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Bibliographical reference

Inter Laboratory Comparison of Environmental Noise Measurement, Jurij Prezelj and Mirko Čudina, Acta Acustica **vol. 94** (Number 5), 2008, pp. 774-783

DOI
https://doi.org/10.3813/AAA.918085

ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 94 (2008) 774 – 783

DOI 10.3813/AAA.918085

Inter Laboratory Comparison of Environmental Noise Measurement

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Summary
Results of an inter laboratory comparison for environmental noise measurements are presented in this article. 18 laboratories took part in this study. A purpose of individual measurement was to quantify environmental noise levels, calculate noise descriptors and compare them with community noise regulations. Measurements and calculations were performed according to standards ISO 1996-1:2005, ISO 1996-2:2007 and national legislation. A loudspeaker was used as a reference noise source. It was mounted at the top of the hayloft just below the roof. The loudspeaker emitted a pink noise, representing a constant broadband noise source. The noise source was operating from 8:00 in the morning to 16:00 at the afternoon, each day for 4 weeks. During this time, laboratories performed all required measurements. Each laboratory performed measurements independently from other laboratories and according to its own procedures. Measurement results of equivalent noise level L_{Aeq}, percentile values L_1, and calculation of noise descriptors L_{d} and L_{den} were compared. An estimation of measurement uncertainty for a given environmental conditions and measurement setup conditions is given.

PACS no. 43.50.Rq

1. Introduction

An environmental noise measurement is a complex task. It includes a spatial sampling and a time sampling of a stochastic environmental noise. In the environmental noise measurement, a multitude of independent signals from different noise sources (transportation, industries, etc.); quite possibly located in different places, contribute to form the noise under analysis. Environmental noise generally occurs in the form of continuous random signals, [1]. Due to the uncorrelated nature of multitude of acoustic sources a statistical description of environmental noise is appropriate [2].

Noise signals are described quantitatively by evaluation indices as for example with the energy equivalent noise level L_{Aeq} and with the percentile level $L_{\%}$. A quantification of these parameters is the aim of the environmental noise measurement. Due to the statistical nature of the environmental noise, a particular measurement can only lead to an estimate of these parameters, whose true values are known only to Mother Nature [2]. A statistical interpretation of the environmental noise measurement is consistent with international standards. Many national legislations also require a quantitative estimate of an error, associated with the noise measurement. Specifically, it is important to quantify the range in which the measured parameter might vary with a specific likelihood. This is generally expressed by a value in brackets representing a confidence interval [2].

A final result of the laboratory, performing environmental noise measurement, is a single numerical value, which should embrace an influence of the environmental noise level time history, the influence of the environmental noise tonal characteristic, and the influence of its impulse characteristic. This single value is usually obtained by an extrapolation from evaluation indices, (L_{Aeq}, L_{imp}, and 1/3 octave spectrum of L_{Aeq}), acquired with short-term measurements. This single value is called noise descriptor (L_{d}, and/or L_{den}). According to standards ISO 1996-1:2005 and ISO 1996-2:2007 following evaluation indices should be determined and presented in the report for each measurement location: L_{Aeq}, L_{E}, Lmax, L_1, L_{99}, and measurement uncertainty. According to national legislation, a noise descriptor, (L_{d}, and/or L_{den}), should be calculated and reported. L_{den} is a descriptor of noise level based on energy equivalent noise level (L_{Aeq}) over a whole day with a penalty of 10 dB(A) for nighttime noise (22.00–7.00) and an additional penalty of 5 dB(A) for evening noise (i.e. 19.00–23.00). Noise descriptors are compared with a community noise regulation in order to asses the influence of the noise source on the environment. If the noise source generates noise level exciding the regulated value, a noise control project has to be implemented.

There is always a residual risk of an incorrect assessment outcome. The inherent variability of environmental sound fields, in both space and time, is often the major

Received 8 January 2008,
accepted 23 June 2008.

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contributor to the overall risk [3]. Environmental noise levels can vary over a wide range as a result of the diversity of site conditions and activities occurring during measurements. This variability is extremely important for a correct measurement interpretation, but it is often a source of disagreement when applying standards and regulations, as there is no consensus about how to estimate and present it [4].

An inter laboratory comparison was organized in order to determine the reproducibility of environmental noise measurements on the national level, the reproducibility of the calculation of noise descriptors, the reproducibility of assessment outcomes, and to evaluate a general measurement uncertainty. An interlaboratory comparisons (ILC) is defined in ISO/IEC Guide 43:1997 as an organization, performance and evaluation of the test on the same or similar test items by two or more laboratories in accordance with predetermined conditions [5]. In some circumstances, one of the laboratories involved in the inter-comparison may be the laboratory, which provides the assigned value for the test item. Interlaboratory testing scheme involves randomly selected sub-samples from a source of material being distributed simultaneously to participating testing laboratories for concurrent testing. Occasionally, this technique is also used for interlaboratory measurement schemes. After completion of the testing, the results are returned to the coordinating body, and compared with the assigned values to give an indication of the performance of the individual laboratories and the group as a whole [6].

2. Planning the ILC

A variation in sound power of the noise source eminently affects the variation in noise level. Noise levels depend on a measurement location relating to the location of the noise sources. Noise levels and noise spectra are constantly changing during the environmental noise sampling at a fixed measurement location. Weather conditions affect a propagation of noise from the noise source to the measurement location. Different laboratories have different measurement procedures. They are using different equipment. Personnel have different experiences. Consequently, differences occur at choosing the microphone location, the time interval, and the sampling time. Different procedures are used to calculate different noise descriptors from evaluation indices obtained with environmental noise measurements. Additionally, practical and financial constraints always limit an environmental noise measurement survey to a finite number of measurement locations over finite periods of time, thus limiting the ability of measured data to provide a true representation of the noise, occurring at other times or locations to which the assessment may equally apply [3].

National regulations often require that noise from different types of sources is dealt separately. This separation, e.g. of traffic noise from industrial noise, is often difficult to accomplish in practice. A noise from sources which are not under consideration and which can be eliminated from measurements is called a residual noise. In our case, traffic noise can be regarded as residual noise.

Measurements are normally carried out outdoors. Wind induced noise, noise from rivers and creeks, hum of the city etc, may also affect results. This noise is called background noise and it can not be eliminated from measurements.

All parameters influencing the environmental noise measurement and calculation of noise descriptors should be included into the ILC plan, in order to be able to observe how individual laboratory deals with these influencing parameters. On the other hand, equal conditions should be assured for all cooperating laboratories, if we want to compare their results. Equal measurement conditions can be easily assured for all laboratories. Measurement of the reference noise source from the same tripod in the anechoic chamber under controlled environmental conditions would be the case. However, it is not an intention of the environmental noise ILC to compare instrumentation. Laboratory procedures and personnel are under consideration, especially sampling of the environmental noise and the calculation of noise descriptors. Therefore, the ILC was designed as a multitude order of environmental noise measurement placed by the ILC organizer (Slovenian Acoustical Society) to different laboratories. Organizer of the ILC had to select the ILC measurement location, to provide the reference noise source, and to analyze results.

Following decisive factors for ILC measurement location were followed during its searching.

1. Residual noise should be present. Its level should be high enough, but it should be easy to remove it from the measurement.
2. Background noise should be low.
3. Noise source should be able to achieve sufficient signal to noise ratio.
4. In the vicinity of the ILC location there should not be too many inhabitants.
5. There should be available power for noise source and timers, used to switch noise source ON and OFF.

After convenient measurement location was found a reference noise source was placed into the ILC environment. Before commencing with environmental noise measurements, a short instruction with basic information about the noise source was given to individual laboratories. Only information about its location with precise border location to adjacent parcels and time of operation were given. Noise was generated by the reference source which was operating from 8:00 in the morning to 16:00 at the afternoon, each day for 4 weeks. Noise of interest was described as continuous broadband noise generated by a loudspeaker. Task of the laboratory was to assess the influence of a noise source to surrounding resident buildings. Laboratories had to determine measurement locations according to national legislation and to perform measurements according to ISO 1996-1:2005 and ISO 1996-2:2007. Personnel of individual laboratory had to independently determine measurement locations, time of measurement, sampling time, number of repetitions, criterion for removing

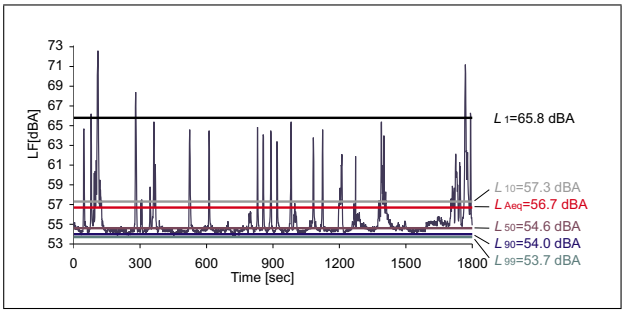

Figure 1. Typical noise level time chart at the reference measurement position with the operating reference noise source.

residual noise and correction of background noise. Laboratories reported their measurements results and calculations in their standard form, just like in real case scenario. All measurements were performed under real environment conditions.

2.1. Residual noise AND background noise

Just beside the hayloft there is a road with substantial traffic. Traffic was a main source of residual noise. Additional residual noise was coming from the construction site, from church bells and from activities in nearby workshops. Barking of the dogs and singing of the cocks also kept interrupting measurements. Participants were present during the measurements and sources of residual noise were immediately identified. Residual noise was excluded using "*pause*" and "*back erase*" options on the integrating sound level meters. This was the only possible way, for the majority of collaborating laboratories, to estimate the noise level, generated by the reference noise source. A typical noise level time chart is presented in Figure 1. Peaks on the chart present noise of passing cars, busses and trucks. Church bells caused elevation of noise level just after 1700 sec. Other less significant peaks belongs to activities in nearby workshops. The majority of instruments used in the ILC had no time recording; therefore personnel had to use subjective criteria for excluding residual noise events. This procedure is a source of the measurement uncertainty.

A background noise was 35 dBA ±3 dBA. A signal to noise ratio was over 15 dBA at the measurement location MM1 (depicted in Figure 3), and no correction was needed. However, at the measurement location MM2 (depicted in Figure 3), signal to noise ratio was just around 10 dB. Only 6 laboratories measured background noise, and only 3 of them performed correction of background noise. This was an additional source of the measurement uncertainty.

2.2. Noise source

According to the definition of an ILC [5] a reference sample should be available to all cooperating laboratories for longer period of time. In an environmental noise measurement a reference sample is a noise source with a constant sound power. Therefore, the most important activity during the planning of the ILC was a search for appropriate noise source. After analysis of different industrial noise sources (ventilation fan of disused mine, cooling tower, electric station, etc...) and literature review [7], we came to the conclusion, that it would be most suitable to use a loudspeaker generating pink noise with a continuous amplification as a reference noise source. Its sound power was set to a level, which assured more then 10 dB signal to noise ratio at all anticipated measurement locations. A good reference sample is the base for valid ILC result. Therefore a reference noise source was closely monitored for short-term and long-term stability. L_{Aeq} was measured. Sampling interval was 2 minute and special attention was paid for removal of residual noise.

2.2.1. Short-term stability of the reference noise source

Analysis of the reference source short-term stability is based on results provided by laboratories. Results from the measurement location MM1 (depicted in Figure 3), were used. Laboratories performed, according to their procedures, few repetitions of measurement the L_{Aeq}, in order to assess stability of the noise source, stability of weather conditions and stability of their equipment. Results of short-term reproducibility are given in Table I.

Unfortunately only 11 laboratories included repetition data in their results. From Table I we can see, that majority of laboratory measured L_{Aeq} in short term interval with standard deviation lower then 0.15 dB. An average standard deviation of results was also below 0.15 dBA. Two laboratories performed only one repetition. A significant deviation of results can be observed for two laboratories. Their results were not included in the average value of the standard deviation.

Since a distance between the noise source and the measurement location is less then 25 m the influence of environmental conditions is not significant. All laboratories were using sound level meters type 1. Therefore the influence of measurement equipment also didn't contribute significantly to combined variation of results. We can conclude, that short-term stability of the reference noise source, influence of environmental conditions, and used measurement equipment were suitable for the environmental noise ILC.

2.2.2. Long-term stability of the reference source

A stability of the reference noise source was also monitored over a longer period of time. A monitoring of the long-term stability started on the 18th of October 2006 and lasted until the 14th of November 2006. A reference location, where Lea was measured, was in the center of the garden, (Location depicted by REF in Figure 3). Measurements for the monitoring of the long-term stability were performed during different parts of the day, but usually between 13:00 and 16:00. Results of monitoring the long-term stability are presented in Figure 2. Each result is an average value of 6 measurements. Integration time for each

Table I. Short-term stability. Measurement location MM1. Average standard deviation is 0.11.

	Lab 1	Lab 4	Lab 7	Lab 8	Lab 9	Lab 11	Lab 12	Lab 13	Lab 14	Lab 16	Lab 17
1	50.7	50.3	50.4	51.3	51.3	50.6	50.5	50.7	50.9	50.5	50.2
2	50.6	50.1	50.2	50.7	51.5	50.7	50.4	50.7	50.8	50.5	50.4
3	50.7		50.3		51.2	50.8	50.3	50.5	50.6	50.6	50.4
4	50.7		50.2			50.8	49.5		50.6		50.3
5	50.7		50.3			50.8	50.3		50.9		50.2
6	50.7					51.0	49.6				50.5
7						51.0					50.5
8						50.7					50.5
9						50.6					
10						50.6					
Std.dev. [dBA]	0.04	0.14	0.08	**0.42**	0.15	0.15	**0.43**	0.12	0.15	0.06	0.13
Duration [min]	17	92	14	78	9	37	17	9	13	31	35

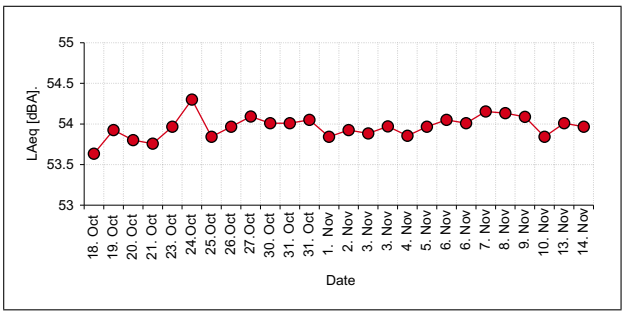

Figure 2. Long-term stability of noise generated by the reference source and measured at the reference position.

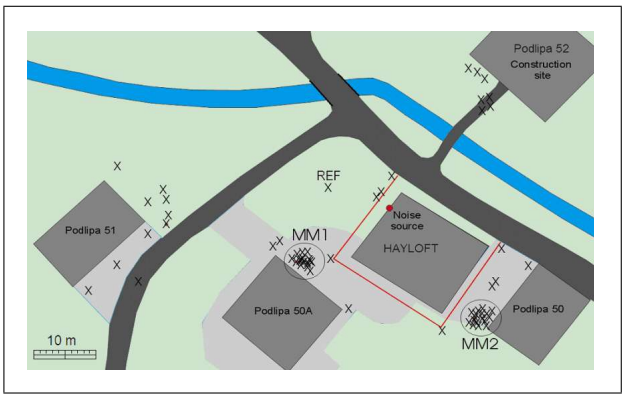

Figure 3. Ground plan of the ILC site with marked measurement locations.

measurement was 2 minutes. Residual noise was eliminated with "*pause*" and "*back erase*" functions. A maximum average value of L_{Aeq} was 54.3 dBA and a minimum value was 53.6 dBA. A grand average value was 53.9 dBA with standard deviation of 0.14 dBA. These results indicate that reference noise source is sufficiently stable for use in the environmental noise ILC. A value, recorded on the 24 of November, had higher level due to the inadequate removal of residual noise. Analysis has shown that subsonic frequency residual noise, which could not be heard, had influence on the result in 0.1 dBA range, so it could be ignored.

2.3. Measurement locations

Four resident buildings border on the hayloft with the noise source. All laboratories measured noise levels in front of the two nearest buildings, Podlipa 50A (MM1) and Podlipa 50 (MM2), Figure 3. Measurement location of individual laboratory is marked with an x. For assessing noise at the location MM1, all laboratories placed measuring instruments approximately 3 m from the main entrance. All laboratories independently positioned their instruments within a radius of 1.2 m. When assessing noise at the location MM2 individual microphone locations were more scattered, however all laboratories manage to place instruments within a radius of 1.6 m. Only half of collaborating laboratories additionally measured noise at other two buildings, Podlipa 51 and Podlipa 52 (Construction site).

2.4. Measurement uncertainty

Variability of procedures and financial constrains create a significant risk of irregular assessment outcome when using environmental noise measurements for decision making regarding noise pollution. In order to be able to design an environmental noise measurement survey which would properly take into account the risk of incorrect assessment outcomes, a complete understanding of all factors contributing to the measurement uncertainty is required. A broad range of different survey design options will normally be available to the practitioner. Considering the measurement uncertainty as important factor during the development of a measurement strategy provides the best chance of developing an approach that will gather the information required to minimize outcome risk while at the same time not causing excessive delay or unnecessary cost [3].

A measurement uncertainty is a parameter, associated with the result of a measurement. It characterizes the dispersion of the values that could reasonably be attributed to the measured quantity [8]. In the context of practical

environmental noise assessment, the measurement uncertainty is the doubt over the ability of an environmental noise measurement to provide a representation of environmental noise levels that could occur in other time periods or locations within which the measurement could have reasonably been taken. There is no way that any method based on extrapolation can compete in terms of underlying accuracy against estimates based on real long term data [4]. The uncertainty therefore arises when there is insufficient information to determine how and why environmental noise levels could vary from those prevailing during the course of a measurement survey. This uncertainty is directly caused by the inherent variability of sound fields, but variability does not necessarily imply uncertainty [3]. It is clear that estimate of measurement uncertainty should reflect as closely as possible what it is actually happening in real measurements. Professional judgment is just that and could easily be wrong. In practical environmental sound studies, it is frequently more important to understand the causes and magnitude of the variability of measured sound levels than it is to necessarily minimize this variability. Understanding variability in this way is frequently the most effective means of averting the risk of incorrect assessment outcomes [3].

Accredited laboratory should estimate measurement uncertainty of results, as given in ISO-17025. All sources of measurement uncertainty needs to be identified. Influence of main sources of measurement uncertainty needs to be quantified.

2.4.1. Assessment of the measurement uncertainty for the individual laboratory result

According to standard ISO 1996-2:2007, sources of measurement uncertainty for L_{Aeq} are grouped in four segments, and for assessment of combined standard uncertainty following equation should be used [9],

$$\sigma_t = \sqrt{A^2 + X^2 + Y^2 + Z^2}.$$

Here, A represents a standard deviation of measurements performed with different operator, different equipment, at the same location and with all other constant parameters. This value is set to 1 and refers to L_{Aeq} measurements with type 1 sound level meters. X presents a standard deviation, determined from at least 3, and preferably from 5 measurements under repeatable conditions (same measurement procedure, same instrument, same operator, same location) and at a position where variations in meteorological conditions have little influence on the results. For long-term survey, more measurements will be required to determine the deviation. Y presents a standard deviation of results due to conditions of noise propagation. The value will vary depending upon the measurement distance and the prevailing meteorology. A method using a simplified meteorological window is provided in Annex "A" of standard [9]. For long-term measurements different weather categories will have to be dealt with separately and then combined together. For short-term measurements variations in ground conditions will be small. However, for long-term measurements, these variations may add considerably to the measurement uncertainty. Z will vary depending on the difference between measured values and the residual sound. Higher uncertainties are to be expected on maximum levels, at higher frequency band levels and with tonal levels.

An individual laboratory can asses the measurement uncertainty of result for each measurement location according to this procedure. Because the deviation due to the reproducibility is estimated with fixed 1 dBA for L_{Aeq} in broad range of measurement conditions, it is inherit in final evaluation of measurement uncertainty. Therefore, by following to the standard, estimate of measurement uncertainty can not be properly reduced. An environmental noise ILC results can be used to assess the variation due to the reproducibility, article A from the above equation.

2.4.2. Assessment of the measurement uncertainty for the result of the interlaboratory comparison group as a whole

Instead of following to the procedure given in ISO 1996-2:2007, measurement uncertainty can be assessed with a different approach. In any case, recognizing the sources of measurement uncertainty is necessary. Sources of measurement uncertainty can be divided into three groups as presented in Table II: Parameters describing the measurement uncertainty due to the variations in sound power level, variations of operating conditions of the noise source, parameters influencing the sound pressure at the noise imission point due to variations in the propagation conditions, and parameters influencing the conversion of sound pressure into the evaluation indices (L_{Aeq}, L_1, L_{99}).

If a mathematical relationship between the influencing parameter and measured value is known, then this parameter is identified source of measurement uncertainty. Influence of some parameters can be exactly determined by measurements, like an influence of humidity on the noise attenuation during the propagation over long distances, for example. All laboratories monitored wind speed at microphone position. Only few of them recorded wind direction as well. Since the distance from the reference source to the measurement position was less than 25 m wind speed was monitored only due to wind induced noise on the microphone itself.

In literature, different influencing parameters are listed and evaluated. However there are many parameters which have a significant influence on measurement result, but they cannot be mathematically evaluated. Quantifying their influence is left to the intuition of experienced personnel. Such examples are obstacles on the propagation path, conditions of the ground and other similar parameters. To avoid subjective assessments, larger number of measurements needs to be done. With the increasing number of measurements performed under different measurement conditions, the average value is getting closer and closer to the long term average value. At the same time, a standard deviation of results slowly starts to characterize the measurement uncertainty. 18 laboratories cooperated in our study. Each laboratory measured at least at

Table II. Sources of measurement uncertainty.

	Source of measurement uncertainty	Range of values of individual parameters influencing the measurement
Source	Short term stability of noise source	within single repetition, sampling time from 1 min to 15 min
	Long term stability of noise source	between repetitions, noise time constant in months
Propagation	Environmental conditions:	Temperature (from 8 °C to 26 °C), Pressure (990 Pa to 1015 Pa), Humidity (45% to 95%), Wind speed at microphone location (from 0 m/s to 2.1 m/s)
	Ground	(dry high grass, wet low grass)
	Obstacles	Parked cars, foliage
	Positioning of Sound level meter	(15±1.2 m and 25±1.6 m)
Receiver	Measurement equipment	Norsonic 118, B&K 2260, Larson Davis
	Different integration time of L_{Aeq}	1 min 10 repetitions vs. 15 min 1 repetition
	Different background noise level	MM1: S/N = 15 dB, MM2: S/N = 10 dB
	Subjective criterion for elimination of residual noise (Traffic, barking, church bells. . . .)	
	Algorithms and calculation procedures for noise descriptors	

two locations. On average each lab performed 3 repetitions at each location. Few labs performed long term measurements with sampling time of 24 hours. Based on huge amount of data obtained in variety of conditions, we can simply use standard deviation of all results, which is the standard deviation of averages from each laboratory, for final estimation of measurement uncertainty of the ILC study.

Individual laboratory will be able to assess measurement uncertainty of their results in similar situations (distances up to 25 m from the source to the microphone, environmental conditions within interval given in Table II, and more then 15 dB S/N ratio) more accurately.

3. Evaluation of individual laboratory

Quality control is the main motive of individual laboratories to cooperate in an ILC. The ILC is one of the most important tools for demonstrating the reliability of the laboratory work. A positive result of the individual laboratory confirms that its procedures, its equipment and its personnel are assuring credible results. An independent organization needs to analyze and evaluate results of all laboratories and give the final outcome, PASS/ FAILED for each laboratory. Results, provided by laboratories collaborating in ILC, were analyzed using two different criterions: absolute and relative criterion.

3.1. Absolute criterion

A measurement result of an individual laboratory is compared with a reference value and a predetermined level of acceptable deviation. The reference value is usually provided by a national reference laboratory. The deviation level is proposed by the ILC organizer. Establishing a reference laboratory for environmental noise measurements is not reasonable, because reference measurement conditions are impossible to establish. Therefore, a measurement result of the individual laboratory was compared with the average value of results provided by all laboratories. If a result of the individual laboratory lies near the reference value, within the predetermined level of acceptable deviation, it could be considered as credible. Acceptable levels of deviation are given in Table III as absolute criterion. All laboratories, collaborating in ILC, agreed upon acceptable deviation levels before ILC measurements were started.

Table III. Predetermined absolute and relative criterion of individual laboratory successfulness.

Absolute Criterion	Relative Criterion
L_{eq} : ±2.5 dB	$E_n = \frac{x_{\mathrm{lab}} - x_{\mathrm{ref}}}{\sqrt{U_{\mathrm{lab}}^2 + u_{\mathrm{ref}}^2}}$
L_{d} : ±3 dB	
L_{dvn} : ±3.5 dB	$\lvert E_n \rvert \leq 1$ PASSED
L_1 : ±5 dB	$\lvert E_n \rvert$ 1 FAILED

3.2. Relative criterion

This criterion is usually applied in the international ILC for evaluation of national reference laboratories. In such cases a reference value is not available in advance. The reference value is acquired with the averaging of all results, after all measurements are finished. Measurement uncertainty of the ILC, (denoted with U_{ref} in Table III) and measurement uncertainty of the individual laboratory (denoted with U_{lab} in Table III) are taken into consideration, during the assessment, according to relative criterion, presented in Table III. This criterion evaluates, if the reference value lies within the confidence interval of the result of the individual laboratory.

4. Measurements results

Results of measuring noise indices L_{Aeq}, L_1, and calculation of noise descriptors L_{d}, L_{den} are given in Tables IV and V. Results are given with higher resolution then usual,

Table IV. Measurement results [dBA] for equivalent noise level L_{Aeq}, statistical parameter $L_{1\%}$ and calculation results of noise descriptor for day and day-evening-night levels at measurement MM1. The last column depicts the estimated L_{Aeq} uncertainty of the individual results.

Lab	L_{Aeq}	L_d	L_{den}	L_1	
1	50.7	51.2	57.0	52.0	2.0
2	50.7	48.9	45.9	51.0	2.4
3	51.3	51.3	52.8	#	#
4	50.2	48.5	45.5	51.9	2.0
5	49.3	47.5	45.0	49.8	2.0
6	50.0	48.0	45.0	50.5	3.0
7	50.3	48.5	45.5	51.0	2.4
8	49.9	48.1	45.2	51.0	3.4
9	51.3	49.6	46.6	#	2.3
11	50.8	49.0	46.0	51.6	2.5
12	50.1	48.0	45.0	51.5	2.7
13	50.6	49.0	46.0	52.0	2.6
14	50.7	48.9	46.0	51.6	1.9
16	50.7	51.0	57.0	52.7	#
17	50.2	50.0	57.0	51.6	#
18	50.6	49.0	47.5	52.0	5.0
20	50.8	49.0	46.0	51.7	2.2
Criterion	50.5 ±2.5	49.1 ±3.0	45.8 ±3.5	51.5 ±5.0	
ILC Unc.	1.2	2.4	1.6	1.6	

Table V. Measurement results for equivalent noise level L_{Aeq}, statistical parameter L_1% and calculation results of noise descriptor for day and day-evening-night levels at location MM2. The last column depicts the estimated L_{Aeq} uncertainty of the individual results.

Lab	L_{Aeq}	L_d	L_{den}	L_1	
1	46.5	46.0	52.0	48.6	2.0
2	45.7	43.9	40.9	47.0	2.4
3	45.9	45.9	52.3	#	#
4	44.5	42.5	40.0	48.7	2.0
5	46.1	46.3	43.0	47.2	2.0
6	46.0	44.0	41.0	47.0	3.0
7	46.3	44.0	41.0	48.0	2.4
8	45.7	43.1	40.3	48.0	3.4
9	44.7	43.0	40.0	#	2.3
11	45.2	43.4	40.4	46.9	2.5
12	46.5	45.0	42.0	49.9	2.7
13	45.2	43.5	40.5	46.0	2.6
14	45.8	45.4	42.0	49.2	1.9
16	46.3	46.0	53.0	53.2	#
17	45.4	45.0	52.0	49.9	#
18	46.8	45.0	43.5	50.0	5.0
20	45.2	43.0	40.0	45.7	2.2
Criterion	45.8 ±2.5	44.4 ±3.0	41.1 ±3.0	48.4 ±5.0	
ILC Unc.	1.5	2.6	2.4	4.1	

(0.1 dBA). Laboratories estimated uncertainty of their results and their assessment is given in last column. All given measurement uncertainty values are referring to measurement of L_{Aeq}. Measurement uncertainty of the ILC includes a deviation of the reference noise source. Results in Table IV are given for measurement location MM1 and in Table V for measurement location MM2. Cells in Tables IV and V marked with "#" indicate that laboratory did not report value of the parameter. A criterion is defined according to the predetermined acceptable levels of deviation around the average value obtained from each laboratory (Table III). Gray cells indicate result which doesn't meet the absolute criterion.

Measurement uncertainty of the individual result at measurement locations MM1 and MM2 should differ. However, all participating laboratories ignored background noise and signal to noise ratio when assessing measurement uncertainty. Therefore their assessment of measurement uncertainty for measurement locations MM1 and MM2 doesn't differ.

5. Analysis of results

The ILC was designed as a precise experimental measurement of the unknown environmental noise level, generated by the reference noise source. Random variations of conditions could not be controlled; they could only be observed and quantified. These random variations were therefore included into an experimental plan. Result of an individual laboratory was simply regarded just as one repetition of the experimental measurement under closely monitored conditions.

A background noise level at the location MM1 was for 15 dB lower then the noise level of the operating noise source. At the location MM2, a background noise level was for 10 dB lower then the noise level of reference source. 6 laboratories performed measurements of background noise to ascertain if there is sufficient signal to noise ratio. Three laboratories demonstrated that there is no need for background noise correction. Three other laboratories performed correction of background noise. Consequently, the variation of noise descriptors (L_d, L_{den}) is higher then the variation of evaluation index L_{Aeq}. Variation of noise descriptor results was anticipated due to different procedures. An estimation, that the absolute criterion for noise indicators will be wider then the absolute criterion for L_{Aeq}, proved to be valid.

Laboratories didn't differentiate between evaluation of measurement uncertainty at measurement location MM1 and MM2. Laboratories assessed measurement uncertainty in general. They took into consideration only environmental conditions and measurement repeatability. None of the laboratories included influence of background noise into the assessment of measurement uncertainty.

Measurement uncertainty of the ILC result of the group as a whole is for noise descriptor L_{den} better then for L_d. Results of four laboratories which were over the absolute criterion were excluded from the calculation of measurement uncertainty for L_{den}. Remaining results did not deviate significantly. All results of L_d lie within the absolute

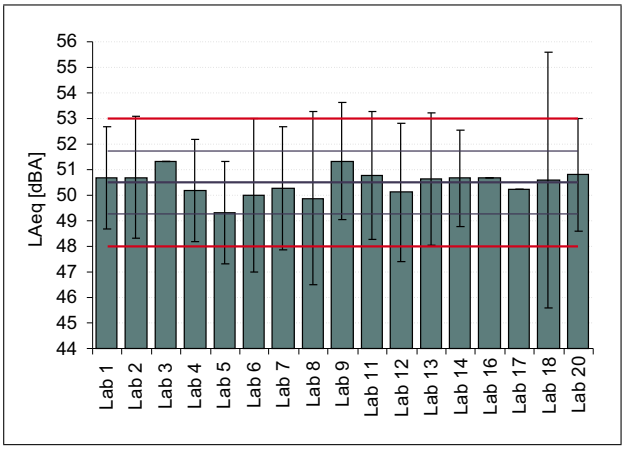

Figure 4. L_{Aeq} at measurement location MM1.

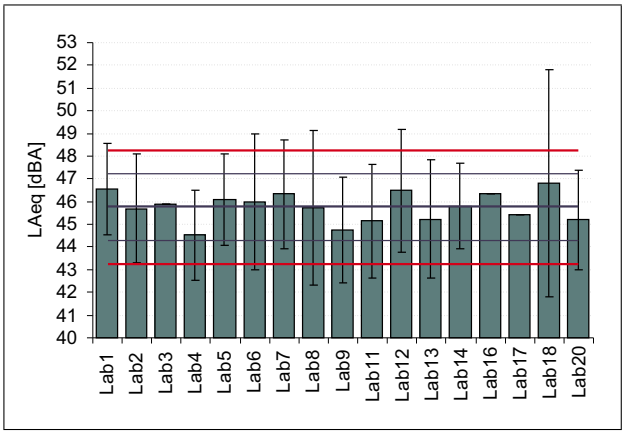

Figure 5. L_{Aeq} at measurement location MM2.

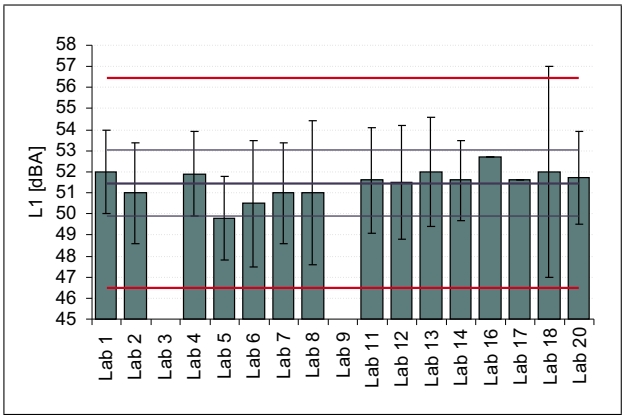

Figure 6. L_1 at measurement location MM1.

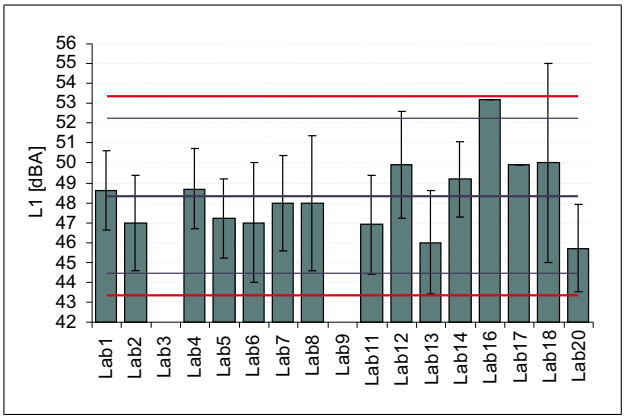

Figure 7. L_1 at measurement location MM2.

criterion. Consequently they all were used in calculation of measurement uncertainty for L_{d}. Four results were only just within the criteria resulting in poorer measurement uncertainty.

5.1. L_{Aeq}

Figures 4 and 5 clearly indicate that measurement results of all laboratories lie in the predetermined interval of absolute criterion (red thick line) and within the interval of ILC measurement uncertainty (blue thin line). At the measurement location MM1, the average value of L_{Aeq} was 50.5 dBA with the standard deviation of 0.5 dBA. At the measurement location MM2 the average value is 45.7 dBA with the standard deviation 0.65 dBA. At the measurement location MM1 a minimum value was 49.3 dBA and maximum value was 51.3 dBA, that is a maximum difference of 2.0 dBA. At the measurement location MM2 a minimum value was 44.5 dBA and a maximum value was 46.8 dBA, that is a maximum difference of 2.3 dBA. If we take under consideration that laboratories performed measurements during different time intervals, given in Tables 4 and 5, under different weather conditions, at different measurement locations, using different equipment, and following different procedures, then the reproducibility of measured values of L_{Aeq} is very good.

5.2. Percentile levels

Measured percentile levels L_1 are presented for two measurement locations (MM1 and MM2) in Figures 6 and 7. Lab 3 and Lab 9 didn't provide results for L_1. At the measurement location MM1, the average value of L_1 was 51.5 dBA with the standard deviation of 0.7 dBA. At the measurement location MM2 the average value was 48.3 dBA with the standard deviation 1.9 dBA. The highest measured value of L_1 was 52.7 dBA at the measurement location MM1 and 53.2 dBA at the measurement location MM2. The lowest measured value of L_1 was 49 dBA at the measurement location MM1 and 45.7 dBA at the measurement location MM2. A difference between highest and lowest measured value is again higher at the measurement location MM2.

According to our expectations, a dissipation of L_1 is more pronounced. Results of all laboratories lie within the predetermined interval of the absolute criterion (red thick line). All results acquired at the measurement location MM1 remain also within the interval of ILC measurement uncertainty (blue thin line). At the measurement location MM2 one result exceeds the interval of ILC measurement

uncertainty (blue thin line). It is important to emphases that the interval of ILC measurement uncertainty at the location MM2 is much broader then at the location MM1. A margin of the measurement uncertainty interval is close to the value of the absolute criterion.

A variation of measured values for L_1, and consequently measurement uncertainty, is much higher at the measurement location MM2 then at location MM1. This can be annotated to lower signal to noise ratio and to higher residual noise level at the location MM2, where signal to noise ratio was just around 10 dB. At the location MM2 a residual noise (traffic, church, barking) also had stronger influence on measurement results then at the location MM 1, because it was closer to the road and to other workshops.

5.3. Noise descriptors L_d and L_{den}

While all laboratories acquired measured values of L_{Aeq} and L_1 within narrow interval, a calculation of noise descriptors L_d and L_{den} was more erratic. L_d is a descriptor of noise level based on energy equivalent noise level (L_{Aeq}) over the day time interval (7:00–19:00). L_d can be calculated from energy equivalent noise level (L_{Aeq}), by applying some corrections, following

$$L_d = 10\log\left[\frac{1}{12}\sum_{i=1}^{n} t_i \cdot 10^{(L_{Aeq}(Td)+K1i+K2i+K3i)/10}\right], \quad (1)$$

where $L_{Aeq}(Td)$ is measured value for given time interval, $K1$ and $K2$ are correction factors for impulse and tonal noise. All laboratories appropriately neglected these two corrections. $K3$ is correction factor for background noise. Some laboratories applied this correction, and some did not. The reference noise source was operating for 8 hours each day so the $t_1 = 8$. Some laboratories used equation (1) directly and measured values of L_{Aeq} and ti=8 were simply entered. Other labs calculated noise descriptor L_d considering background noise during the time when main noise source was not operating, equation (2). Since background noise has more then 10 dB lower value then noise source, this is not very important at the measurement location MM1, but it has slight influence on the calculation results from the measurement location MM2.

$$L_d = 10\log\left[\frac{1}{12}\left(8 \cdot 10^{L_{Aeq}(Td)/10} + 4 \cdot 10^{L_{background}/10}\right)\right]. \quad (2)$$

L_{den} is a descriptor of noise level based on energy equivalent noise level (Leq) over a whole day with a penalty of 10 dB(A) for night time noise (22:00–7:00) and an additional penalty of 5 dB(A) for evening noise (19:00–22:00). Equation for its calculation is simple:

$$L_{den} = 10\log\frac{1}{24}\left[12 \cdot 10^{L_d/10} + 4 \cdot 10^{(L_e+5)/10} + 8 \cdot 10^{(L_n+10)/10}\right], \quad (3)$$

where L_d is noise descriptor for day, defined in equation (1). L_e is noise descriptor for evening and L_n is for night.

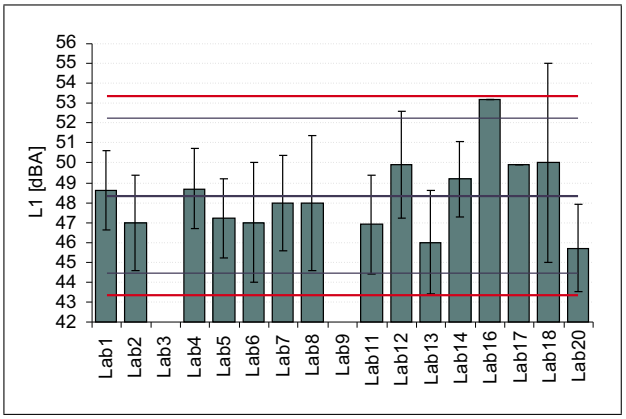

Figure 8. L_d at measurement location MM1.

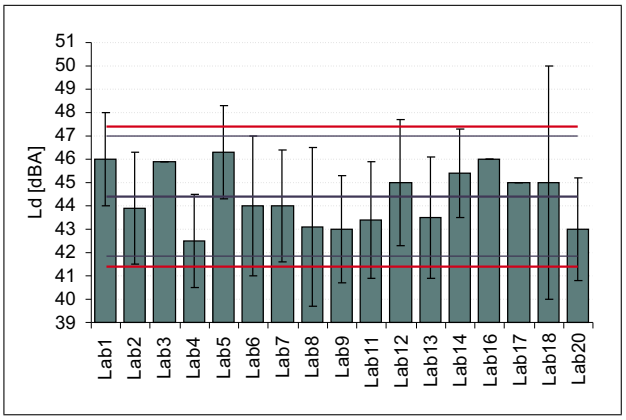

Figure 9. L_d at measurement location MM2.

Different laboratories used equations equation (3) differently. Entered values were describing different noise parameters. Measured, estimated, or even some theoretical values of noise descriptors were used with these equation. Different time intervals of supposed operating time interval resulted in broader distribution of the calculated values.

Some labs also performed noise measurements in the evening and during the night. By considering noise during this time they obtained higher values of L_{den}. If noise levels of L_e and L_n are more than 10 dB lower from L_d then difference is less then 2.5 dBA.

ILC results for noise descriptors clearly show that different procedures of individual laboratories significantly affect results. The uncertainty of assessment the noise descriptors (L_d, L_{den}) is much higher then the measurement uncertainty of L_{Aeq}. This deviation occurs due to different procedures. Such result was expected, however 4 laboratories completely miscalculated final result.

6. Conclusions

The reference noise source emitted pink noise and had very stable sound power on a time scale of seconds and on a time scale of days. Because noise level of the reference noise source was constant ($L_{Aeq} - L_{99} < 3$ dB), majority of

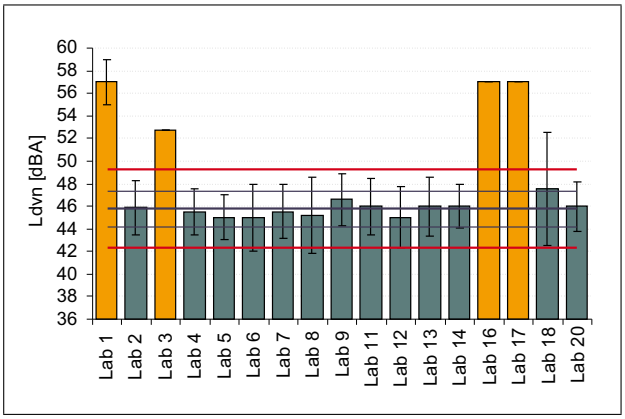

Figure 10. L_{den} at measurement location MM1.

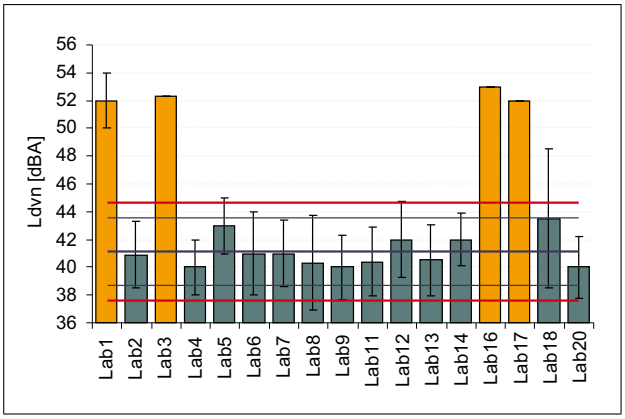

Figure 11. L_{den} at measurement location MM2.

collaborating laboratories decided for short measurement intervals in duration between 1 min and 5 min and for 2 to 10 repetitions. Three laboratories performed complete noise survey and have been measuring noise levels for 24 hours with 1 hour integration intervals. All laboratories didn't provide all necessary results. Only 6 laboratories measured and reported results of background noise and percentile value L_{99}. Therefore, only analysis of the most important evaluation indices (L_{Aeq}, and L_1) and noise descriptors, (L_{d}, and L_{den}) was performed.

Analysis of results has shown that measurement results of all laboratories lie within predetermined interval of absolute criterion. Measurement results of all laboratories, which provided assessment of uncertainty of their results, also lie within the relative criterion.

Laboratories perform measurements according to their own procedures. Such procedures are necessary, because more detailed instructions must be given to laboratory personnel for defining measurement locations and instruments setup. Result of ILC can be also regarded as a validation of their procedures. Calculation of noise level descriptors (L_{d} and L_{den}) is a very simple operation; however, it still adds to the dissipation of results and consequently expands the interval of the evaluation uncertainty. The most obvious deviation was observed for calculation of L_{den}. Four labs calculated very high value of this noise descriptor. Reason for this is simple. They presumed that noise source is working 24 hour a day instead 8 hours a day. It was also noticed that laboratories evaluate measurement uncertainty of their results regardless to the measurement location. They didn't took a signal to noise ratio or a residual noise into consideration when assessing uncertainty. Generally, laboratories assessed measurement uncertainty at the measurement location MM 1 to loose on one hand and to optimistic for the measurement location MM2 on the other hand.

Acknowledgement

Many thanks to all laboratories taking part in this study: A-PROJEKT, BUREAU VERITAS d.o.o., EKOSYSTEM d.o.o., EPI SPEKTRUM d.o.o., IMP LAB d.o.o., IVD d.o.o., KOMPLAST d.o.o., KOVA d.o.o., RTCZ d.o.o., SINET d.d., SINT d.o.o., VARNOST Maribor d.d., ZAG - INSTITUTE for building construction, ZVD - INSTITUTE for occupational health, ZZV Celje - Health institute Celje, ZZV Koper- Health institute Koper, ZZV Kranj - Health institute Kranj, and ZZV Novo Mesto -Health institute Novo Mesto

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