L+ and lower L- limits of confidence which have been calculated using:

$$L\pm = 10\lg\left(p_m{}^2 \pm 1.96 \cdot S / \sqrt{N-1}\right) \qquad (4)$$

The factor 1.96 is based on a double side error probability of 0.05.

Seemingly, the sound levels decrease from 2002 to 2003 at site 1 by 0.6 dB and increase at site 5 by 1.4 dB! If the decrease is caused by less traffic in Period I the difference at site 5 would be 2 dB if this is taken into account!

The changes at both sites are significant. At site 1 it is three times the uncertainty and at site 5 four times the uncertainty.

It should be noted that the uncertainties given in table 1 were calculated under the assumption, that all measured levels are statistically independent.

3 Autocorrelation

This assumption can be checked looking at the autocorrelation function levels which are defined as

$$\theta(\tau) = \frac{1}{s^2} \int \left(p^2(t) - p^2{}_m\right)\left(p^2(t+\tau) - p^2{}_m\right) dt \qquad (5)$$

For the night-time autocorrelation function the time scale consists only of night hours. Measured values taken during rain, high wind speed etc. are not taken into account

In Fig. 1 to 4, the green line represents the autocorrelation function, the upper curve depicts the measured half hour L_{eq}'s. If the data are valid, they are depicted black, those excluded due to rain, wind etc. are depicted in red. The autocorrelation is depicted as percentage from -100 to +100. The night-time autocorrelation function in Fig.3 and 4 includes only night-time!

The autocorrelation functions for site 1 show for the L_{den} and the L_n a very strong periodicity with respect to 24 hours (see Fig. 1) and 8 hours (see Fig. 3). This results from the diurnal change of the traffic flow. The autocorrelation function falls under 50 % after 72 hours or 3 days (Fig. 1 and 2).

From Fig. 3 and 4 for the night-time it is obvious that the autocorrelation at site 5 drops far more quickly and a 12 hours autocorrelation time seems to be sufficient.

If independence for the L_{den} is assumed after 18 hours, the uncertainty range increases to ±1 dB for site 1 and to ±4 dB for site 5. This means that the observed uncertainties are in the same order of magnitude as the observed differences between measurement periods I and II.

It further means that the estimation of the yearly average based on a 6 to 8 week measurement varies at 25 m between ±1 dB and at 1200 m between ±4 dB. To reduce uncertainties, representative sampling or data evaluation has to be used.

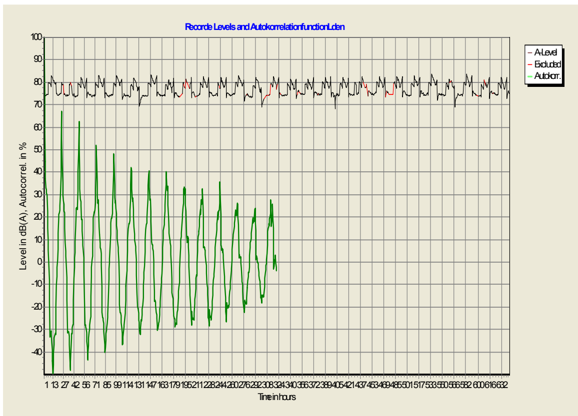

Figure 1: Autocorrelation function measurement period I for L_{den} site 1

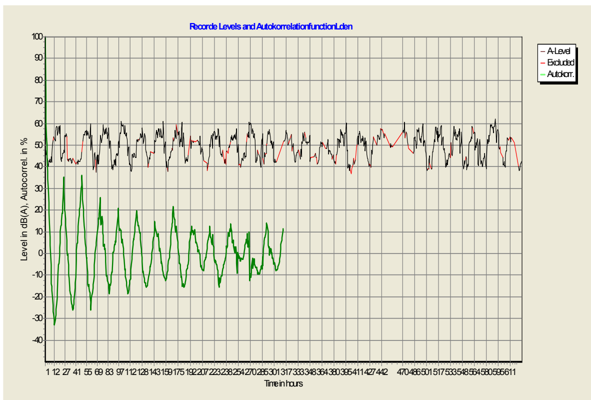

Figure 2: Autocorrelation function measurement period I for L_{den} site 5

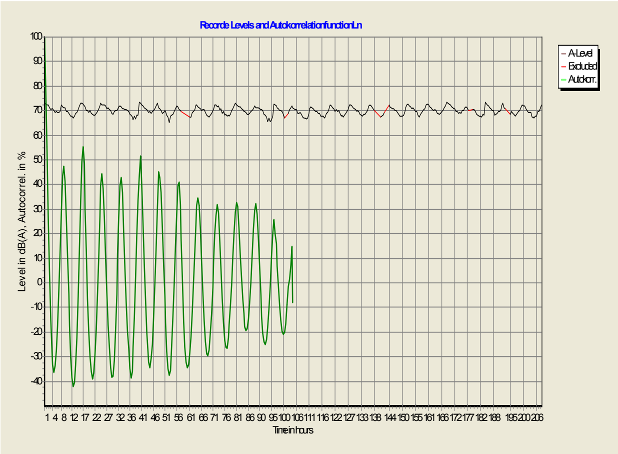

Figure 3: Autocorrelation function measurement period I for L_{den} site 1

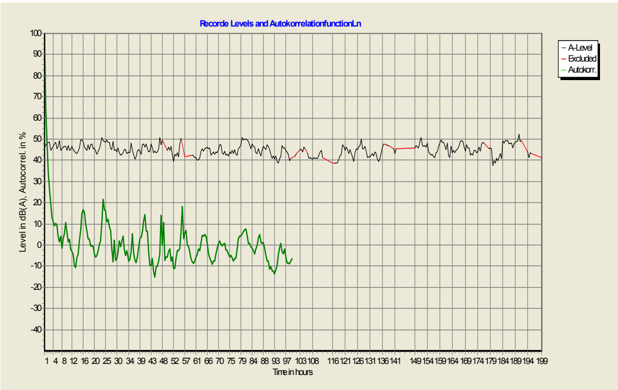

Figure 4: Autocorrelation function measurement period I for L_n site 5

4 Representative Sampling

In this approach the measured data are sorted into different classes or strata, which represent influencing parameters such as a wind direction of 120° ± 30° and a wind speed between 1 and 2 m/s etc. The most obvious and simplest approach is to reduce the variance by sorting the data according to the time of day.

4.1 Stratification according to the time of day

The standard deviation of a stratified sample is given by [3]:

$$S^2 = \sum_{k=1}^{n} W_k \frac{S_k{}^2}{n_k} \qquad (6)$$

where S_k is the standard deviation of stratum k and n_k is the number of samples in stratum k and W_k is the weighting factor or the frequency of occurrence of stratum k in the long term.

In Fig. 5 the 24 hourly average $L_{eq's}$ including the additions D are depicted for site 5. The curves in black depict the hourly L_{eq}'s + D as averaged over the measurement period for each hour of the day. The red curves show the standard deviation for each hour as a level. As can be seen from Fig. 5, the standard deviation is greater than the mean value. The blue curves depict the number of measurements for each hour of the day. The long term level can now be estimated under the assumption that each hour in an average year should be equally represented:

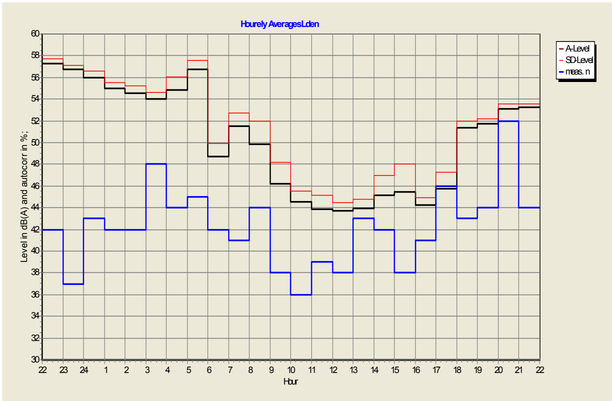

Figure 5: Hourly L_{eq}'s +D (black), standard deviation expressed as level (red), number of usable data in each hour (blue), period I site 5.

$$\overline{L}_{eq,long,1} = 10 \lg \frac{1}{24} \sum_{j=0}^{23} \left(10^{0.1 \cdot \overline{Leq}(j) + LDi)} \right) \qquad (7)$$

where j is the hour of the day. $\overline{Le}(j)$ is the equivalent level over all n_j measured data available in hour j:

$$\overline{L}_{eq}(j) = 10 \lg \left(\frac{1}{n_j} \sum_{i=1}^{nj} 10^{0.1 L(j)_i} \right) \qquad (8)$$

The standard deviation of the mean value $10^{0.1 Leq,long,1}$ is given by:

$$S_{long}{}^2 = \left(S^2 - S_m{}^2 \right) \frac{1}{n} \qquad (9)$$

where S is the standard deviation of the unweighted sample and Sm of the average:

$$S_m{}^2 = \frac{1}{n} \sum_{j=1}^{23} \left(10^{0.1 \overline{Le}(i)} - 10^{0.1 \overline{L}} \right) \cdot n_j \qquad (10)$$

where $\overline{L}$ is the equivalent level over all measurements, n_i is the number of measurements in hour j and n the total number. The confidence limits are obtained as given in eq.4 using S_{long}:

Table 2: Comparison of the hourly weighted averages, wind directions equally distributed

	I		II	
Site	1	5	1	5
L_{den}	78.0	52.6	77.4	53.7
Uncertainty	±0.06	±0.21	±0.08	±0.32
L_n	70.3	45.8	69.6	47.0
Uncertainty	±0.1	±0.27	±0.13	±0.37

Again a difference of 0.6 dB is observed between period I and II at site 1 and of 1.1 dB at site 5. Both differences are significant.

The autocorrelation functions are shown in Fig. 6 and 7.

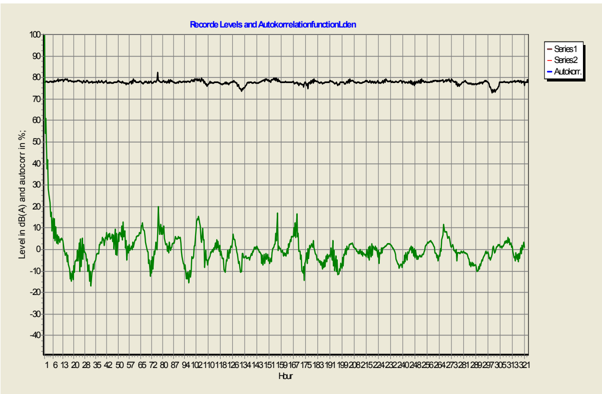

Figure 6: Autocorrelation function period II site 1 including corrections for the hourly dependence of the level (black corrected level recording, green control)

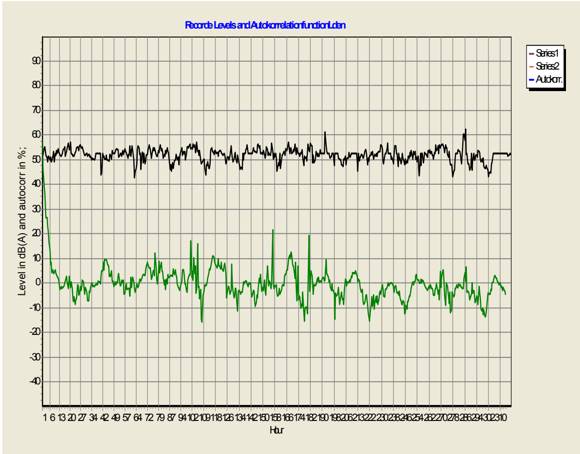

Figure 7: Autocorrelation function period II site 5 including corrections for the hourly dependence of the level (black corrected level recording, green control)

The autocorrelation falls quickly below 10 % after 6 hours and remains there more or less. This means that independence can be assumed after 6 hours. This will double the uncertainties as given in table 2. However the differences remain significant between period I and II.

4.2 Stratification including meteorological consideration

In a further step we can now consider to introduce meteorological weighting. The simplest approach is to look for the dependence with respect to wind direction for daytime, evening and night-time. This is depicted in Fig. 8 to 9 for site 5. Site 1 shows no wind direction dependence.

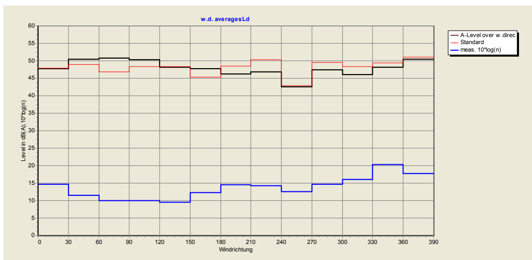

Figure 8: MP5 period II, level compared to wind direction,day time (360-390=calme)

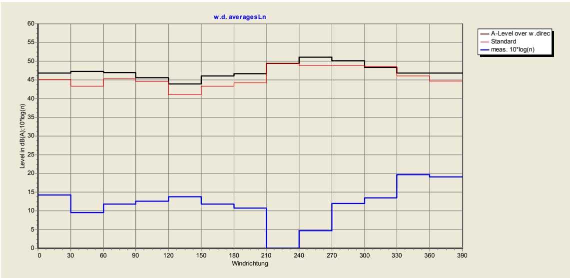

Figure 9: MP5 period II, level compared to wind direction, night Monin-Obukhov lengh [6] greater zero

However, using meteorological data from the German Weather Office, the occurrence of the different wind directions for the long term (basis 10 years) can be obtained (propagation classes derived for a standard year (AKT).

At present we do not have these data. To demonstrate how the procedure works we can assume that each wind direction has the same frequency of occurrence.

During daytime the highest levels are observed in northeast wind situations (see Fig. 8), during the evening the lowest and highest levels are observed for west wind directions and during night-time for west wind directions and the lowest values for southeast wind directions. This may be explained by inversion. Therefore, night-time is separated into two strata, one for positive Monin-Obukhov lengths [6] and one for negative.

This approach is applied at site 5 for both periods.

From table 2 it can be seen that at site 5 an increase of 1.1 dB is observed from period I to II. This difference remains nearly unchanged. The level-increase may be caused by a change in the ground impedance or different temperature and humidity for both periods.

An analysis of this reveals considerable differences:

Table 3:. Temperature and humidity in both measurement periods

	Period I		Period II	
	T °C	H %	T °C	H %
Day	23.7	63.5	11.3	49.5
Evening	23.2	61.4	9.9	49.7
Night	17.8	82.0	5.5	66.5

The changes in air absorption for 1200 m between period I and II are given in table 4 using ISO 9613-2 [7]:

Table 4: Air absorption in the mayor octave bands for road traffic noise at a distance of 1200 m for period I and II and the differences for day and night time

	Frequency				
	250	500	1 k	2 k	Hz
ΔDay I-II	0.48	1.90	1.80	-4.80	dB
ΔNight I-II	0.90	0.80	0.90	-3.40	dB

Positive values in table 4 mean that in period II the air absorption was less compared to period I.

Applying the data given in table 4 it can be seen that from Period I to II a level increase of 1.3 dB is caused by the change in air absorption between Period I and II. The difference between both measurement periods is reduced to less than 0.3 dB, which may be caused by changes of the impedance, which have not been accounted for. However, this difference is not statistically significant.

5 Conclusion

Measurements Close to the Road

In cases where meteorological influences and effects of ground impedance may be considered to be of minor importance, the measurement should be performed at least over 72 hours and stratified according to the time of day.

Measurement at Larger Distances

The measurement periods day, evening and night should be considered separately. To calculate the representative average, the frequency of occurrence of the important meteorological parameters should be taken into account. This means that the three dimensional wind vectors should be measured. If long term climatological data are available, these should be used. If those data are not available, simplifications can be used such as

- equal distribution of the wind directions
- 50 % inversion at night-time

or maps are provided where those data are given per area as e.g. in the French Standard on Road Traffic [4].

However, to achieve an uncertainty of less than ±1 dB, more than one week of measurement is necessary and a correction for temperature and humidity is necessary.

Short Term Measurements Using Additional Information

Short term measurements, meaning few hours of measurement, are only possible if additional information is available about the traffic flow and the frequency of occurrence of wind directions and stability, wind speed is of less importance. Humidity, temperature and ground impedance changes should also be considered. In this case few measurements may be used to extrapolate the result to the long term value.

Uncertainty

It should be noted that the above given uncertainties cover the uncertainties resulting from the measurement under the assumption that the sound level obtained for each hour or half hour has no uncertainties. This means that the above given uncertainties are only a part of the uncertainties budget as described by GUM [5]. At least 0.4 dB instrument uncertainty should be assumed.

Distribution Assumption

Above, the assumption is used that the sound pressure squared is normally distributed. This leads for short term measurements to the estimation of negative values. This may be avoided by introducing a distribution assumption which results only in positive values. The distribution may be

- log normal or
- gamma distribution or
- equal distribution between a maximum and minimum value.

References

[1] *Validation of Harmonoise Models*, Doc. Identity: HAR 28TR-041109-TNO10 Doc., see Harmonoise web site: www\Harmonoise.org

[2] *European Noise Directive*, Assessment and Management of Environmental Noise, 2002/49/EU

[3] W.J. Dixon, F.J. Massy Jr., *Introduction to Statistical Anlyses*, McGraw Hill Boot Company

[4] *Bruit des Infrastructures Routières*, NMPB-Routis 96, Janviers 1997

[5] International Organisation for Standardisation, *Guide to the Expression of Uncertainty in Measurement*, 1993 (GUM)

[6] Roland B. Stull, *An Introduction to Boundary Layer Meteorology*, Kluwer Academic Publishers, 1988

[7] ISO 9613-2, *Acoustics – Attenuation of Sound during Propagation Outdoors – Part 2: General Method of Calculation*, 1996