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MEASUREMENT UNCERTAINTY IN THE FIELD OF ENVIRONMENTAL NOISE AND BUILDING ACOUSTIC MEASUREMENTS: EXPERIENCE FROM INTERLABORATORY COMPARISONS

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Abstract: *In this paper the problem of measurement uncertainty in acoustic measurements has been discussed regarding the results of interlaboratory comparison (ILC). The measurement results of ILC in the field of environmental noise and in the field of sound insulation measurements (airborne and impact) have been examined regarding the proposed methods for calculation standard deviations in repeatability and reproducibility conditions. In the field of environmental noise measurements, of point sound source, the measurement results (19 laboratories) precision and accuracy are discussed regarding the microphone positions (on the reflection plane and close to the reflection plane). The results for expanded measurement uncertainty calculations, obtained following instructions from old ISO 1996-2:2007 and new ISO 1996-2017 are compared and discussed. In the field of building acoustic measurements the measured parameters of airborne and impact sound insulation (31 laboratories, 5 independent measurements) are compared regarding the obtained mean values and measurement uncertainties by removing outliers and finding standarddeviations in repeatability and reproducibility conditions according to ISO 5725-2 and ISO 12999-1:2014 and by approach described in GUM adopted for input parameters in each individual measurement and calculating overall standard uncertainty. In addition, the possibility to measure airborne sound insulation parameters by using acoustic camera has been considered regarding averaging the large number of measurement microphone positions in source and receiving room and finding measurement uncertainties for sound pressure levels and reverberation times in large number of measurement positions.*

Key words: environmental noise parameters, building acoustic measurements, expanded measurement uncertainties calculations for each independent measurement and by using ILC results.

1. INTRODUCTION

The accreditation procedure according to ISO 17025:2017 for laboratories which are doing acoustic measurements (in the field of environmental noise, sound insulation measurements) is tedious task [1]. They have to verify and validate they own procedures according relevant international standards which can be changed every few years. Quality control is the main motive of individual laboratories to cooperate in the ILC but it can be used to make detail analysis of all individual results of laboratories included in environmental noise and sound insulation parameters measurements [2]. All of these laboratories certify the environmental noise parameters of the noise sources (industrial and small workshop sites, road, rail and air traffic), and sound insulation performance of different building elements for external customers. In addition to measurements, the calculation procedures like estimating the environmental noise by knowing sound power of sound sources determined according to ISO 3744:2010 [3] or estimating the sound insulation parameters of building structures according ISO 12354-1,2,3:2017 [4-6] can also be in the field of accreditation.

1.1. Measurement of environmental noise parameters

The environmental noise measurements are conducted now in accordance to the ISO 1996-2:2017 [7]. The special attention has to be provided regarding measurement accuracy and precision due to influence of measurement equipment, procedures and people who are conducting the measurements and making reports.

The main influence on measurement accuracy and uncertainty according to the new ISO 1996-2:2017 [7] standard are different regimes of sound source working and meteorological conditions when noise levels are measured at longer distances from the source in some particular part of the year.

The interlaboratory comparison has been organized in 2015. by Croatian Acoustic Society for 19 labs which have accreditation according ISO 17025:2005 in the field of environmental noise measurements. They usually measure the environmental noise parameters defined in ISO 1996-1:2016 [8] ($L_{A,eq}$, L_1,L_{95}, $L_{C,peak}$) from the new sound source in the environment with some residual noise at short distances without significant influence of meteorological conditions (wind speed and direction).

In this paper the measurement results of 19 labs are presented with obtained measurement uncertainty for each individual lab and overall uncertainty obtained for ILC comparison without outliers. The measurement uncertainties for considered measurement situation (small distances) are compared with calculations described in old ISO 1996-2:2007 [9] and new ISO 1996-2:2017 standard [7]. The overall measurement uncertainty is discussed and compared with each individual lab measurement uncertainty. The results for background noise and noise source are presented for two different measurement positions (in front of the reflecting surface and on the reflecting surface).

1.2. Measuring building acoustic parameters

In the field of building acoustics the sound insulation parameters are measured according ISO 16283-1:2014 [10], ISO 16283-2:2016[11] and ISO 16283-3:2016 [12] standards with measurement uncertainty calculated from ISO 12999-1:2014 standard [13]. Each one of lab (31 participants) performed five independent measurements of airborne sound insulation parameters (sound reduction index, standardized sound level difference, in repeatability condition by changing microphone positions when sound pressure levels and reverberation times are measured in each individual measurement) on the measurement object (lightweight partition) according IS0 16283-1:2014 and during measurement of impact sound insulation parameters of floating floor (normalized and standardized impact sound pressure levels) according to [11].

There are two different approaches in measurement uncertainty calculations described in [13]. The first calculation method for measurement uncertainty is based on standard deviations in reproducibility conditions determined from several interlaboratory comparisons according to the ISO 5725-2:1994 [14].

The second approach is based on measurement uncertainty calculations for each individual measurement of sound insulation parameters [15]. In this approach described in [15] the standard deviations and measurement uncertainty are determined from all measured parameters (sound pressure levels in the source and receiving room, reverberation time, the influence of instruments' measurement uncertainty is taken into account).

The problem with single-number values for sound insulation parameters and their uncertainties determined according to ISO 717-1:2013 [16,17] and ISO 717-2:2013 are described in [18, 19]. There is a big problem to find correlation coefficients for different types of testing objects (separating walls) between one-third octave bands in the frequency range of interest (50 Hz-5000 Hz) for determination of weighted sound insulation parameters uncertainties.

In this work the results of 31 laboratories are presented with their individual measurement uncertainty determined as standard deviations in repeatability conditions. Also overall measurement uncertainty from all measurement results without outliers has been determined according to [13].

2. THEORETICAL BACKGROUND FOR UNCERTAINTY CALCULATIONS

In agreement with modern statistical methods, the concepts of standard deviations in repeatability and reproducibility conditions have been used to state the precision of the measurements carried out according to a testing methods.

2.1. General statistics

Assuming a measurand Y is going to be determined from N measurements of independent variables X_1, X_2, X_3,.., X_N, then Y will be a function of those quantities which can be written with equation (1).

$$y=f(X_1,X_2,X_3,..X_k....X_N) \quad (1)$$

The values x_1, x_2, x_3,.., x_n are estimates of the input quantities X_1, X_2, X_3,.., X_N, as a consequence each estimate, x_i, will have an uncertainty associated, $u(x_i)$, which is expressed from experimental standard deviation given with eq. 2 [7].

$$\sigma = s(x_i) = \sqrt{\frac{1}{N-1} \cdot \sum_{k=1}^{n} (x_i - \bar{X})^2} \quad (2)$$

Standard measurement uncertainty is in general statistics defined as experimental standard deviation of mean value of each measured parameter by using eq. (3). The standard deviation of mean value is given by the standard deviation of the observations divided by the square root of the number of observations.

$$u(x_i) = \frac{s(x_i)}{\sqrt{N}} \qquad (3)$$

The equation (3) for experimental standard deviation in repeatability conditions is valid if the difference between measured values (expressed in dB) are small. In the general case the more correct equation is given by using eq (4) when measured quantities are converted to relative numbers and vice verse [7]:

$$u(x_i) = 10 \cdot log_{10}\left(10^{0,1 \cdot L_k} + S(x_i)\right) - L_k \qquad (4)$$

where L_k is energy averaged sound pressure level of N_m independent measurements in the meteorological and emission window according to eq. 5 [7].

$$L_k = 10 \cdot log_{10}\left(\frac{1}{N_m} \cdot \sum_{i=1}^{N_m} 10^{0.1 \cdot L_i}\right) \qquad (5)$$

This equation is valid only if each of the independent measurements last equal time. If the independent measurements last non-equal in time then additional time weighting should be used when calculating averaged value. $S(x_i)$ is obtained with eq. (2) converting the measurands in dB into relative numbers according to the eq (6).

$$S(x_i) = \sqrt{\frac{1}{n-1} \cdot \sum_{k=1}^{n} \left(10^{\frac{L_i}{10}} - 10^{\frac{L_k}{10}}\right)^2} \qquad (6)$$

$u(x_i)$ is the standard measurement uncertainty for each individual measurand. The overall measurement uncertainty is given for the case if there is no correlation with eq.(7).

$$u = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 \cdot u^2(x_i)} \qquad (7)$$

If the measured variables are correlated then the equation is a little bit complicates and is given with eq. (8).

$$u = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 \cdot u^2(x_i) + 2\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \cdot \frac{\partial f}{\partial x_j} \cdot u(x_i, x_j)} \qquad (8)$$

There is a big problem to find correlation coefficient $r(x_i,x_j)$ between individual measurands defined with eq. (9).

$$r(x_i, x_j) = \frac{u(x_i, x_j)}{u(x_i) \cdot u(x_j)} \qquad (9)$$

If the estimates x_i and x_j are independent, $r(x_i, x_j) = 0$, and a change in one does not imply an expected change in the other.

It should be noted that in new ISO 1996-2:2017 and old ISO 1996-2:2008 the measurement uncertainty in repeatability conditions is defined with equation (7) by assuming sensitivity coefficients of 1.

There is also interesting research about the influence on logarithmic values on the PDF functions for A-weighted equivalent continuous sound pressure levels for the traffic noise [20]. It is shown that PDF function with logarithmic values is asymmetric around mean value (arithmetic or logarithmic) so special attention should be aimed in detection of outliers assuming apriori normal distribution of measurands. The similar is observed when impact sound insulation parameters are measured and distributions for normalized and standardized sound pressure levels at different frequencies are shown in [21].

2.2. Detection of outliers in ILC

The results of several independent measurements are averaged and the mean value of interest is checked with Grubb's statistics and standard deviations should be checked with Cochran's statistics [14].

Cochran's test is used to check if there are cell standard deviations of several (n≥5) independent measurements exceptionally large and would inflate the estimate of the repeatability standard deviation if retained.

Grubb's test is used to check if there are means in laboratory results that are exceptionally high or low and would inflate the estimate of the reproducibility standard deviation if retained.

The treatment of outliers is dealt with in clause 7 of ISO 5725-2 [14], particularly in clauses 7.1 to 7.3. An outlier can be considered as a result which is sufficiently different from all other results to warrant further investigation. When carrying out the outlier tests, it should be understood that outliers should not be discarded or rejected purely from a statistical point of view.

After Cochran's test has been carried out, the tabulated mean values for each particular level of interest are arranged where results with bad standard deviations are removed from calculations. Several Grubbs' tests are then carried out.

Firstly, the test is carried out to establish whether the highest or lowest mean value can be identified as a single outlier. If an outlier is indicated, it is discarded and the test is repeated for the other extreme value. For a particular level of interest, Grubbs' test for one outlier enables the calculation of the quotient of the difference between the suspect value and the mean of all the values for that level, and the standard deviation of all values. This ratio is then compared with computed or tabulated (critical) ratio values at 95 % and 99 % confidence levels.

In the environmental noise parameters measurements' analysis, the measurement uncertainty (not standard deviation) for equivalent A-weighted value under repeatability conditions (the same operator with same instrument makes the several measurements **at the same position**) have been compared, together with expanded measurement uncertainty of each individual lab (which was approximately the same ±3,6 dBA for each laboratory). In addition the measurement uncertainty calculation according the new standard ISO 1996-2:2017 on the same measurement situation is calculated.

In the building acoustics parameters measurements the five independent measurement have been done under repeatability conditions (the same operator, the same equipment, the different positions of microphone in the source and receiving rooms). The standard deviations and means value of each individual lab are tested by using Cohran and Grubbs statistics according ISO 5725-2:1994 and overall mean and measurement uncertainty has been found as well as the individual measurement uncertainty of each lab participated into interlaboratory comparisons.

It should be noted that repeatability conditions are not defined in the same way for environmental noise parameters measurements (at the same measurement position according ISO 1996-2:2008, ISO 1996-2:2017) and different positions when sound pressure levels for building acoustics parameters determination are measured.

It should be also noted that standard uncertainty of the measurement results for environmental noise parameters (*L'*-parameter measured form source with residual noise, L_{res}-residual noise measurement result) and for sound insulation parameters is defined in different ways. Measurement uncertainty for building acoustics parameters determined by verification of labs' own procedure is defined as standard deviation *s* (eq. 2), not as experimental standard deviation of mean as *u* (eq. 3.) for environmental noise parameter results.

2.3. Environmental noise parameters measurement uncertainty calculations

In the environmental noise parameters measurement uncertainty calculations, it is assumed that there are no correlation between parameters and overall uncertainty budget depends on sound source itself, other sources which cause background noise, propagation path uncertainty due to different meteorological conditions and measurement chain at the receiver point and also the measurement position (free field, close to the reflection surface and on the reflection surface). The functional equation L=f(L',L_{res}) between measurand *L'* (under the influence of residual noise) and estimated value noise level from the source *L* during the specified conditions for which a measured value is wanted is derived according eq. (10).

$$L = L' + \delta_{slm} + \delta_{sou} + \delta_{met} + \delta_{loc} + \delta_{res} \quad (10)$$

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, this is changeable part so that is the reason why the measurements are divided in meteorological classes.

δ_{loc} is the error due to the selection of receiver position and δ_{res} is the error due to residual noise. Each source of error is function of each several other sources of error. The clear derivation is only for measured value under the influence of residual noise given in eq. (11-14).

It is assumed that intensity of two sources (residual noise and sound source) is the same as SPL in the far field (which is usually not true for low frequencies in spectrum) but for equivalent levels it is true assumption as well as assumption that these two noise sources are not correlated. The derivation for the influence of residual noise on the true value is given with eq. (11-16).

$$I = I' - I_{res} \quad / \cdot \frac{1}{I_0}, \frac{I}{I_0} = \frac{I'}{I_0} - \frac{I_{res}}{I_0} \quad (11)$$

$$10 \cdot log_{10}\left(\frac{I}{I_0}\right) = 10 \cdot log_{10}\left(\frac{I'}{I_0} - \frac{I_{res}}{I_0}\right) \quad (12)$$

$$L = 10 \cdot log_{10}\left(\frac{I}{I_0}\right), L' = 10 \cdot log_{10}\left(\frac{I'}{I_0}\right), \quad (13)$$

$$L_{res} = 10 \cdot log_{10}\left(\frac{I_{res}}{I_0}\right) \quad (14)$$

$$L = 10 \cdot log_{10}\left(10^{\frac{L'}{10}} - 10^{\frac{L_{res}}{10}}\right) = 10 \cdot log_{10}\left(10^{\frac{L'}{10}}(1 - 10^{\frac{L_{res}-L'}{10}})\right) \quad (15)$$

$$L = 10 \cdot log_{10}\left(10^{\frac{L'}{10}}\right) + 10 \cdot log_{10}(1 - 10^{-0,1 \cdot (L' - L_{res})})$$

$$L = L' + 10 \cdot log_{10}(1 - 10^{-0,1 \cdot (L' - L_{res})}) \quad (16)$$

The sensitivity coefficients for each parameter are given with equation (17) and (18).

$$c_{L'} = \frac{\partial L}{\partial L'} = \frac{1}{1 - 10^{-0,1 \cdot (L' - L_{res})}} \quad (17)$$

$$c_{L_{res}} = \frac{\partial L}{\partial L_{res}} = \frac{-10^{0,1(L' - L_{res})}}{1 - 10^{-0,1 \cdot (L' - L_{res})}} \quad (18)$$

The overall uncertainty will be expressed as an expanded uncertainty *U*. This quantity will, with a statement of confidence, define an interval where the measurand Y will be. This will be obtained by multiplying the combined standard uncertainty by a numerical factor, known as the coverage factor, k given with equation (19).

$$U = k \cdot u \quad (19)$$

A coverage factor of 2 is normally used, which corresponds to a coverage probability of 95% for environmental noise measurements and coverage factor k=1 with one side coverage probability of 84%.

The measurement uncertainty budget in the new ISO 1996-2:2017 standard is rather complicated even for simple situation and in the case compared to the old standard for A-weighted continuous equivalent sound pressure level. The measurement uncertainty in old standard ISO 1996-2:2007 is given by eq. (20) for A-weighted equivalent sound pressure level.

$$u = \sqrt{1^2 + X^2 + Y^2 + Z^2} \quad (20)$$

Where 1 dB(A) is measurement uncertainty because of instruments (1 class), it can be different operator, different equipment, same measurement place.

X- measurement uncertainty due to under repeatability conditions. It should be 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;

Y- this 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 the Standard ISO 1996-2:2006 (in this case $Y = \sigma_m$). 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- The value will vary depending on the difference between measured total values and the residual sound.

This component of measurement uncertainty is derived in [22] assuming that there is no difference in residual noise when measurement of the source noise ($L_{res,\ during}$) and when there is no noise from the source ($L_{res.after}$) is given with eq. (21).

$$L = 10 \cdot log_{10}\left((10^{\frac{L}{10}} + 10^{\frac{L,res,during}{10}} - 10^{\frac{L_{res,after}}{10}}\right) \quad (21)$$

The total measurement uncertainty due to influence of the residual noise is given by equation (22).

$$Z = \sqrt{2} \cdot u_{res} \cdot 10^{0{,}1 \cdot (L_{res,after} - L\ \ )} \quad (22)$$

When several measurements are done averaged values for residual noise and corrected noise levels from the source are included in equation (22). The laboratories usually measure the overall level with the source turned on and then turn off the source and measure residual noise several times after. They usually don't do turning on and off the source because this is not possible in practical situations.

The measurement uncertainties for all labs in repeatability conditions for A-weighted equivalent continuous sound pressure level have been calculated in this way for each individual lab where only a small difference in X and Z contribution and two other contributions (instrumentation, meteorological influence) same has been done for overall results. The similar calculation for considered situation is repeated according to the recommendations in the new ISO 1996-2:2017 standard.

The quantities and uncertainty budget are given for simple situation according ISO 1996-2:2017 are given in **Table 1.** The measurement uncertainty due to instruments (Class 1) is reduced on 0,5 dB(A) and sensitivity coefficient for source and sound level meter are added. There are other factors having influence on the measurement uncertainty (meteorological conditions, location of measurement position).

Table 1. a) Uncertainty budget according new ISO 1996-2:2017 [7]

Quantity	Estimate (dB)	Standard uncertainty u (dB)	Sensitivity coefficient
$L' + \vartheta_{slm}$	L'	0,5	$\frac{1}{1 - 10^{-0{,}1 \cdot (L' - L_{res})}}$
ϑ_{sou}	0	u_{sou}	1
ϑ_{met}	0	u_{met}	1
ϑ_{loc}	0-6	u_{loc}	1
$L_{res} + \vartheta_{res}$	L_{res}	u_{res}	$\frac{-10^{0{,}1(L' - L_{res})}}{1 - 10^{-0{,}1 \cdot (L' - L_{res})}}$

ϑ- are input quantities to allow for any uncertainty from assumed operating condition of the source, assumed meteorological conditions and residual noise.

In the standard [7] it is not clearly written that *u* are standard deviation of mean value and not standard deviation value. The standard deviation of mean value is obtained by dividing standard deviation with number of observations.

2.4. Building acoustics parameters measurement uncertainty

The measurement uncertainty calculations for building acoustic parameters are defined in standard ISO 12999-1:2014 by using standard deviations in reproducibility conditions determined experimentally from different interlaboratory comparisons. The laboratory verifies their own measurement procedure by doing measurements in repeatability conditions (with changed positions of microphones and comparing their results with standard deviations in repeatability conditions from ISO 12999-1:2014 or those obtained from ILC).

In this paper the obtained uncertainties are compared by using GUM and ISO 5725-2 approaches.

In the GUM approach the measurement uncertainty is calculated for each individual measurement (by knowing uncertainties of each variable included in calculations [15]).

In agreement with ISO 5725-2, the concepts of standard deviations in repeatability and reproducibility conditions have been used to state the precision of the measurements carried out according to a test method.

Standard deviations in repeatability conditions (s_r) shows the closeness of agreement between mutually independent test results obtained with the same method on identical test material in the same laboratory with the same equipment by the same operator within short time intervals.

Standard deviations in reproducibility conditions (s_R) shows the closeness of agreement between test results obtained with the same method on identical test material in different laboratories with different operators by using different equipment. The determination of the standard deviations in repeatability and reproducibility conditions of a test method obtained by an interlaboratory comparison, taking into account the procedures given in international standards ISO 12999-1:2014 and ISO 5725:1994. Tentative values of sr and s_R are given in ISO 12999:1-2014 [13]. The s_r and s_R values may also be used to verify the proper operation of test procedures of a laboratory which has not taken part in the comparison.

3. MEASUREMENT SITUATIONS AND PARAMETERS

3.1. Environmental noise parameters

The point source was located on h_s=3m and receiver position (h_r=1,5 m) was chosen on the façade and in front of the façade with distance from the source of 25 m. The ground between source and receiver was grass and equation (11) [7] for critical distance where meteorological conditions does not have influence on measurement results and uncertainty was satisfied.

The measured parameters were:

L_{Aeq} (dB(A)) – A-weighted equivalent sound pressure level (corrected to free field conditions) when the source is turned on and off

L_{95} (dB(A)) – time and A-weighted value exceeded in 95% of considered time interval

L_1 (dB(A)) - time and A-weighted value exceeded in 1% of considered time interval;

$L_{C,peak}$ (dB(C)) – C-weighted peak sound pressure level;

A-weighted one-third octave band levels when the source is turned on;

L_{res} (dB(A)) – equivalent level of residual noise;

A-weighted one-third octave band levels when the source is turned on.

In the results shown here, we have compared in details parameters at the two different positions with probability density functions and measurement uncertainties.

Fig. 3.1. Measurement situation for environmental noise parameters and windows settings where labs choose their measurement positions

3.2. Building acoustics parameters

In the ILC the lightweight partition made of 20 mm chip floor slab between two rooms, for the airborne sound insulation measurements and timbre floor for impact sound insulation. In the ILC-s, not only acoustic insulation parameters (R'-apparent sound reduction index, D_{nT}-standardized level difference and L'_n-normalized impact sound pressure levels, L'_{nT}-standardized impact sound pressure levels) are compared, but also the geometrical parameters of rooms (volumes without furniture and area of the considered partition). Reverberation times in the receiving room are also compared because acoustic insulation parameters depend on them [10-12].

3.2.1. Airborne sound insulation parameters

There are two parameters used for expression of the airborne sound insulation: the standardized level difference $D_{n,T}$ between rooms or the apparent sound reduction index *R'* of the separating element as a function of frequency, whichever is appropriate. The each lab in this ILC-s determined all parameters but sound reduction has been considered more in details. Sound reduction index *R*' which depends on the area of measured element (*S*), and on the equivalent absorption area *A* which is calculated from geometrical dimensions (volume of the receiving room) and measured reverberation time in the receiving room.

The standardized level difference is given with eq. (23) which includes the difference in the energy-average sound pressure levels between the source and receiving rooms:

$$D_{nT} = D + 10 \cdot log\frac{T}{T_0} \qquad (23)$$

T_0- is the reference reverberation time; for dwellings, T_0 = 0,5 s. *T* is the reverberation time in the receiving room. The sound reduction index is given by eq. (24) [10]:

$$R' = D + 10 \cdot log_{10}(\frac{S}{A}) \qquad (24)$$

The equivalent absorption area A of the receiving room is given by eq. (25):

$$A = 0{,}161 \cdot \frac{V}{A} \qquad (25)$$

where *V* is the receiving room volume (m^3) with the furniture excluded because it has influence on the reverberation time *T* [10-12].

3.2.2. Impact sound insulation parameters

The impact sound insulation can be expressed with two parameters: the normalized impact sound pressure level (L'_n) and the standardized impact sound pressure level ($L'_{n,T}$) as a function of frequency. Normalized impact sound pressure level (L'_n), given with eq. (3), is impact sound pressure level in the receiving room L'_i (averaged in time and space) increased by a correction term, which is given in dB, being ten times common logarithm of the ratio of the measured equivalent absorption area *A* of the receiving room eq. (26) to the reference absorption area A_0 = 10 m^2.

$$L'_n = L'_i + 10 \cdot log\frac{A}{A_0} \qquad (26)$$

Standardized impact sound pressure level, $L'_{n,T}$, is the impact sound pressure level L_i reduced by a correction term which is given in dB, being ten times common logarithm of the ratio of the measured reverberation time *T* of the receiving room to the reference reverberation time T_0 = 0.5 s [12]:

$$L'_{n,T} = L'_i - 10 \cdot log\frac{T}{T_0} \qquad (27)$$

The measurement setups for airborne and impact sound insulation parameters are shown in **Fig 3.2.**

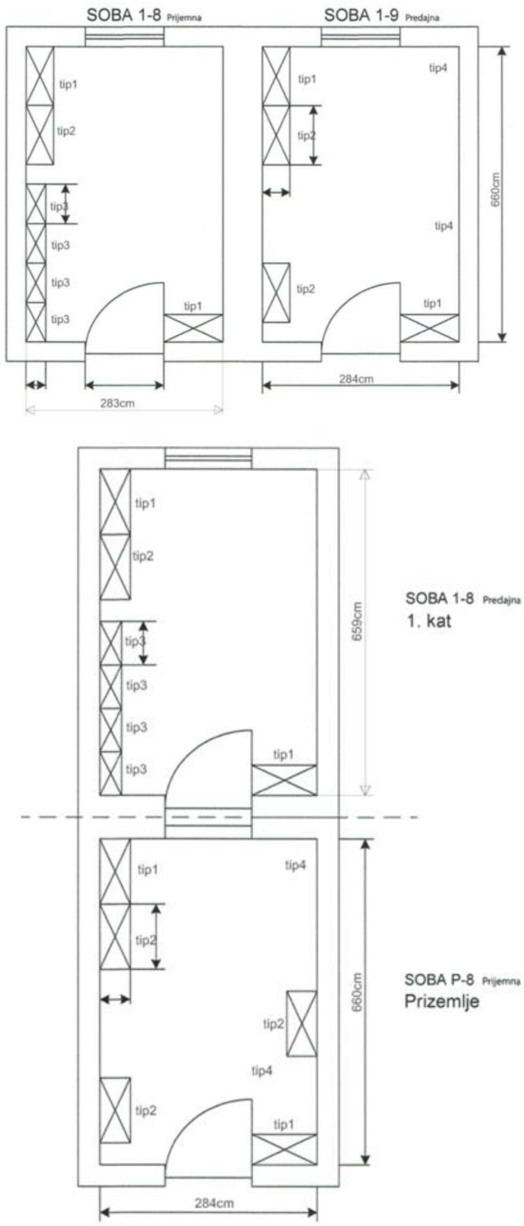


Fig 3.2. The transmitting and receiving room in the considered situation for a) airborne and b) sound insulation parameters measurements

The measurement of sound pressure levels with sound level meter is restricted only in few positions depending on the rooms' size and we tried to increase the number of measurement positions by using acoustic camera with 80 microphones and averaging the sound pressure levels in 80*5 positions in source and receiving rooms (**Fig 3.3**). The .wav files form all microphones were recorded and imported in MATLAB where analysis for finding equivalent sound pressure levels for 15 s recordings (broadband and in one-third octave bands) has been done by using Audio System toolbox.

Fig 3.3. Measurement SPL and reverberation time with acoustic camera in large number of positions

4. MEASUREMENT RESULTS

4.1 Environmental noise parameters

There were a big problems in detecting a penalty due to tonal component in spectrum appeared due to standing wave in the window setting shown in **Fig 3.1.** The tonal component has been reported from 4 labs on the position directly on the facade and for 2 labs for the position in front of the facade.

There were no tonal components in the sound source signal which was pink noise emitted from loudspeaker.

The results for rated A-equivalent noise parameters when the source is on and off at two different positions are shown in **Fig 4.1.** The averaged results of all labs (without excluded outliers) are shown in Table 4.1.

a) Residual noise- the source is turned off

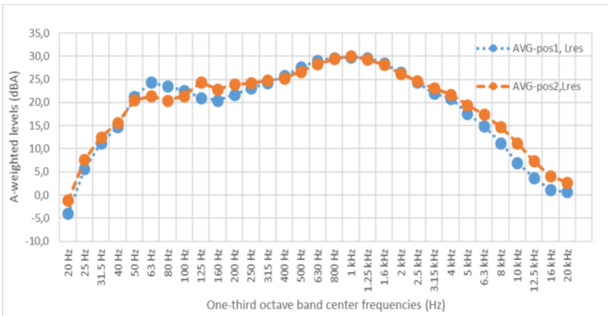
Label	$L_{A,eq}$ (dBA)	L_{95} (dBA)	L_1 (dBA)	$L_{Z,eq}$ (dB)	$L_{A,max}$ (dBA)	$L_{A,min}$ (dBA)	$L_{Z,max}$ (dB)	$L_{Z,min}$ (dB)
AVG-pos1	38,7	35,2	45,2	59,1	50,7	34,3	70,0	53,1
u1-pos1	0,4	0,5	0,6	0,4	0,9	0,6	1,1	0,5
AVG-pos2	38,9	35,6	44,8	60,5	50,6	34,8	72,0	54,0
u2-pos2	0,4	0,5	0,6	0,5	1,0	0,6	1,1	0,5
Difference Mean (p1-p2)	-0,2	-0,3	0,4	-1,3	0,1	-0,6	-2,0	-0,9

b) Environmental noise parameters when the source is turned on

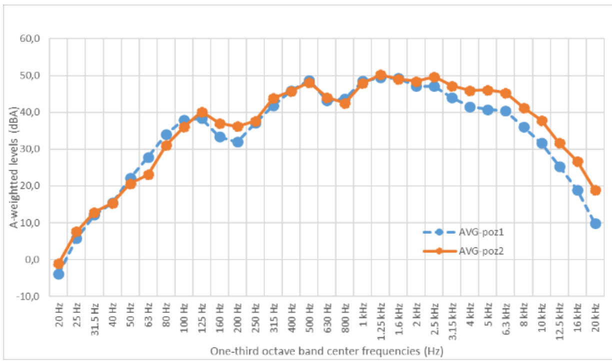
Label	AVG pos1	u-pos1	AVG-pos2	u-pos2	Difference of mean (pos1-Pos2)
L_{Aeq} (dBA)	58,1	0,2	59,0	0,2	-0,9
L_{Req} (dBA)	58,1	0,2	59,0	0,2	-0,9
L_{95} (dBA)	57,6	0,2	58,3	0,2	-0,7
L_1 (dBA)	59,5	0,5	60,0	0,2	-0,4
$L_{C,peak}$(dBC)	80,0	0,7	79,4	0,5	0,5
L_{Zeq} (dB)	64,7	0,3	65,6	0,3	-0,9
L_{ceq} (dBC)	64,3	0,2	64,3	0,2	-0,1
$L_{A,max}$ (dBA)	59,7	0,3	61,3	0,4	-1,5
$L_{A,min}$ (dBA)	57,1	0,2	58,0	0,2	-1,0
$L_{Z,max}$(dB)	71,5	0,8	73,4	1,3	-1,9
$L_{Z,min}$(dB)	62,2	0,2	62,7	0,2	-0,5

Table 4.1. Compared environmental noise parameters levels at two different postions (pos 1 on the facade and pos 2 in front of the facade)

The comparison between A-weigted spectral values at two different positions are shown in **Fig 4.1.**



a)



b)

Fig. 4.1. Difference between A-weighted spectral values for two different positions for a) residual noise and b) source noise

The laboratories have chosen different time intervals and different numbers of measurements (from 5 min up to 30 minutes from 3 measurements up to 5 measurement intervals).

The overall results for position 1 with expanded measurement uncertainties of each lab are shown in **Fig 4.2.** It is evident that each lab reported almost the same expanded measurement uncertainty (±3,6 dB(A)) calculated by using eq. (20). The average value of all labs is marked with red (58,1 dB(A)).

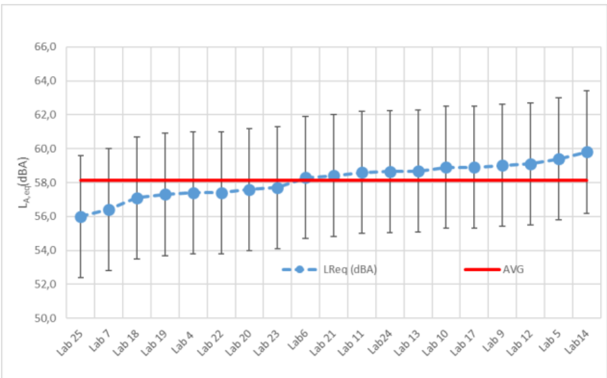


Fig. 4.2. The average value (arithmetic) and expanded measurement uncertainty of all labs

In addition, PDF functions of rated values $L_{A,eq}$ are shown in **Fig 4.3** for residual noise and source noise at two different positions. Several different distributions were tested especially at position 1 where results show strong asymmetric behaviour.

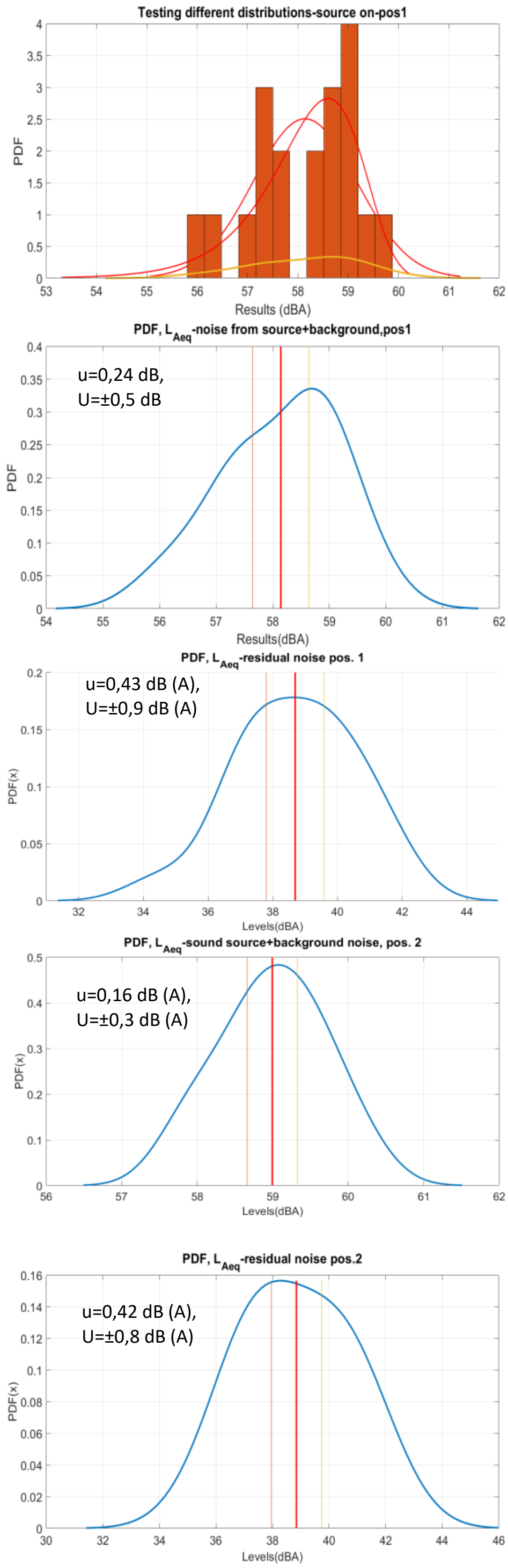


Fig. 4.3. PDF functions of measured $L_{A,eq}$ mean values with standard deviations for different measurement positions

It is visible that for residual noise and source noise the PDF function of A-weighted equivalent noise level is symmetrical around mean value. For source noise, the PDF function is asymmetrical at position 1 on the facade.

There is also difference for the mean determined by assuming arithmetic and logarithmic average from all valid results. Also, the standard deviations (u) are significantly different and the results are shown in **Table 4.2.**

Table 4.2 Comparison between means and expanded uncertainties obtained with different ways of calculation (arithmetic and logarithmic)

Situation/Parameter	Arithmetic mean (dBA)	U_k (dBA)	Logarithmic mean (dBA)	U_k (dBA)	Max PDF (dBA)
Residual noise-pos1	38,7	0,9	39,1	1,5	38,8
Source -pos1	58,1	0,5	58,3	1,4	58,7
Residual noise-pos2	38,9	0,9	39,2	1,5	38,3
Source -pos2	59,0	0,3	59,1	1,4	59,1

4.2. Sound insulation parameters

The measurement uncertainty from one individual measurement of each parameters is rather complicated because includes all parameters with their functional dependence.

For standardized level difference (D_{nT}) the derivation of the measurement uncertainty by knowing measurement uncertainties and sensitivity coefficients from all parameters which enter in the equation for calculation is given in reference [15] and we have derived the equation (28) for R'.

$$u(R') = \sqrt{(c_{L1}\cdot u(L_1)^2 + \left(c_{L2}\cdot u(L_2)\right)^2 + (c_{Lres}\cdot u(L_{res}))^2 + (c_S\cdot u(S))^2 + (c_A\cdot u(A))^2 + (c_{inst}\cdot u(L_{inst}))^2} \quad (28)$$

Where c are sensitivity coefficients and u are standard uncertainties from all variables in equation for R' (levels in source and receiving rooms, reverberation time, residual noise uncertainty, surface of the wall, equivalent absorption area, instrumentation). In this approach it is assumed that these parameters are not correlated so simplified form eq. (7) is used.

Different problems in calculations due to large number of parameters like converting dB onto Pa are considered in [15].

We have derived the equations for sound reduction index (R') and estimated measurement uncertainties when measurements are done for two loudspeaker positions and calculation of sound reduction index are done for each loudspeaker position (R'_1 and R'_2).

The averaged value of airborne sound insulation for measurement results for two loudspeaker positions is given with eq. (29).

$$R' = -10\cdot\log(\tfrac{1}{2}\cdot\left(10^{\frac{R_1}{10}} + 10^{\frac{R_2}{10}}\right)) \quad (29)$$

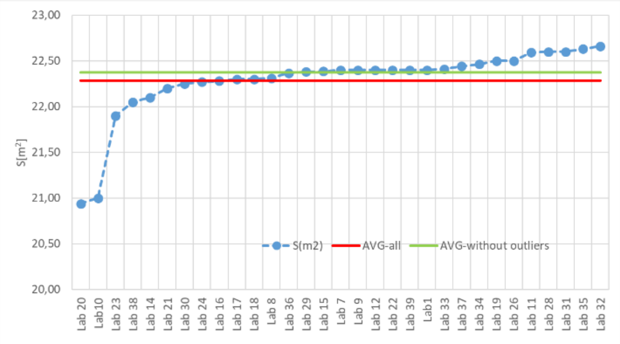
The measurement uncertainty $u(R')$ from known measurement uncertainties from results for two different loudspeaker positions is given by using eq. (30).

$$u(R') = \sqrt{(c_{R1}\cdot u(R_1)^2 + \left(c_{R2}\cdot u(R_2)\right)^2} \quad (30)$$

This calculation for each individual source position should be repeated for all sound insulation parameters according new ISO 16283-1,2,3 standards.

The main problem is to find uncertainty for sound pressure when continuous moving microphone is used because there is only one measurement result for one loudspeaker position.

All input parameters for calculation of standardized level difference ($D_{n,T}$) apparent sound reduction index (R') (surface of the wall, reverberation time, level difference) have been analysed by using Grubbs and Cochran statistics having purpose to find outliers. The results for surface of the wall, volume of receiving room and reverberation time in receiving room obtained in ILC (mean value and standard deviation) without outliers are shown in **Fig 4.4** in situation when airborne sound insulation is measured. The problem with geometrical parameters measurements is that not all labs have measured the geometry parameters 5 times so only averaged result is shown. The results for apparent sound reduction index in one third octave bands are shown in **Figure 4.5.**



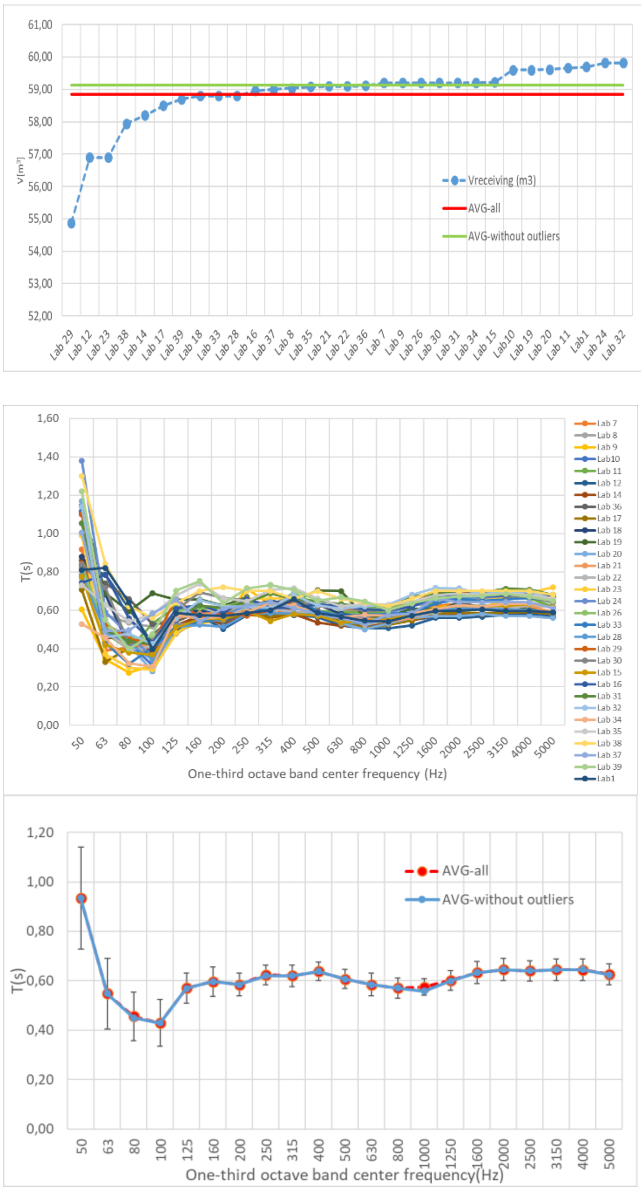


Fig. 4.4. Measurement results of all labs, surface, volume of receiving room, all results for reverberation time and mean value of reverberation time in one-third octave bands and standard deviations (with and without outliers).

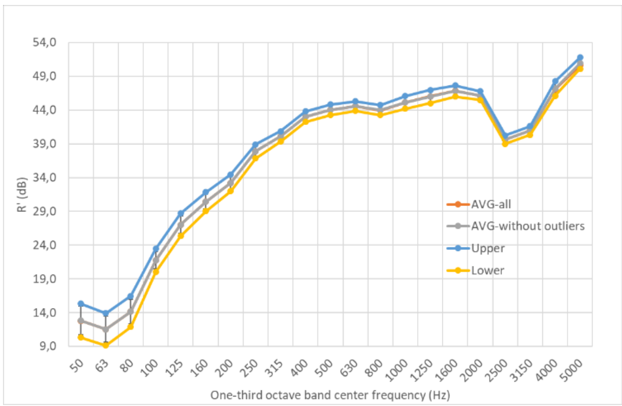


Fig. 4.5. Mean value of sound reduction index in one-third octave bands and standard deviations with upper and down curve of sound reduction index calculated from obtained standard deviations in repeatability conditions of MLU results

The single number values for each lab (averaged 5 independent measurements) with measurement uncertainties obtained by using no correlation and full correlation assumptions between five independent measurements are shown in **Fig 4.6.** The basic difference that averaged value form 5 independent measurement results can be determined by averaging 5 single number values or averaging the one-third octave bands values and finding mean value by moving reference curve.

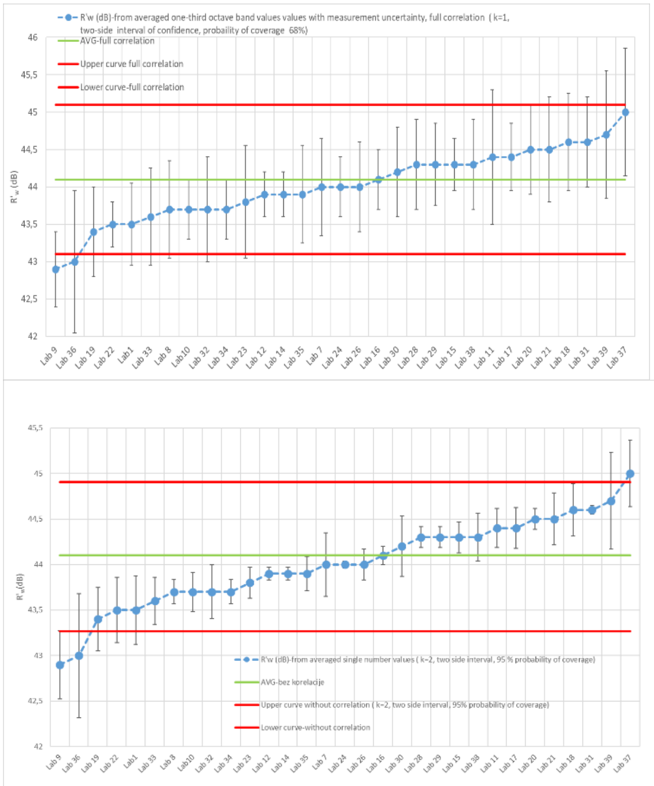


Fig. 4.6. Single number values for sound reduction index and measurement uncertainties under two different assumptions (no correlation and full correlation between 5 independent measurements)

It is visible that some labs have larger measurement uncertainty when no correlation assumption is considered compared to the situation when full correlation is assumed.

The same procedure is repeated for impact sound insulation parameters and the results for normalized impact sound pressure levels in one-third octave bands is shown in **Fig 4.7.**

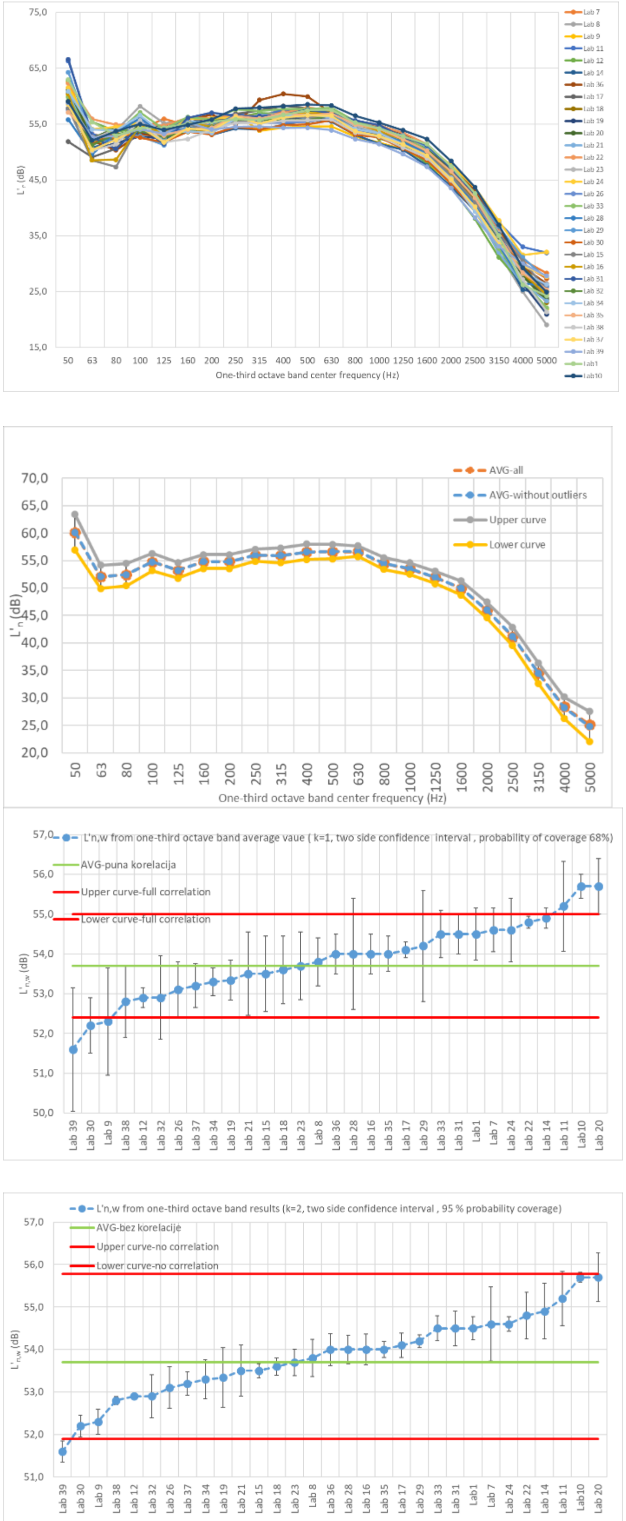


Fig. 4.7. Results for normalized impact sound pressure levels in one-third octave bands and single number values with measurement uncertainties assuming full correlation and no correlation between one-third octave bands' results

The comparison for calculations of measurement uncertainties in one third octave bands with tentative values given in ISO 12999-1:2014, standard deviations from repeatability conditions obtained in MLU and from individual measurement of one lab for sound reduction index in another situation (not in ILC) are shown in **Fig 4.8.** The approach with averaging overall sound pressure level and for each loudspeaker position are considered.

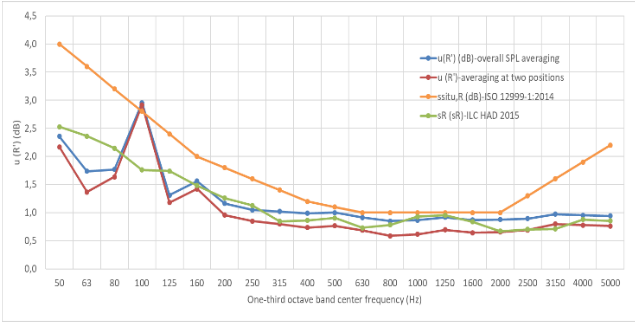


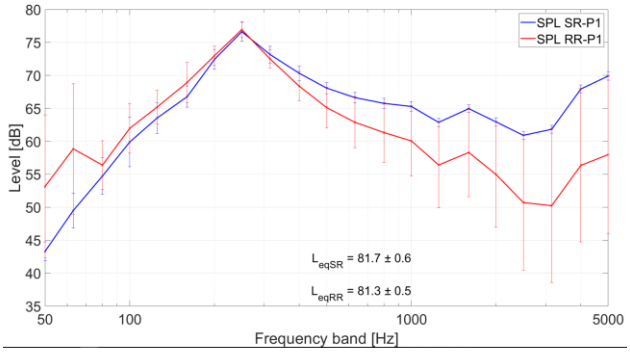
Fig. 4.8. Comparison between different way for obtaining measurement uncertainties (from independent measurement) and by using standard deviations in reproducibility conditions

The same calculations will be provided in the future for each individual measurement of each lab and for overall results of ILC in the future.

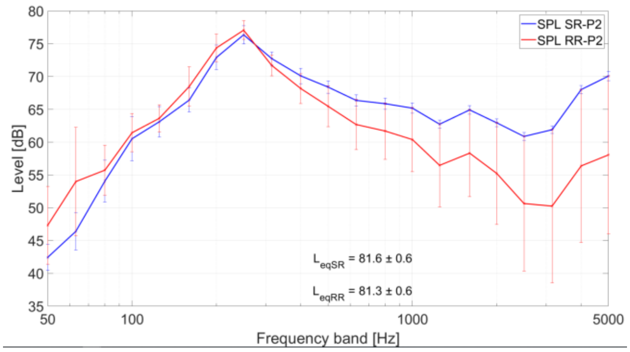
4.3. Comparison between acoustic camera and classical sound level meter measurement results

Having purpose to test standard deviations between multiple measurement positions the measurement of sound pressure level in receiving and transmitting room has been done with acoustic camera with 80 microphones at 5 positions. The standard deviations from all measurement results in each octave bands are given in **Fig 4.9** a) for sound pressure levels and for reverberation times.

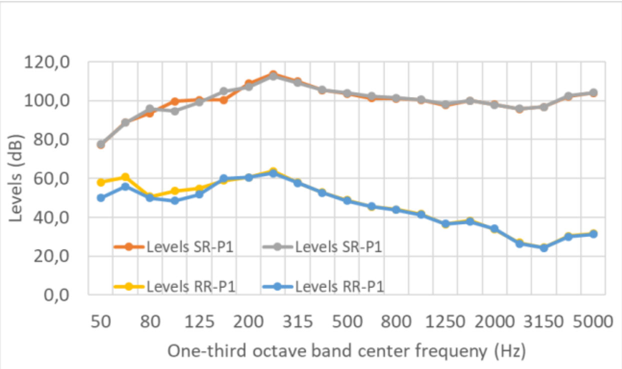
The averaged results for sound pressure levels in the source room and receiving room for two loudspeaker position are shown in **Fig 4.9.**



a)



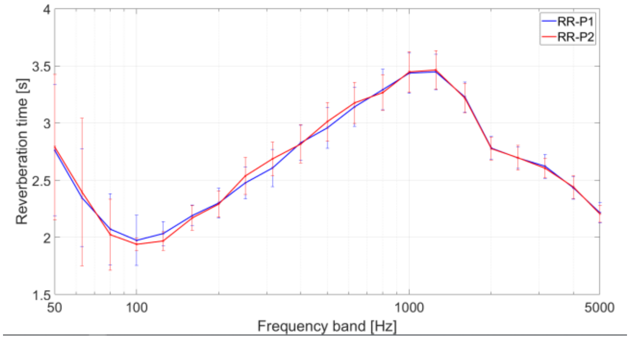
b)



c)

Fig. 4.9. Averaged results for sound pressure levels from 80 microphones at five camera positions for (a) first and (b) second loudspeaker position in source and receiving rooms and for sound level meter averaged results in one-third octave bands

The same is repeated for reverberation times at large number of measurement positions.



a)

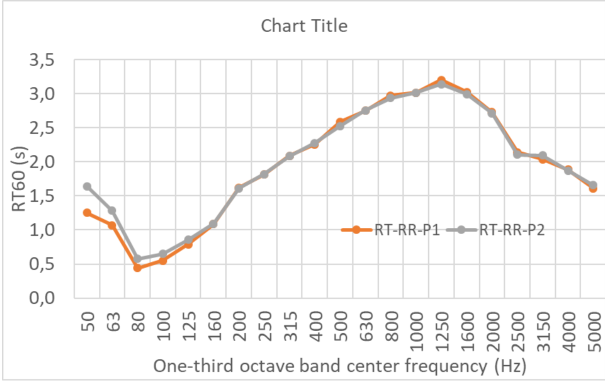


Fig 4.10. The averaged results for reverberation times with standard deviations at two loudspeaker positions in the receiving rooms (a) acoustic camera and b) sound level meter

The standard deviations obtained per loudspeaker positions with acoustic camera and sound level meter are compared in **Table 4.3.**

Band [Hz]	Camera $S_{SPL\ SR-P1}$	SLM $S_{SPL\ SR-P1}$	Camera $S_{SPL\ SR-P2}$	SLM $S_{SPL\ SR-P2}$	Camera $S_{SPL\ RR-P1}$	SLM $S_{SPL\ RR-P1}$	Camera $S_{SPL\ RR-P2}$	SLM $S_{SPL\ RR-P2}$
50	1.5	1,9	2.0	2,9	10.8	7,8	5.9	6,2
63	2.6	2,9	2.8	4,5	9.9	4,4	8.3	3,4
80	2.8	3,0	3.2	4,7	3.7	4,1	3.8	3,5
100	3.8	4,2	3.4	3,1	3.8	1,9	2.9	1,2
125	2.3	5,4	2.3	1,2	2.6	3,3	2.1	0,5
160	1.6	2,3	1.8	2,8	3.1	2,6	3.0	1,3
200	1.5	1,8	1.9	1,4	1.5	0,8	2.1	1,6
250	1.4	2,5	1.4	2,3	1.2	1,0	1.4	1,2
315	1.3	1,0	1.0	0,5	1.4	0,9	1.6	1,0
400	1.1	0,3	1.2	1,1	2.2	0,7	2.3	0,9
500	0.8	0,5	0.9	0,8	3.1	0,7	3.1	0,6
630	0.8	0,5	0.8	0,9	3.8	0,3	3.8	0,7
800	0.8	0,7	0.8	0,6	4.5	0,6	4.3	0,3
1000	0.7	0,5	0.8	0,6	5.3	0,5	4.9	0,4
1250	0.6	0,4	0.6	0,7	6.5	0,2	6.3	0,1
1600	0.6	0,5	0.6	0,4	6.7	0,5	6.7	0,2
2000	0.6	0,4	0.6	0,4	8.0	0,2	7.8	0,4
2500	0.6	0,5	0.6	0,4	10.2	0,3	10.3	0,2
3150	0.6	0,5	0.6	0,5	11.6	0,3	11.7	0,2
4000	0.6	0,4	0.6	0,6	11.6	0,4	11.7	0,1
5000	0.6	0,6	0.7	1,0	12.0	0,3	12.1	0,2

a)

Band [Hz]	Camera S_{RT-P1}	SLM S_{RT-P2}	Camera S_{RT-P2}	SLM S_{RT-P2}
50	0.6	0,4	0.6	0,3
63	0.4	0,5	0.6	0,2

80	0.3	0,1	0.3	0,1
100	0.2	0,1	0.1	0,1
125	0.1	0,1	0.1	0,1
160	0.1	0,1	0.1	0,1
200	0.1	0,1	0.1	0,2
250	0.1	0,1	0.2	0,2
315	0.2	0,1	0.1	0,1
400	0.2	0,1	0.2	0,2
500	0.2	0,1	0.2	0,1
630	0.2	0,1	0.2	0,1
800	0.2	0,1	0.2	0,1
1000	0.2	0,1	0.2	0,1
1250	0.2	0,1	0.2	0,1
1600	0.1	0,1	0.1	0,1
2000	0.1	0,1	0.1	0,1
2500	0.1	0,0	0.1	0,0
3150	0.1	0,1	0.1	0,0
4000	0.1	0,0	0.1	0,0
5000	0.1	0,1	0.1	0,0

b)

Table 4.3. Comparison between standard deviations obtained with acoustic camera and sound level meter for each loudspeaker position in source and receiving rooms for levels and reverberation times.

It is evident that results for levels (absolute values) and their standard deviations are not comparable between acoustic camera and sound level meter especially in receiving room because sensitivity of microphones has been changed due to lower level of sound signal in the receiving room.

5. DISSCUSION AND CONCLUSION

5.1. Results for environmental noise parameters

It is visible that for equivalent A-weighted value parameters (all valid results in MLU obtained by using Grubbs statistics) that the PDF function for rating level at position 1 (on the façade) is asymmetric around maximum value of PDF. The logarithmic and arithmetic mean in that case have different values (>0,5 dB(A)) which can slightly underestimated mean value if results of al labs are considered.

If the measurement uncertainty is taken into assessment with limit values (according to maximum increase of level for 1 dB(A)) into account for this situation measurement uncertainty doesn't not give any wrong decision rule. But for example, if residual noise level is much closer to the level of noise when the source ins on than the measurement uncertainty have significant influence of assessment and decision rule according to the new ISO 17025:2017 standard. If the limit value for example was mean value of overall results, when high uncertainties obtained by using calculation according to the ISO 1996-2:2007 (**Fig 4.2**) or ISO 1996-2:2017 are taken into account all labs would give negative assessment of measured value due to asymmetric PDF function and very large expanded measurement uncertainties obtained by suggested calculations in old and new ISO 1996-2 standard.

For example, if we consider the 19 results of labs as independent results the example of measurement uncertainty of overall ILC results are compared in **Table 5.1.**

Quantity	Estimate	Standard Uncertainty	Sensitivity Coefficient	Uncertainty Contribution
$L_{A,eq}$	58,3	0,5	1,0	0,5
δ_{slm}	0,0			0,0
δ_{sou}	0,0	0,2	1,0	0,2
δ_{met}	0,0	2,0	1,0	2,0
δ_{loc}		0,0	0,0	0,0
δ_{res}		0,4	0,0	0,0
$L_{A,eq,res}$	39,1			
$u=sqrt(u_1^2+u_2^2+..)$				2,1
$L_{A,eq,\ corrected}$	58,2		Expanded k=2	4,2

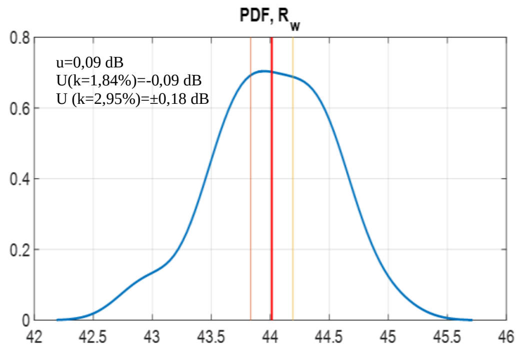
Table 5.1. Measurement uncertainties calculations for all ILC results (19) according to ISO 1996-2:2017 for position 1

It is visible that due to influence of meteorological conditions measurement uncertainty is higher when new standard ISO 1996-2:2017 recommendations are used in calculations.

5.3. Results for sound insulation

It is noticeable that also for sound insulation parameters there can be different approach in measurement uncertainty calculations.

When PDF functions for sound insulation parameters measured from 31 laboratories are considered (apparent sound insulation index and normalized sound pressure levels) the PDF distribution is almost symmetrical around mean value and obtained measurement uncertainty is much lower compared to the situations when standard deviations in repeatability conditions are used for calculations of measurement uncertainties. The PDF function and overall measurement uncertainty from all ILC results when observing *R'* parameter is given in **Fig 5.1a)** and for L'_n in **Fig 5.1b).**



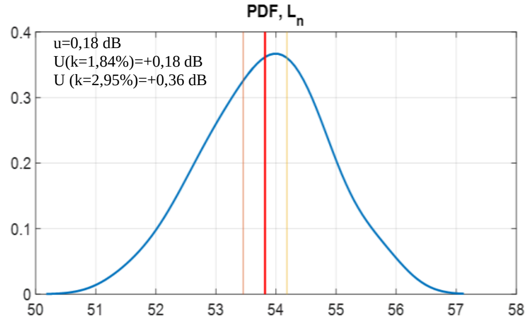


Fig.5.1.a) PDF function for *R'* and b) for L'_n with measurement uncertainty (standard deviation in repeatability conditions) calculated assuming normal distribution of single number values

The comparison between obtained measurement uncertainties for these two parameters measured in ILC (averaged 31 results with 5 independent measurements) assuming standard deviation in repeatability conditions given in ISO 12999-1:2014 standard and those obtained in this ILC are shown in **Table 5.2.**

Parameter	Standard deviations in reproducibility conditions from ILC	Standard deviations in reproducibility conditions from standard ISO 12999-1:2014
R'_w	-1,0	-1,5
R'_w+C	-1,0	-1,8
R'_w+C_{tr}	-1,5	-2,3
$R'_w+C_{50\text{-}5000}$	-1,5	-2,8
$R'_w+C_{tr,50\text{-}5000}$	-2,0	-3,5

Parameter	Standard deviations in reproducibility conditions from ILC	Standard deviations in reproducibility conditions from standard ISO 12999-1:2014
$L'_{n,w}$:	+1,3	+1,3
$L'_{n,w}+C_i$	+0,8	+0,8
$L'_{n,w}+C_{i,50\text{-}2500}$	+1,3	+1,3

Table 5.2. Measurement uncertainty for overall ILC results assuming different standard deviations in reproducibility conditions (sound reduction index and normalized impact sound pressure level)

There is some difference between measurement uncertainties obtained from one individual measurement compared to the standard deviations.

There is also visible, that there is no significant difference between results for standard deviations obtained by using acoustic camera with large number of microphones and classical sound level meter at 5 different positions.

6. ACKNOWLEDGEMENT

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