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* Corresponding author.
Email address: c.scrosati@itc.cnr.it (C. Scrosati)

Uncertainty of Facade Sound Insulation by a Round Robin Test. Evaluations of Low-Frequency Procedure and Single Numbers.

Chiara Scrosati [a]*, Fabio Scamoni [a], Andrea Prato [b], Simone Secchi [c], Patrizio Fausti [d], Arianna Astolfi [e], Luca Barbaresi [f], Francesco D'Alessandro [g], Antonino Di Bella [h], Corrado Schenone [i], Giovanni Zambon [j]
*Corresponding author : Chiara Scrosati;
email: c.scrosati@itc.cnr.it; Tel: +39 02 9806432; Fax: +39 02 98280088

(a) ITC - CNR, Construction Technologies Institute of the National Research Council of Italy, San Giuliano M.se, Italy;
(b) National Institute of Metrological Research - INRIM, Torino, Italy;
(c) Department of Industrial Engineering DIEF – University of Florence, Florence, Italy;
(d) University of Ferrara, Department of Engineering, Ferrara, Italy;
(e) Politenico di Torino, Energy Department, Torino, Italy;
(f) Department of Industrial Engineering (DIN) University of Bologna, Bologna, Italy;
(g) Department of Civil and Environmental Engineering – University of Perugia, Perugia, Italy;
(h) Department of Industrial Engineering - University of Padova, Padova, Italy;
(i) Department of Mechanical Engineering (DIME) - University of Genova, Genova, Italy;
(j) DISAT, Department of Earth and Environmental Sciences of the University of Milano - Bicocca, Milano, Italy.

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The international standard ISO 140-5 for the measurement of the sound insulation of building facades has been recently replaced by the new standard ISO 16283-3. The revised standard includes the procedure for measurements at low frequencies down to 50 Hz. The uncertainty of facade sound insulation, in particular at low frequencies, was evaluated by a Round Robin Test, conducted in a full-scale experimental building at the Construction Technologies Institute of the National Research Council of Italy (ITC-CNR). Each of the 10 teams involved in the RRT replicated the tests 5 times, for a total of 50 measurements. The different measurement positions inside the receiving room were compared. In particular, all the teams involved in the RRT followed the low-frequency procedure, assessing corner and center room positions; the energy average values according to ISO 16283-3 were considered and the relative uncertainty, in terms of repeatability and *in situ* reproducibility standard deviations, was compared with the ones measured and calculated following the default measurement procedure. It was found that the uncertainty of the low-frequency procedure is higher than that of the default procedure. This would suggest the need to investigate further the reliability of the low-frequency procedure. At high frequency, the significant uncertainty values found are probably caused by the loudspeakers directivity and position; this aspect need to be investigated in greater detail, as well.

Keywords: uncertainty; facade sound insulation; low frequencies; single number quantities; ISO 16283-3

1 INTRODUCTION

This paper is a revised and expanded version of the paper “Uncertainty of facade sound insulation measurements obtained by a Round Robin Test: the influence of the low frequencies extension” [1] presented at the 22nd International Congress on Sound and Vibration ICSV22.

When reporting the result of the measurement of a physical quantity, it is compulsory that some quantitative indications of the quality of the result be given so that those who use it can assess its reliability. Without such indications, measurement results cannot be compared, either with one another or with reference values given in a specification or standard. It is therefore necessary, in order to characterize the quality of the result of a measurement, to evaluate and to express its uncertainty. In general, uncertainties should preferably be determined following the principles laid down in ISO/IEC Guide 98-3 [2], the Guide to the expression of uncertainty in measurement (GUM:1995). According to current knowledge, it seems impossible to formulate these models for the different quantities in building acoustics. Therefore, the concepts of repeatability and reproducibility are necessary to determine the uncertainty of building acoustics measurements.

In their paper, Scrosati and Scamoni [3] underlined that the standard ISO 12999-1 [4], on measurement uncertainties in building acoustics, gives the medium uncertainty on all the Inter Laboratory Tests (ILTs) and Round Robin Tests (RRTs) considered (and available at the time when the standard draft was being written), for airborne sound insulation, without distinction of the type of measurand. At the current level of knowledge and due to the number of cooperative tests available, this seems to be the only way to give an idea of the uncertainty magnitude. The fact that the values of ISO 12999-1 [4] are the best estimates for the uncertainty of sound insulation measurements that can be obtained today, was also underlined by Wittstock [5] in his paper describing how the average uncertainty values standardized in ISO 12999-1 [4] were derived. This specific standard is inaccurate as far as the facade sound insulation is concerned, because its uncertainty is considered equal to the airborne sound insulation uncertainty; indeed, the facade sound insulation measurement method is extremely different from the airborne sound insulation measurement method for party walls and floors. Therefore RRTs on facade sound insulation are the only way to improve the level of knowledge of the facade sound insulation uncertainty. Notwithstanding the importance of the uncertainty of the measurement method in building acoustics, the uncertainty of field measurements, in particular facade sound insulation, has not been comprehensively investigated. There is only one example in the literature of an RRT conducted on a window of a facade [6] and only one example of an RRT conducted on a facade [7]. In addition to the need to estimate the measurement uncertainty of facade sound insulation, the knowledge of the uncertainty of the low frequency measurements and their influence on the uncertainty of the measurement method is necessary. In fact, in recent years the attention to the measurements in the low frequency range has considerably increased. Scholl et al. [8] proposed for the revision of ISO 717 new Single Numbers Quantities (SNQs) that include in their definitions the spectrum adaptation terms C and C_{tr}. These quantities have the subscript living for including $C_{50\text{–}5000}$, traffic for including $C_{tr,50\text{–}5000}$ and speech, which includes the frequencies from 200 to 5000 Hz as proposed by Park *et al.* [9]. Rasmussen and Rindel [10] discussed the suitability of various descriptors and suggested harmonizing the airborne and impact sound insulation descriptors in building regulations. The implications of extending the measurements, and in particular the in situ measurements, down to 50 Hz, and the consequent uncertainty of these measurements were analyzed in various works. Some recent studies [11–16] on the uncertainty of SNQs extended to the low frequencies range show an increase in the SNQs uncertainty due to the low frequency (LF) extension. Garg and Maij [11], in their study on the correlations and implications of SNQ for rating airborne sound insulation in the frequency range 50 Hz to 5 kHz, showed that $R_{traffic}$ ($R_w + C_{tr}$ in the enlarged frequency range) is highly sensitive to low frequency sound insulation as compared to the current SNQ and R_{living} ($R_w + C$ in the enlarged frequency range). The authors stressed the fact that testing of sound transmission loss characteristics in the extended frequency range of 50 Hz to 5 kHz also implies the need to reformulate the sound regulation requirements in buildings including the low frequency spectrum adaptation terms. Scrosati *et al. 2013* [12], based on an on-site round robin test on a lightweight wall and a heavy floor for measuring airborne sound insulation, demonstrated that the extension at low frequencies range increases the uncertainty of the SNQs, in particular the reproducibility standard deviation of $R_{traffic}$. Mahn and Pearse [13] studied the effect on uncertainty of expanding the frequency range included in the calculation of the single number ratings, using laboratory measurements of 200 lightweight walls as data. They found that the uncertainty of the single number ratings is highly dependent on the shape of the sound reduction index curve. The uncertainty obtained for R_{living} was greater than that of the traditional weighted sound reduction index (R_w) for 98% of the 200 lightweight building elements included in the evaluation. Hongisto *et al.* [14] focused their study on the two most important SNQs proposed by Scholl *et al.* [8]; that is, $R_{traffic}$ and R_{living}, and how their reproducibility values differ from the reproducibility values of their counterparts $R_w + C_{tr}$ and R_w. They found that the reproducibility values of the proposed single-number quantities (50–5000 Hz; R_{living}, $R_{traffic}$) are larger than the reproducibility values of the present SNQs (100–3150 Hz; R_w, $R_w + C_{tr}$). Machimbarrena *et al.* [15] presented an alternative procedure, aiming at evaluating the need of performing individual uncertainty calculations and the effect of extending the frequency range used to calculate sound insulation single number quantities. For this purpose, they performed calculations in a set of 2081 field airborne sound insulation measurements on 22 different types of separating wall partitions of *in situ* airborne sound insulation measurements. The results obtained by Machimbarrena *et al.* [15] show that the frequency range used for the evaluation affects the uncertainty of the single number quantity. In almost all the cases shown in

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their paper, the uncertainty is increased when the frequency range is extended. António and Mateus [16] studied the influence of low frequency bands on airborne and impact sound insulation single numbers for typical Portuguese buildings. They found that the uncertainty is higher for the $D_{nT,w} + C_{tr}$ descriptor than for $D_{nT,w} + C$. They also found that when the low frequency bands are included in the calculation, the uncertainty of the descriptor increases and this is more evident when the adaptation term is for traffic noise.

Regarding the facade sound insulation, in the only literature study available on an RRT of a facade, Scrosati *et al. 2015* [7] found that the low frequency uncertainty is not well reflected in the SNQs uncertainty. Their work was based on an on-site RRT on a prefabricated concrete facade with a 4 mm single glazing wood-aluminum frame window with a MDF (Medium Density Fiberboard) shutter box. Based on that RRT [7], in their paper on a multilevel functional principal component analysis of facade sound insulation data, Argiento *et al.* [17], by using the estimated intracluster correlation, found that the proportion of the total variability due to the frequencies between 50 and 100 Hz was 88.4%.

Based on a work of Simmons [18], Hopkins and Turner [19] proposed a measurements protocol for sound pressure level measurements at low frequencies that includes additional measurements in the corners of the room. In that paper Hopkins and Turner suggested the need for the low-frequency measurement procedure to improve the reliability of field measurements in rooms with non-diffuse fields (with volumes less than 50 m^3). This protocol was adopted in the revision of international standards on field measurements of airborne, impact and facade sound insulation for room volume below 25 m^3. In his work on this topic Hopkins [20], presenting the main technical changes concerning the new ISO 16283 [21] series, described the low-frequency procedure for one-third octave bands below 100 Hz for rooms with volumes below 25 m^3 using additional corner measurements to determine the spatial average sound pressure level and using the 63 Hz octave band rather than one-third octave bands to measure the reverberation time. The choice of the room volume below 25 m^3 for the application of the low-frequency procedure in the new standards, instead of 50 m^3 as for the previous reference indications [19], was made more for practical than for scientific reasons.

The present work is aimed at investigating both the facade sound insulation uncertainty by an RRT and the influence of the low frequency measurements procedure on this uncertainty. A comparison between the default procedure and the low-frequency procedure was made on the same facade sound insulation measurement, where the receiving room volume was 41 m^3, above the new standard suggestion [21]) but below the other reference suggestions [19], which allows for the application of the default measurement procedure [21] and, therefore, for the relevant comparison. This study analyzed the uncertainty of the measurement method of facade sound insulation for field measurements, with the global loudspeaker method, in terms of repeatability and *in situ* reproducibility standard deviations, by applying the statistical procedures prescribed for this kind of cooperative tests in ISO 5725 standards [22]. The measurements were carried out on the same building's facade so the airborne and structure-borne sound fields involved remain constant. Therefore, the variability in results and the standard uncertainty are related only to the measurement method itself.

2 ROUND ROBIN TEST

Ten laboratories, coordinated by ITC-CNR - Construction Technologies Institute of the Italian National Research Council - were involved in this RRT, each of them operating with its own equipment.

No deviations occurred from the test procedure laid down in standard ISO 140-5 [23] and in ISO 16283-3 [24] (low-frequency procedure) but, repeating the measurements several times, the parameters left open in the measurement procedure were represented as accurately as possible. In particular, the set of microphone positions (including the height of each microphone) and source positions were selected anew for each repeated measurement. Significantly, one of the authors was the I-RRT supervisor who carefully checked the correctness of the positions of the microphones and the source chosen by the operators.

As stated in ISO 12999-1 [4], from a statistical point of view, the number of laboratories should be at least $p = 8$ and the number of test results from each laboratory should be at least $n = 5$; the combination of p and n should be chosen so that

$$p(n-1) > 35 \qquad (1).$$

Each of the 10 laboratories involved in the RRT repeated the tests 5 times, including the reverberation time both in 1/3 octave band and 1/1 octave band, and the corner positions measurements (i.e. low frequency procedure); therefore the minimum requirement was met.

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The building under test is an existing experimental building located at ITC-CNR headquarters, made of prefabricated concrete panels. The building element tested was a prefabricated concrete facade with a PVC frame with double glazing 4/12/4 window. The facade is situated at the first floor. The receiving room is an empty rectangular room with the following dimensions: 2.67 m in height, 3.25 m in width and 4.72 m in depth; its volume is 41 m^3 and the facade surface is 8,7 m^2.

3 ONE-THIRD-OCTAVE BAND ANALYSIS

For each quantity under test and for each laboratory, 21 levels were considered, corresponding to one-third-octave band from 50 to 5000 Hz.

Each team operated under repeatability and *in situ* standard deviation conditions; where the *in situ* standard deviation is a reproducibility standard deviation of the same object in the same location. Under repeatability conditions [22], independent test results are obtained with the same method on identical test items in the same laboratory by the same operator using the same equipment within short intervals of time. Under reproducibility conditions [22], test results are obtained with the same method on identical test items in different laboratories by different operators using different equipment. Under *in situ* standard deviation conditions [4] test results are obtained with the same method, by different operators using different equipment on the same object in the same location (laboratory or usual building). The only difference between reproducibility and *in situ* standard deviation are the fact that under *in situ* conditions the test object is exactly the same and the location as well, while under repeatability conditions the test object could be exactly the same (e.g. a window) or similar (e.g. a wall) and the locations are different (different laboratories); and the equations used to calculate s_R and s_{situ} are the same [7, 22].

Each team followed the provisions of ISO 140-5 [23] and ISO 16283-3 [24] (low-frequency procedure), to decide the position of microphones in the receiving room and the outside loudspeaker position. In particular, the positions of the set of microphones over which averaging is carried out in one measurement were selected anew for each repeated measurement. As the receiving room volume is larger than 25 m^3, it was possible to apply both the low frequencies measurements procedure and the default procedure, for a comparison of the results.

As stated in the introduction, all teams performed measurements following the global loudspeaker method, which yields the level difference of a facade in a given place relative to a position 2 m in front of the facade. All teams positioned the outside microphone 2 m in front of the facade, and the loudspeaker on the ground, with the angle of sound incidence equal to (45±5)°; some of them positioned the loudspeaker directly in front of the facade while some others in a lateral position (see Fig. 1).

Figure 1. Different loudspeaker positions: on left side in front of the facade, on right side in a lateral position. Contoured in red the test facade.

3.1 Outliers Teams

In the graphs of Fig. 2 are plotted the one-third octave curves, obtained following the default measurement procedure, of the standardized level difference of facade $D_{ls,2m,nT}$, which is the level difference in decibels, corresponding to a reference value of the reverberation time in the receiving room:

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$$D_{ls,2m,nT} = D_{2m} + 10\log(T/T_0) \qquad (2)$$

where:

ls simply indicates that a loudspeaker was used, instead of real traffic noise (notation tr);

T is the reverberation time in the receiving room;

T_0 is the reference reverberation time; for dwellings, $T_0 = 0.5$ s.

D_{2m} is the level difference, i.e. the difference, in decibels, between the outdoor sound pressure level 2m in front of the facade, $L_{1,2m}$, and the space and time average sound pressure level, L_2, in the receiving room:

$$D_{2m} = L_{1,2m} - L_2 \quad (3)$$

On the left side of the graphs of Fig. 2 are plotted the $D_{ls,2m,nT}$ of the 10 teams participating in the RRT; on the right side of Fig. 2 are plotted the $D_{ls,2m,nT}$ of the 8 teams, once the outlier teams No 5 and No 6 were excluded. The statistical analysis of the data provides a tree step procedure [12,22] for the identification of stragglers and outliers. Following this procedure, laboratories No. 5 and No. 6 were identified as outlier laboratories and excluded because they showed a significant presence of stragglers and outliers starting from 500 Hz to 3150 Hz. Even if it turned out that there was nothing wrong with the microphones and the measurement instrumentation, it was found that the differences between including and excluding these laboratories were remarkable. As the method was correctly followed, the presence of stragglers and outliers, without any other physical explanation, can only be attributed to an external event. Referring to laboratories No. 5 and No. 6, it turned out that the most plausible explanation of an external event was the window accidentally not properly closed. Therefore laboratories No. 5 and No. 6 were excluded from the further analysis of $D_{ls,2m,nT}$.

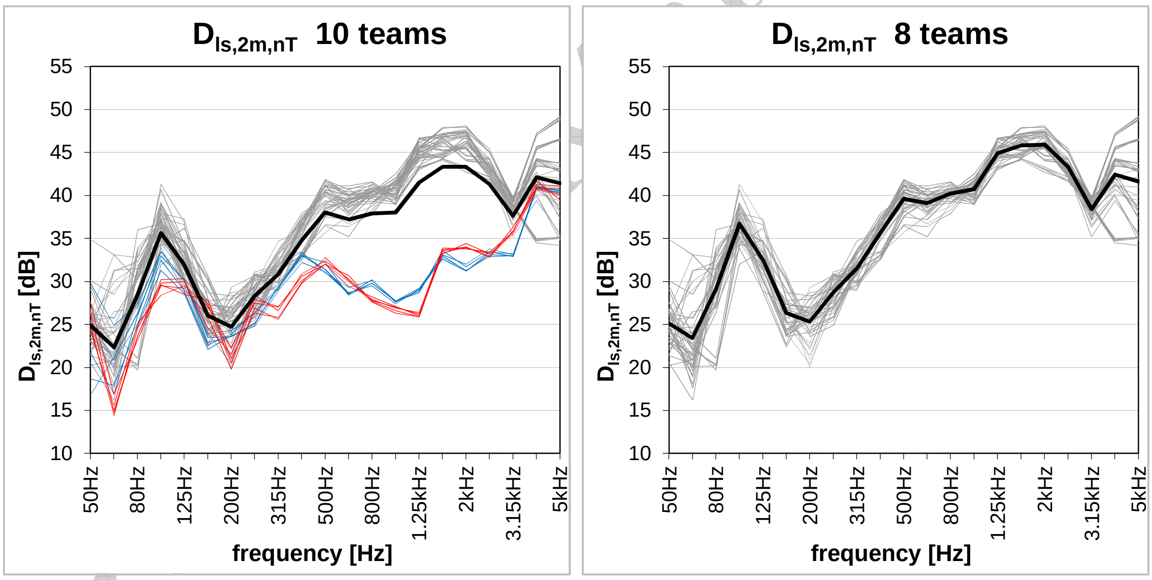

Figure 2. Left side: standardized level difference of the facade ($D_{ls,2m,nT}$), obtained following the default measurement procedure, of the 10 teams (5 repetitions for each of the 10 teams); total average (black), outlier team No 5 (blue) and outlier team No 6 (red). Right side: $D_{ls,2m,nT}$ of the 8 teams (5 repetitions for each of the 8 teams); average (black).

3.2 Repeatability and *in situ* standard deviation results

3.2.1 Reverberation time

Reverberation time has been evaluated following the prescriptions of ISO 16283-3 [24], for both the default and low-frequency procedures. In particular, as stated in the introduction, the low-frequency procedure requires that the reverberation time is measured in the 63 Hz octave band instead of the 50 Hz, 63 Hz, and 80 Hz one-third octave bands and that this single measured value is used to represent the 50 Hz, 63 Hz, and 80 Hz bands in the calculation of $D_{ls,2m,nT}$. Table 1 shows the average and standard deviation values s_{situ} and s_r of reverberation time (*T*) for the 10 laboratories, both measured in 1/3 octave bands and 1/1 octave band at low frequencies. The 1/3 octave band reverberation times of all repetitions of all laboratories are shown in Figure 3. As expected [12, 25], at low frequencies and in non-diffuse field conditions, relative standard deviations are around 20% (50 and 63 Hz 1/3 octave bands) and around 14% (80 Hz 1/3 octave band and 63Hz 1/1 octave band), which is still high with respect to other approaches recently proposed to obtain more accurate and precise measurements for frequencies below 100 Hz in small rooms [26] and to improve the prediction of reverberation times [27].

Table 1 – Average and standard deviation values s_{situ} and s_r of reverberation time (*T*) for the 10 laboratories, both measured in 1/3 octave band and 1/1 octave band at low frequencies.

	1/3 oct			1/1 oct
	50Hz	63Hz	80Hz	63Hz
average (s)	1.85	1.78	1.55	1.86
s_r (s)	0.23	0.23	0.09	0.14
s_{situ} (s)	0.35	0.35	0.20	0.26

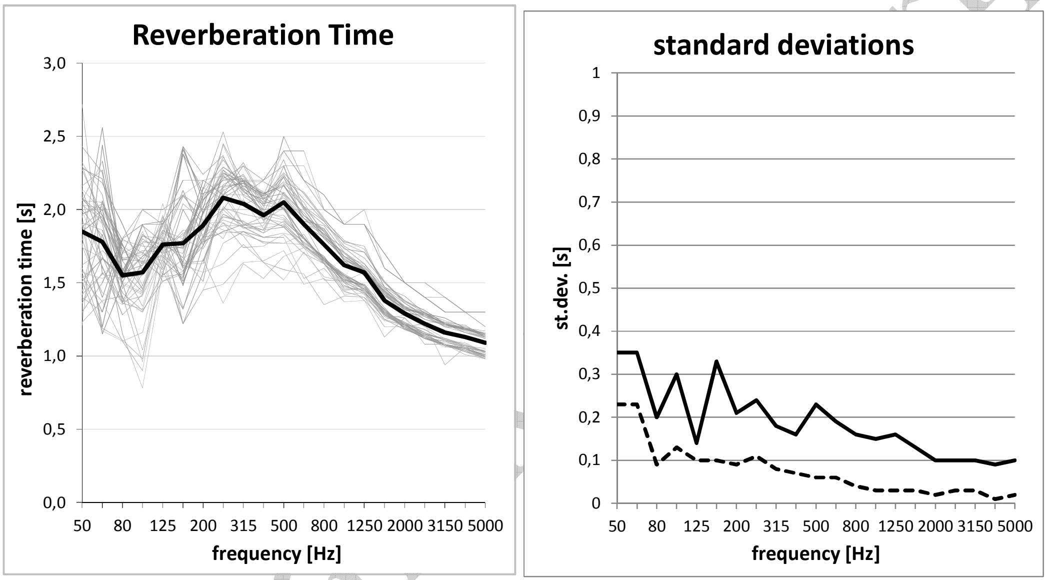

Figure 3 – Left side: 1/3 octave band reverberation time measurements of the 10 teams; 5 repetitions for each of the 10 teams (gray) and average (black). Right side: in situ standard deviation s_{situ} (continuous line) and repeatability standard deviation s_r (dotted line) of reverberation time for the 10 laboratories.

3.2.2 Facade sound insulation: default measurement procedure

The repeatability (s_r) and *in situ* standard deviation (s_{situ}) obtained for the default measurement procedure for the 8 laboratories are given in Table 2.

Regarding the low frequency range (from 50 to 80 Hz) the high values of s_r and s_{situ} are obtained in the presence of natural room modes, in fact at the first three 1/3 octave bands (50, 63 and 80 Hz), the measured levels can be strongly influenced by the measurement position (see section 3.2.3).

In a previous RRT on facade sound insulation, Scrosati *et al.* 2015 [7] found that an important contribution to the overall uncertainty is the uncertainty in the reverberation time measurements at low frequencies. In that case, the uncertainties in $D_{ls,2m,nT}$ were heavily contaminated by the inappropriateness of the reverberation time correction at low-frequencies and a comparison between the uncertainties of the standardized level difference $D_{ls,2m,nT}$ and the level difference $D_{ls,2m}$ showed the magnitude of the reverberation time at low frequencies. The variations between laboratories at low frequencies are still very high even if the reverberation time correction is not included in the calculation (i.e., only considering $D_{ls,2m}$), which implies that for the sound pressure level measurements the low frequencies also have a high uncertainty.

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Table 2 - s_{situ} and s_r of $D_{ls,2m,nT}$ for the 8 teams

Fz (Hz)	s_r (dB)	s_{situ} (dB)
50Hz	2.3	2.9
63Hz	3.3	4.3
80Hz	1.4	4.1
100Hz	1.2	2.0
125Hz	1.4	2.2
160Hz	1.2	2.2
200Hz	1.7	2.3
250Hz	0.9	1.7
315Hz	1.1	1.4
400Hz	0.6	1.7
500Hz	0.6	1.7
630Hz	0.6	1.3
800Hz	0.5	0.8
1kHz	0.4	1.0
1.25kHz	0.4	1.1
1.6kHz	0.5	1.2
2kHz	0.3	1.6
2.5kHz	0.3	1.0
3.15kHz	0.6	1.1
4kHz	0.6	3.8
5kHz	1.5	4.8

In the present study no differences were found in the uncertainty behavior including or not the reverberation time correction (i.e. no differences between the $D_{ls,2m,nT}$ and the $D_{ls,2m}$ uncertainties behavior; see Fig. 4). The s_{situ} and s_r behavior of both $D_{ls,2m,nT}$ and $D_{ls,2m}$ is not similar to the behavior of the uncertainties of ISO 12999-1 [6], in terms of reproducibility s_R and *in situ* standard deviation, which increase steadily and rapidly below 100 Hz, as can be seen in the graphs of Fig. 4. Contrary to what was found by Scrosati *et al.* 2015 [7], this difference is not attributable to the reverberation time measurements. This different behavior could be attributable to the differences in the facade test samples: the facade of the previous RRT [7] is a prefabricated concrete facade with a 4 mm single glazing wood-aluminum frame window with an MDF shutter box; the facade of the present study is a prefabricated concrete facade with a PVC frame with double glazing 4/12/4 window. Also the loudspeaker position could be relevant and its influence is investigated in the second part of this study, which is currently being drafted.

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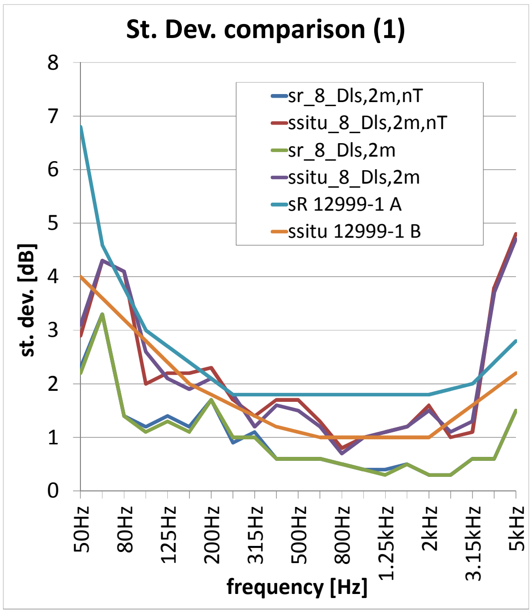

Figure 4. Comparison of standard deviation values from RRT (calculated for both $D_{ls,2m,nT}$ and $D_{ls,2m}$) and from ISO 12999-1.

With respect to the high frequency range, in particular at 4000 and 5000 Hz, the RRT and ISO 12999-1 [4] standard deviations values show the same behavior, i.e. an increase with frequency, but the RRT s_{situ} values are higher than the ISO 12999-1 values. Moreover the RRT high frequency s_{situ} values are higher than the low frequency s_{situ} values of both RRT and ISO 12999-1. This is probably due to the different positions of the loudspeaker with respect to the facade (see Fig. 1 and Fig. 6). This topic is investigated in deeper detail in the second part of this study, as mentioned above; nevertheless, a first analysis of the high frequency issue is studied in the following section 3.2.3. Scrosati *et al.* 2015 [7] in their facade RRT, where all the teams involved placed the loudspeaker in the same position (directly in front of the facade), found that the high frequency uncertainty was lower (see Fig. 4), in particular lower than ISO 12999-1 [5] values and much lower than the low frequencies uncertainty. Berardi *et al.* [28] and Berardi [29] considered the position of the loudspeaker as a variable, but its influence on the high frequencies was not comprehensively evaluated.

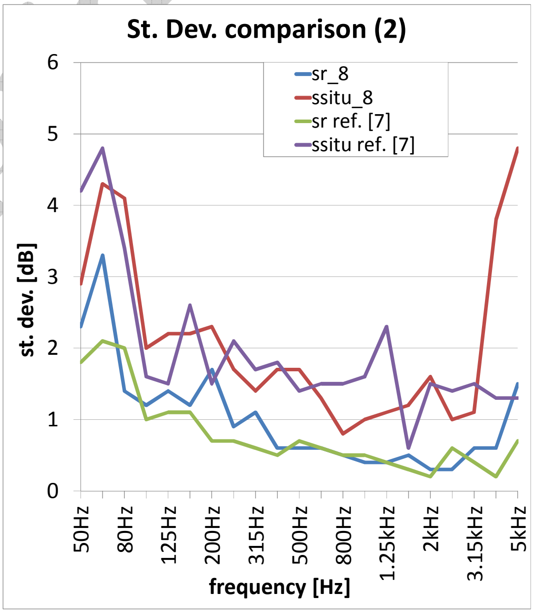

Figure 5. Comparison between standard deviation values from RRT - $s_{situ}8$ (red) and s_r8 (blue) of $D_{ls,2m,nT}$ for the 8 teams - and from Scrosati *et al.* RRT [7] - s_{situ} ref.[7] (purple) and s_r ref. [7] (green) of $D_{ls,2m,nT}$.

Another difference between the results of the Scrosati *et al.* 2015 [7] RRT and the present study (see Fig. 5) is the presence of the shutter box that influences the standard deviation behavior. In fact, a

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high variation of the s_{situ} values in the Scrosati *et al.* 2015 [7] RRT, larger than s_R values of ISO12999-1 (situation A) [4], is observed at 1250 Hz, corresponding to the critical frequency of the shutter box (20 mm of MDF). A slight increment of the s_{situ} values was also observed in the region of the critical frequency of the 4 mm glass (3120 Hz). A similar behavior was observed in the Austrian RRT [6], where the RRT values exceed the values of the ISO 140-2 [31] (the standard on acoustics measurement uncertainty available at the time of Lang's RRT) in the range of mass-spring-mass resonance frequency and in the range of the coincidence frequency of the double glass. Lang suggested that such behavior may be caused by the difficulty of arranging the loudspeaker at an angle of incidence of 45°. As investigated deeper in the second part of this study, the loudspeaker position and its directivity influence in particular the high frequencies (4000 and 5000 Hz), which were not included in the Lang's RRT [6]. Such behavior is thus exclusively attributable to the nature (i.e. critical frequencies) of the measurand itself. In fact, in this study the s_{situ} standard deviation values exceed the value of ISO 12999-1 (situation A) in the range of the mass-spring-mass resonance frequency of the double glass (see Fig. 3, the peak at 200 Hz).

3.2.3 High frequency uncertainty

Referring to Figure 4, at high frequency, in particular at 4000 and 5000 Hz, the RRT s_{situ} values are higher not only with respect to the ISO 12999-1 values, but also with respect to the low frequency s_{situ} values of both RRT and ISO 12999-1.

This is probably caused by the loudspeakers directivity, which is particularly relevant at these frequencies, and by the different positions used by each RRT participant as well, as indicated in Figure 6. All the implications of the sound source directivity, the sound source position and the combination of these two variables are examined in deeper detail in the second part of this study, which analyses the sound sources measurement in an anechoic room and the repetitions of the RRT measurement, using the same equipment both with a directional and a dodecahedron sound sources.

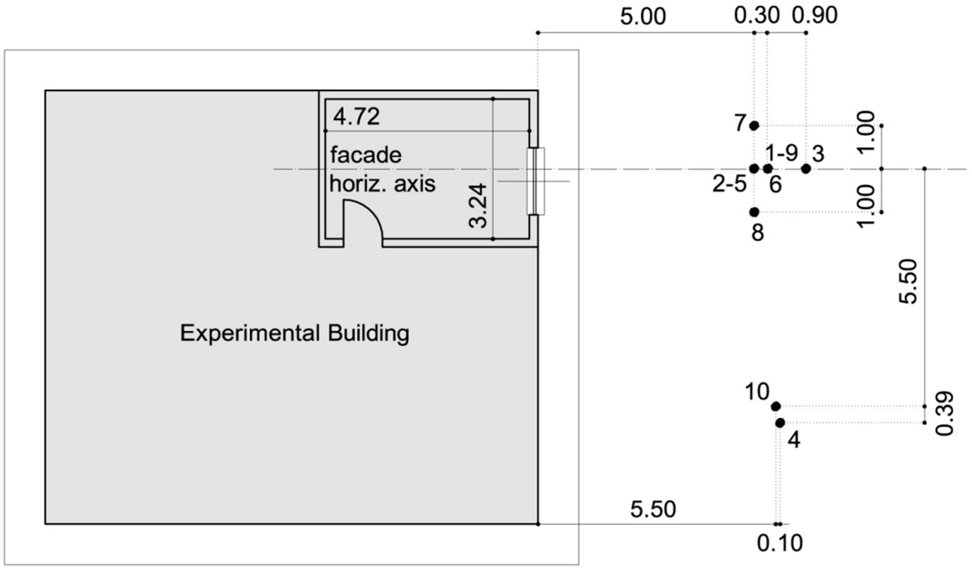

Figure 6. Loudspeaker positions (1 to 10) of the laboratories involved in the RRT

Table 3 shows the loudspeakers used by each laboratory participating in the RRT. Some laboratories used different devices of the same loudspeaker type and model, as indicated in column "item" (8 different loudspeakers), and, in the case of laboratories No. 1 and No. 3 and laboratories No. 7 and No. 8, exactly the same loudspeaker. Table 3 also indicates the loudspeakers tested in the anechoic room (5 loudspeakers), which are representative of all the loudspeakers used in this RRT; when the same model of loudspeaker is used, the individual device actually tested is clearly indicated (e.g. for laboratory No. 1, No. 3 and No. 5 the loudspeaker of laboratory No. 1 was tested in the anechoic room and the result extended to the other laboratories).

Table 3 – Loudspeaker type and model for each laboratory participating in the RRT

Laboratory	Loudspeaker	Item	Tested in anechoic room
LAB1	B&K Sound Source 4224	1	YES
LAB3	B&K Sound Source 4224	1	
LAB5	B&K Sound Source 4224	2	
LAB9	Look Line Sound source FL01	3	YES
LAB2	Look Line Sound source FL02	4	
LAB7	Look Line Sound source FL01	5	
LAB8	Look Line Sound source FL01	5	
LAB4	MKC Proline Active Monitor 15” 2-way	6	YES
LAB6	Montarbo	7	YES
LAB10	01dB Sound source NGS1	8	YES

For these five different loudspeakers, the directivity was measured in the large anechoic room of the University of Ferrara, following the procedures normally used in order to determine the polar diagram of the sources, considering the standard AES-56 [31] and averaging the narrow band results into 1/3 octave bands.

The directivity, D_I, was obtained at intervals of 5 degrees both in the horizontal and vertical planes at each frequency band from 50 Hz to 10 kHz according to eq. (4).

$$D_I = L_{pi} - L_{p0}\ [dB]\ (4)$$

where:
L_{pi} is the sound pressure level measured in the particular direction at a distance *r* from the source [dB];
L_{p0} is the sound pressure level measured in the normal direction at a distance *r* from the source [dB].

Table 4 shows the directivity in the vertical plane for all loudspeakers, at the frequency bands of 4000 and 5000 Hz, referred to the angle between the direction of emission toward the center of the facade (normal axis to the loudspeaker) and the direction toward the external microphone at 2 m from the facade. All values are normalized to the directivity measured in the axial direction, i.e. each value indicates the increment (positive values) or reduction (negative values) of directivity with reference to the axial direction of the loudspeakers.

Table 4 - Directivity for different loudspeakers/ laboratories referred to the angle of emission between center of facade and microphone at 2 m form the facade.

Laboratory	Angle between facade center and microphone at 2 m [deg]	Directivity D_I [dB]	
		4000 Hz	5000 Hz
LAB1	13.1	-2.7	-4.1
LAB2	13.9	-4.9	-7.7
LAB3	11.1	-1.0	-1.7
LAB4	11.0	0.5	-1.5
LAB5	13.9	-2.7	-4.1
LAB6	13.1	3.8	-0.8
LAB7	13.7	-4.9	-7.7
LAB8	13.7	-4.9	-7.7
LAB9	13.1	-4.9	-7.7
LAB10	11.0	-6.9	-7.2

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Figure 7 shows the standard deviation of the directivity between different loudspeakers/ laboratories, considering only 8 laboratories (excluding the outlier laboratories No. 5 and No. 6). In the graphs, two curves are reported; one shows the directivity referred to the real position of the different laboratories (continuous line) and the other the directivity assuming the same position for all laboratories, at 5 meters from the facade (dotted line), as in the case of Lab 2 (Figure 6). In both cases, the standard deviation of the directivity increases at higher frequencies and in particular above 2.5 kHz.

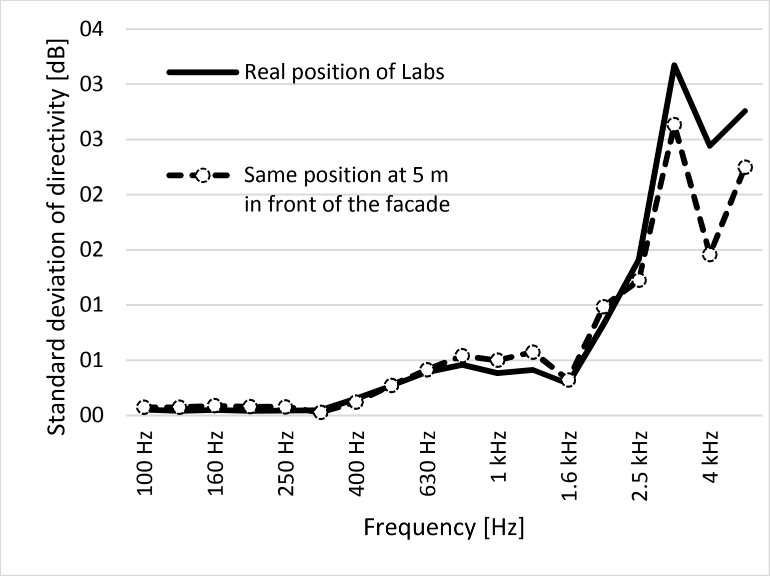

Figure 7. Standard deviation of directivity for different laboratories/loudspeakers. Continuous line: real position of laboratories' sources; dotted line: same position at 5 meter in front of the facade

The loudspeaker directivity modifies the value of the difference between the sound pressure incident on the facade center and on the microphone fixed at 2 meters from the facade. Since the facade sound insulation $D_{2m,nT}$ is obtained, according to Eqns. (2) and (3), from the difference between the sound levels measured at 2m from the facade, $L_{1,2m}$, and in the receiving room, L_2, while the sound power transmitted in the receiving rooms depends on the sound effectively incident on the facade, a difference between these two quantities (due to the directivity of the loudspeaker) may involve a difference in the results of $D_{2m,nT}$. As a consequence, the standard deviation obtained in the RRT at higher frequencies may be partly due to the standard deviation of the directivity of different loudspeakers at these frequencies. It is useful to underline that the directivity of the loudspeakers may have an important role in the case of irregular facade surfaces. In the case of facades shielded by external devices, such as external louvers, the sound pressure level (SPL) distribution over the facade is very influenced by the direction of the incoming sound waves as shown in the study by Zuccherini Martello *et al.* [32].

With respect to the requirements for loudspeakers, ISO 140-5 [23] states that the directivity of the loudspeaker in a free field shall be such that the local differences in the sound pressure level in each frequency band of interest are less than 5 dB, measured on an imaginary surface of the same size and orientation as the test specimen. The ISO 16283-3 [24] requirements are very different, as it states that the loudspeakers shall have approximately uniform, omnidirectional radiation, which implies a dodecahedron.

In the second part of this study the effect of loudspeaker directivity over the facade surface is investigated and the actual omnidirectional radiation of the dodecahedron will be evaluated.

3.2.4 Facade sound insulation: low-frequency procedure

As mentioned in the introduction, in this study a comparison between the default procedure and the low-frequency procedure (prescribed for room volume below 25 m^3 [21]) was made on the same facade sound insulation measurement, where the receiving room volume is approximately 40 m^3. This volume allows for the application of the default measurement procedure [21] and, therefore, for the relevant comparison.

In the low-frequency procedure firstly proposed by Hopkins and Turner [19], for each of the 50, 63 and 80 Hz frequency bands the average low frequency sound pressure level in the room, L_{LF}, is calcu-

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lated from L_2 from the default measurement procedure and $L_{2,corner}$ (the corner sound pressure level) according to:

$$L_{LF} = 10\lg\left[\frac{2\left(10^{0.1L_2}\right)+10^{0.1L_{2,corner}}}{3}\right]\text{dB} \quad (4)$$

where $L_{2,corner}$ is defined [24] as ten times the common logarithm of the ratio of the highest time average squared sound pressure from the set of corner measurements to the square of the reference sound pressure, for the low-frequency range (50, 63, and 80 Hz one-third octave bands).

For the low-frequency procedure [24], sound pressure level measurements are taken close to the corners of the room to identify the corner with the highest level in each band. A fixed microphone shall be positioned in room corners at a distance of 0.3 m to 0.4 m from each room boundary that forms the corner. A minimum of four corners shall be measured using a fixed or manually-held microphone. Two corners should be at ground level and two corners should be at ceiling level. These corners can or cannot be near the facade wall.

Referring to Hopkins and Turner [19], the weighting factor for $L_{2,corner}$ is empirical and has not been determined from theoretical models, so any future work could look at this aspect in more detail; however this equation was adopted by ISO 16283-1 [21] and by ISO 16283-3 [24].

In their work, Hopkins and Turner [18] evaluated also the reverberation time measurements in narrow rooms (for rooms with volumes < 50 m^3) and suggested this criterion: the product of the filter bandwidth, *B*, and the reverberation time, *T*, should be greater than eight ($BT > 8$). For the low frequency 50, 63 and 80 Hz if this criterion is satisfied, the reverberation time measured could be used for the calculation of *R'* or D_n (or, in the case of this paper, for the calculation of $D_{ls,2m,nT}$); otherwise the 63 Hz octave band reverberation time shall be measured and this single value used to represent the 50, 63 and 80 Hz bands. The measurement of the 63Hz octave reverberation time became a part of ISO 16283-1 [21] and of ISO 16283-3 [24], in the low-frequency procedure in case of room volumes < 25 m^3.

To investigate the uncertainty in the low frequency range (50, 63 and 80 Hz), the values and the relative repeatability and *in situ* standard deviation of $D_{ls,2m,nT}$ were calculated following three different measurement procedures: the first following the default measurement method; the second following the low-frequency procedure, considering the reverberation time measured in one-third octave bands (named $LF_{1/3}$); the third following the low-frequency procedure, considering the reverberation time measured in the octave band at 63Hz (named $LF_{1/1}$), in accordance with ISO 16283-3 [24].

As illustrated in Section 3.1, the outlier laboratories could be included in the evaluation of the low frequency uncertainties as the stragglers and outliers are from 500 Hz, thus Table 4 shows the standard deviations values for the case of both 10 and 8 teams.

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Table 5. Low frequency $D_{ls,2m,nT}$ s_r and s_{situ} values for the three measurement method (default, $LF_{1/3}$ and $LF_{1/1}$) for both 8 and 10 teams.

Frequency (Hz)	Measurement method	s_r10 (dB)	s_{situ}10 (dB)	s_r8 (dB)	s_{situ}8 (dB)
50	DEFAULT	2.7	3.1	2.3	2.9
	$LF_{1/3}$	2.5	3.1	2.3	3.2
	$LF_{1/1}$	2.3	3.3	2.3	3.5
63	DEFAULT	3.1	4.8	3.3	4.3
	$LF_{1/3}$	4.5	5.5	5.0	5.2
	$LF_{1/1}$	4.5	5.5	5.0	5.2
80	DEFAULT	1.4	4.0	1.4	4.1
	$LF_{1/3}$	2.3	4.1	2.5	4.2
	$LF_{1/1}$	2.3	4.1	2.6	4.2

With the low-frequency procedure there is an increase in the uncertainty, particularly noticeable at 63 Hz: the repeatability increases by about 1,5 dB while the *in situ* standard deviation increases by about 1 dB. With respect to reverberation time, at 63 and 80 Hz there are no differences considering the measurement of the 63Hz octave reverberation time or the 1/3 octave reverberation time; while some small differences are noticeable at 50 Hz. The results shown in Table 5 indicate that the low-frequency measurement procedure does increase the uncertainty. This cannot be attributed to the operators whose experience is well proven. To deeper investigate this aspect the repeatability and *in situ* standard deviations of the following quantities, for the 10 laboratories, were calculated: D_{2m}, the level difference between $L_{1,2m}$, and the space and time average sound pressure level, L_2, in the receiving room (as defined in Eq. (3)); $D_{2m,corner}$ the level difference between $L_{1,2m}$, and $L_{2,corner}$, in the receiving room; $D_{2m,LF}$ the level difference between $L_{1,2m}$, and the average low frequency sound pressure level L_{LF} (as defined in Eq. (4)), in the receiving room. The results shown in Table 6 underline that the uncertainty of the LF procedure depends on the uncertainty of the corner measurements.

Table 6. Low frequency s_r and s_{situ} values for the three level differences D_{2m}; $D_{2m,corner}$ and $D_{2m,LF}$ for 10 teams.

Level difference	Frequency (Hz)	s_r10 (dB)	s_{situ}10 (dB)
D_{2m}	50	2.4	3.1
	63	3.1	4.7
	80	1.3	3.9
$D_{2m,corner}$	50	2.8	3.6
	63	5.0	5.9
	80	2.6	4.1
$D_{2m,LF}$	50	2.4	3.2
	63	4.5	5.4
	80	2.2	3.9

3.2.5 Low-frequency uncertainty analysis

The evidence of high values of s_r and s_{situ} at low frequencies can be explained by different problems: the non-diffuse sound field, low S/N ratios and the low frequency procedure itself. Calculation of room modes shows the low modal density between 50 Hz and 100 Hz, and proves the non-diffusivity of the sound field at such frequencies in small rooms (Fig. 8). Both the dimensions and the volume of the rectangular receiving room are as described in Sec. 2. For a room of this size, quite distinct peaks of sound pressure levels can be found at natural modes in the low frequency range (below 100 Hz), especially when measured at rectangular room corners. At higher frequencies there is a greater number of modes yielding more resonance peaks, many of which are closer together, even overlapping and tending to produce a uniform transmission (see Ref. [31]). For the room under investigation, the first (significant) axial modes, within the 50-100 Hz frequency range, are found at the following frequencies, respectively: f_{1x} = 53 Hz, f_{1z} = 64 Hz, f_{2y} = 73 Hz[a].

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[a] The axial modes of vibration are those in which the waves travel along one axis, parallel to two pairs of walls. Their frequencies are obtained as follows:

$$f_{n_i} = \frac{c}{n_i l_i} \qquad \text{(Hz)}$$

where c is the sound speed (i.e. 340 m/s), l_i is the dimension of height(l_z), width(l_y), depth(l_x) of the room (in meters), n = 1,2,3,… and i = x,y,z.

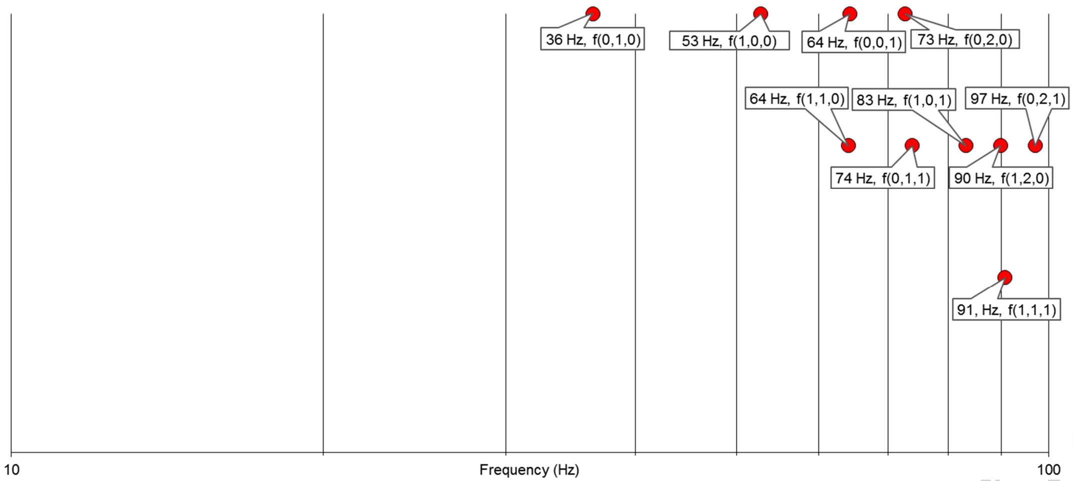

Figure 8. The first 10 room modes.

Facade sound insulation measurements are usually performed with directive and powerful loudspeakers in the standard range 100-5000 Hz. Below 100 Hz, sound power of ordinary sound sources strongly decreases. RRT measurement conditions, especially at low frequencies, were affected by both low sound power levels of sources at low frequencies and potential high background noise due to airborne and structure-borne sound transmission from a close congested road. At low frequencies, insulating properties of facade and windows are usually low and background noise becomes more influential. Such condition yielded to low S/N ratios, in general, for most of laboratories and, although background noise standard requirements were respected, it was not possible to avoid or predict possible high and temporary background noise peaks, especially at low frequencies, where the low frequency procedure for $L_{2corner}$ requires to determine the highest sound pressures levels from the set of 4-corner measurements. This could be a possible reason for the increase of uncertainties with the LF measurement procedure (see Table 6). Such issue, which is not considered in the new standard, should be taken into account in future releases. In addition, although the default procedure entails high dispersion of outdoor and indoor measurements due to background noise peaks, their influence is reduced with respect to low frequency procedure as $L_{1,2m}$ e L_2 values come from averaged measurements.

Given such evidences, as an alternative, the average values of the 4-corner set, corrected with the average values of the background noise measured in the corners, were also investigated. The values in Table 7 refer to 9 laboratories, as laboratory No. 4 provided only the highest corner values while all the other laboratories provided all the measured values of the 4 corners. The $D_{ls,2m,nT}$ values, for the low frequency 1/3 octave bands (50, 63 and 80 Hz), for the following measurement method, are given in Table 7: the default measurement procedure (default); the low-frequency measurement procedure (LF), considering the reverberation time measured in octave band at 63Hz (named $LF_{1/1}$), in accordance with ISO 16283-3 [24]; the LF measurement procedure, considering the reverberation time measured in one-third octave bands ($LF_{1/3}$); the LF measurement procedure considering the average values of the 4-corner set, corrected with the average values of the background noise measured in the corners (LFA), considering the reverberation time measured in octave band at 63Hz (named $LFA_{1/1}$) and the LFA, considering the reverberation time measured in one-third octave bands ($LFA_{1/3}$).

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Table 7. Low frequency $D_{ls,2m,nT}$ average, s_r and s_{situ} values for the five measurement methods (default, LF, LFA, $LF_{1/3}$ and $LFA_{1/3}$) for 9 teams.

Frequency (Hz)	Measurement procedure	$D_{ls,2m,nT}$ average (dB)	$D_{ls,2m,nT}$ s_{situ} (dB)	$D_{ls,2m,nT}$ s_r (dB)
50Hz	DEFAULT	24.6	3.0	2.8
	$LF_{1/1}$	21.6	3.1	2.4
	$LFA_{1/1}$	23.0	2.8	2.2
	$LF_{1/3}$	21.7	3.0	2.6
	$LFA_{1/3}$	23.0	2.7	2.4
63Hz	DEFAULT	22.3	5.0	3.2
	$LF_{1/1}$	16.8	5.8	4.8
	$LFA_{1/1}$	18.7	5.5	4.1
	$LF_{1/3}$	16.5	5.8	4.7
	$LFA_{1/3}$	18.3	5.4	4.0
80Hz	DEFAULT	29.2	3.0	1.4
	$LF_{1/1}$	25.3	3.8	2.5
	$LFA_{1/1}$	26.5	3.3	2.0
	$LF_{1/3}$	24.5	3.8	2.5
	$LFA_{1/3}$	25.7	3.2	2.1

The results in Table 7 show that the *in situ* standard deviation decreases if the average values of the 4-corner set measurements are taken into account: $LFA_{1/1}$ method s_{situ} is lower than $LF_{1/1}$ method s_{situ}, and the same behavior was found considering the reverberation time measured in one-third octave bands, i.e. $LFA_{1/3}$ method s_{situ} is lower than $LF_{1/3}$ method s_{situ}. Moreover, at 50Hz, both $LFA_{1/1}$ and $LFA_{1/3}$ method s_{situ} are lower than the default method s_{situ}.

As already done with the results shown in Table 6, to investigate in more depth the uncertainty of low frequency bands, the repeatability and *in situ* standard deviations of D_{2m} values (as defined in Eq. (3)), for the low frequency 1/3 octave bands (50, 63 and 80 Hz), for the following measurement method, are given in Table 8: default, LF and LFA.

Table 8. Low frequency D_{2m} average, s_r and s_{situ} values for the three measurement methods (default, LF and LFA) for 9 teams.

Frequency (Hz)	Measurement procedure	D_{2m} average (dB)	D_{2m} s_{situ} (dB)	D_{2m} s_r (dB)
50Hz	DEFAULT	18.8	2.9	2.6
	LF	15.9	2.9	2.5
	LFA	17.3	2.7	2.2
63Hz	DEFAULT	16.9	4.9	3.3
	LF	11.1	5.7	4.8
	LFA	13.0	5.4	4.1
80Hz	DEFAULT	24.3	2.9	1.4
	LF	19.6	3.6	2.4
	LFA	20.8	3.1	2.0

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The results in Table 8, which are the standardized level differences without the reverberation time correction (D_{2m}), show that the *in situ* measurement uncertainty decreases if average values of the 4-corner set measurements are taken into account, as in the case of standardized level differences, i.e. the level difference with the reverberation time correction ($D_{ls,2m,nT}$ in Table 7).

Considering the average values, it is important to underline again that the receiving room volume of this RRT is 40 m^3 which allows for the application of the default measurement procedure [21] and, therefore, for the relevant comparison. As shown in Table 7, the average values of the five procedures are very different and the difference between the LF procedure and the default procedure is higher than the difference between the LFA procedure and the default procedure; therefore the LFA procedure seems to better represent the facade sound insulation values at low frequencies, according to ISO 16283-3 [24] requirements (volume of the receiving room under test equal to 41 m^3). Nevertheless in conditions of non-diffuse field the accuracy is still unknown and other methods and procedures, based on a modal approach [34], are nowadays under investigation in order to improve it.

It is known that the RRT is the only way to ascertain the true value of a test element in building acoustics, assuming that the mean of all the repetitions of all the laboratories involved in the test is the value that can best describe the true value of the element. So the mean values of $D_{ls,2mnT}$ are the "true" values in this sense. However, for the purpose of the present study the choice of the RRT mean values has not been defined for non-diffuse field conditions. In fact, these values depend on the measurement method used for their calculation: default, $\mathrm{LF}_{1/1}$, $\mathrm{LFA}_{1/1}$, $\mathrm{LF}_{1/3}$, $\mathrm{LFA}_{1/3}$. The results in tables 7 and 8 show that the differences between these five measurement methods are very high (average values) and therefore it is necessary to understand what is the measurement method that better represents the true value of the facade sound insulation of the test item. In fact, the receiving room volume of this RRT is 41 m^3, which allows for the application of both the default measurement procedure [21] and the LF measurement procedure and, therefore, for the relevant comparison.

4 SINGLE NUMBER QUANTITIES ANALYSIS

Two different procedures have been considered in order to determine the single number quantities (SNQs) of each team for this study. The former procedure consists in determining the SNQs according to ISO 717-1 [35] shifting the reference curve both in steps of 1 dB and 0.1 dB, toward the measured curve, until the mean unfavorable deviation is as large as possible but not more than 32 dB. The obtained SNQs are respectively $D_{ls,2m,nT,w}$ and $D_{ls,2m,nT,w,01}$.

The latter procedure consists in determining the SNQs plus spectrum adaptation terms C and C_{tr} according to ISO 717-1 [35] in the ranges provided by the standard (from 50 to 5000 Hz; from 50 to 3150 Hz; from 100 to 3150 Hz and from 100 to 5000 Hz), with one decimal place using the following equation:

$$X_{Aj} = -10\lg\sum 10^{\left(L_{ij}-X_i\right)/10} = X_w + C_j \tag{5}$$

where: j is the index of spectrum No.1 to calculate C or No.2 to calculate C_{tr} according to ISO 717-1; i is the index of frequencies; L_{ij} are the levels indicated in ISO 717-1 at frequency i for spectrum j; X_i is the standardized level difference $D_{ls,2m,nT}$ at frequency i for the spectrum j; X_w is the SNQ; C_j is the spectrum adaptation term C or C_{tr} if calculated with spectrum No.1 or No.2, respectively. The results of SNQs calculations, for the 8 teams, are shown in Fig. 9; the relative s_r and s_{situ} are shown in Table 9 and Table 10.

Analyzing the results in Fig. 9, it can be seen that the low frequency inclusion, measured with the default procedure, does not significantly influence the SNQs values and their uncertainty, as found in the previous RRT on facade sound insulation [7]. This was also highlighted by Wittstock [5], who found, for SNQs, that extending the frequency range has no significant effect on the standard deviation of reproducibility, whereas a small increase is observed for the *in situ* standard deviation; he also found [5], contrary to the results of this RRT, that extending the frequency range has a larger increase for the standard deviation of repeatability. On the other hand, the low frequency inclusion, measured with the LF procedure, influences the SNQs values, when the C_{tr} spectrum adaptation term is included, and increases their uncertainty, if compared with the default measurement procedure uncertainty (Table 10).

Considering the default measurement procedure, the low frequency uncertainty is not well reflected in the SNQs uncertainty. Therefore, for the extension to low frequencies, the suitability of the reference spectra for rating airborne sound insulation should be validated.

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On this topic, Masovic *et al.* [36] made a study on the suitability of ISO CD 16717-1 [37] reference spectra for rating airborne sound insulation. The ISO CD 16717-1 [37] “living” and “traffic” spectra correspond to the reference spectra C (50–5000 Hz) and C_{tr} (50–5000 Hz) of ISO 717-1 [35], respectively. Masovic *et al.* [36] demonstrated, with an extensive noise monitoring in a number of dwelling recordings of 38 potentially disturbing activities, that the reference spectrum for living noise (L_{living}), should be redefined to better match the typical spectrum of noise in dwellings because it seems to be rather high at lower frequencies, especially below 100 Hz. Moreover, in the case of noise generated by sources of music with strong bass content the reference spectrum for traffic noise ($L_{traffic}$) seems to be more appropriate above 100 Hz than L_{living}. This could suggest one of the reasons why the low frequencies uncertainty is not adequately reflected by the SNQs uncertainty extended to low frequencies and should be considered in greater detail before deciding to perform measurements down to LF range.

In literature, there are some studies (e.g., Rindel [38] and Park and Bradley [39]) on the annoyance of noise from neighborhood at low frequencies that stress the importance of investigating the LF noise; nevertheless, at present time, effective protection systems against low frequency noise are still an open challenge both for researchers and components manufacturers, as underlined by Prato and Schiavi [40]. Hongisto *et al.* [14] suggested that scientifically valid socio-acoustic evidence for the need to include the frequency range 50–80 Hz should be significantly improved before deciding that the low frequency measurements are included in the calculation of the SNQs. Last but not least, if LF measurements are aimed at the protection against LF noise, the fact that the high uncertainty of the one-third octave LF bands affects the reliability of the performance of the test element implies that the potential effectiveness of the protection system against low frequency noise is not quantifiable.

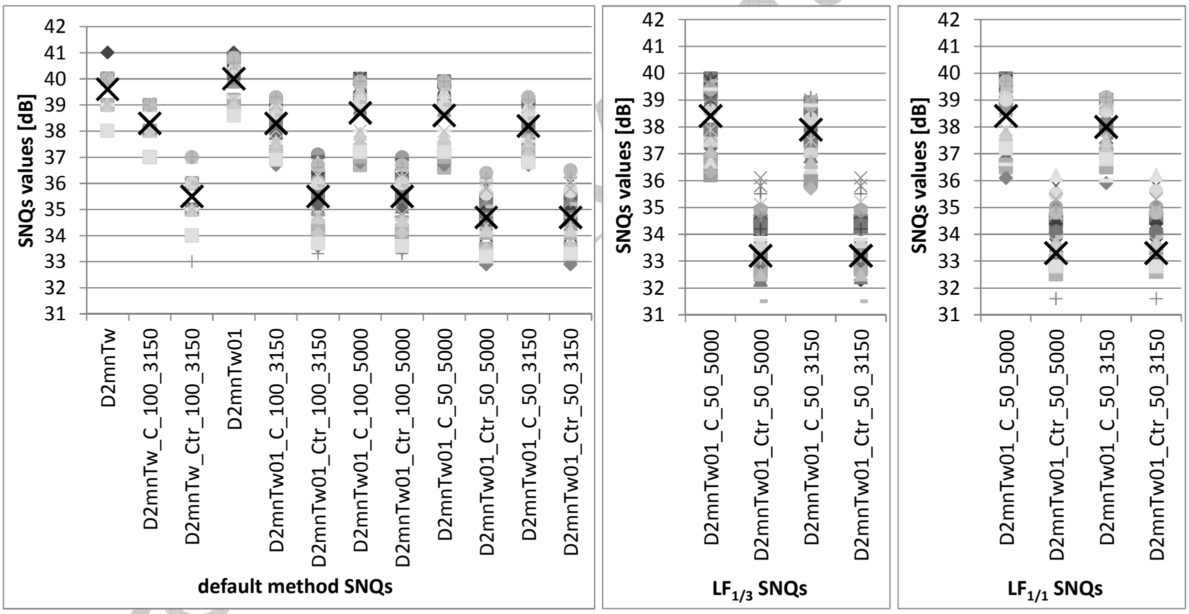

Figure 9. SNQs distribution: grey symbols are the values of the SNQs, the black crosses are the RRT mean values. Left side: default SNQs; center: LF$_{1/3}$ SNQs; right side: LF$_{1/1}$ SNQs.

Table 9. Standard deviations (s_r and s_{situ}) of SNQs without low frequencies for the 8 teams.

Descriptor (SNQs)	s_r (dB)	s_{situ} (dB)
$D_{ls,2m,nT,w}$	0.4	0.7
$D_{ls,2m,nT,w}+C_{(100\text{-}3150)}$	0.6	0.8
$D_{ls,2m,nT,w}+C_{tr(100\text{-}3150)}$	0.8	1.0
$D_{ls,2m,nT,w01}$	0.3	0.7
$D_{ls,2m,nT,w01}+C_{(100\text{-}3150)}$	0.5	0.8
$D_{ls,2m,nT,w01}+C_{tr(100\text{-}3150)}$	0.7	1.0
$D_{ls,2m,nT,w01}+C_{(100\text{-}5000)}$	0.6	1.2
$D_{ls,2m,nT,w01}+C_{tr(100\text{-}5000)}$	0.7	1.0

Table 10. Standard deviations (s_r and s_{situ}) of SNQs with low frequencies for the 8 teams.

Descriptor (SNQs)	Measurement procedure	s_r (dB)	s_{situ} (dB)
$D_{ls,2m,nT,w01}+C_{(50\text{-}3150)}$	DEFAULT	0.5	0.8
	$LF_{1/3}$	0.6	1.0
	$LF_{1/1}$	0.6	1.0
$D_{ls,2m,nT,w01}+C_{(50\text{-}5000)}$	DEFAULT	0.6	1.2
	$LF_{1/3}$	0.6	1.3
	$LF_{1/1}$	0.6	1.2
$D_{ls,2m,nT,w01}+C_{tr(50\text{-}3150)}$	DEFAULT	0.8	1.0
	$LF_{1/3}$	1.9	2.1
	$LF_{1/1}$	1.8	2.0
$D_{ls,2m,nT,w01}+C_{tr(50\text{-}5000)}$	DEFAULT	0.8	1.0
	$LF_{1/3}$	1.9	2.1
	$LF_{1/1}$	1.8	2.0

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From the experience derived from many measurements of facade sound insulation [41, 42], the lower the insulation of a window, the lower the spectrum adaptation term C_{tr}. On the other hand, the higher the window insulation, the higher C_{tr}. For this reason, in the case of the previous RRT [7] the difference between the average values of $D_{ls,2m,nT,w}$ and $D_{ls,2m,nT,traffic}$ (SNQs proposed by Scholl *et al.* [8] which correspond to $D_{ls,2m,nT,w} + C_{tr,50\text{-}5000}$) was only 1.5 dB, while in the case of the present study, the difference between the average values of $D_{ls,2m,nT,w}$ and of $D_{ls,2m,nT,w} + C_{tr,50\text{-}5000}$ is 5.3 dB for standard measurements and 6.8 dB for the low-frequency method; and the difference between the average values of $D_{ls,2m,nT,w}$ and of $D_{ls,2m,nT,w} + C_{tr,100\text{-}5000}$ is 4.5 dB for both the standard and low-frequency methods. It is interesting to note that the average values did not change significantly whether they included or not the high frequencies. The uncertainty in case of the low-frequency method increases very much (twice for $LF_{1/1}$ and more than double for $LF_{1/3}$). At high frequencies, 4000 and 5000 Hz, the uncertainty is very high, and this influences the uncertainty of SNQs, in particular, s_{situ} of $D_{ls,2m,nT,w01}+C_{(100\text{-}3150)}$ is equal to 0.8 dB and, including the high frequency, s_{situ} of $D_{ls,2m,nT,w01}+C_{(100\text{-}5000)}$ increases up to 1.2 dB (Table 10). As stated in section 3.2.3 this is probably caused by the loudspeaker directivity and position and it is examined in greater detail in the second part of this study.

To study the influence of the LF measurement procedure on the SNQs, in Table 11 are shown the 7 laboratories' SNQs average values, with their standard deviations (s_r and s_{situ}), which are not affected by the low frequencies inclusions, i.e. the SNQs in range 100-3150 Hz. Table 12 shows the 7 laboratories' SNQs average values, with their standard deviations (s_r and s_{situ}), which are affected by the low frequencies inclusions, i.e. the SNQs in range 50-3150 Hz. In tables 11 and 12, 7 laboratories are considered for the relevant comparison between the different procedures (i.e. default, $LF_{1/1}$, $LFA_{1/1}$, $LF_{1/3}$

and LFA$_{1/3}$ procedure), because it was necessary to exclude laboratory No. 4, in addition to the exclusion of the outlier laboratories No. 5 and No. 6. In fact, laboratory No. 4 provided only the highest corner values while all the other laboratories provided all the measured values of the 4 corners; therefore it was not possible to calculate the average values of the 4-corner set measurements for laboratory No. 4.

Table 11. Average and standard uncertainties values of SNQs without low frequencies for the 7 teams.

Descriptor (SNQs)	Average (dB)	s_r (dB)	s_{situ} (dB)
$D_{ls,2m,nT,w}$	39.7	0.6	0.3
$D_{ls,2m,nT,w}+C_{(100\text{-}3150)}$	38.4	0.8	0.6
$D_{ls,2m,nT,w}+C_{tr(100\text{-}3150)}$	35.6	1.0	0.8
$D_{ls,2m,nT,w01}$	40.1	0.7	0.3
$D_{ls,2m,nT,w01}+C_{(100\text{-}3150)}$	38.4	0.8	0.5
$D_{ls,2m,nT,w01}+C_{tr(100\text{-}3150)}$	35.6	1.1	0.8

Table 12. Average and standard uncertainties values of SNQs with low frequencies for the 7 teams, for the five measurement procedures (default, LF$_{1/1}$, LFA$_{1/1}$, LF$_{1/3}$ and LFA$_{1/3}$).

Descriptor (SNQs)	Measurement procedure	Average (dB)	s_{situ} (dB)	s_r (dB)
$D_{ls,2m,nT,w}+C_{(50\text{-}3150)}$	DEFAULT	38.3	0.8	0.6
	LF$_{1/1}$	38.1	1.0	0.6
	LFA$_{1/1}$	38.2	0.9	0.6
	LF$_{1/3}$	38.0	1.0	0.7
	LFA$_{1/3}$	38.2	0.9	0.6
$D_{ls,2m,nT,w}+C_{tr(50\text{-}3150)}$	DEFAULT	34.9	1.0	0.8
	LF$_{1/1}$	33.4	2.1	1.9
	LFA$_{1/1}$	34.1	1.4	1.2
	LF$_{1/3}$	33.3	2.2	2.0
	LFA$_{1/3}$	34.0	1.5	1.3

As found in the 1/3 octave band analysis (section 3.2.4), the results in Table 12 show that the *in situ* measurement uncertainty decreases if the average values of the 4-corner set measurements are taken into account: LFA$_{1/1}$ method s_{situ} is lower than LF$_{1/1}$ method s_{situ}, and the same behavior was found considering the reverberation time measured in one-third octave bands, i.e. LFA$_{1/3}$ method s_{situ} is lower than LF$_{1/3}$ method s_{situ}. Again, as found in the 1/3 octave band analysis (section 3.2.4), the difference in the average values between the LF procedure and the default procedure is higher than the difference between the LFA procedure and the default procedure.

The differences between the average values and relevant uncertainty (s_{situ}) of the five procedures are slight in the case of SNQ with *C* spectrum adaptation term compared with the SNQs with C_{tr} spectrum adaptation term (obviously, because C_{tr} considers more the LF).

5 CONCLUSIONS

This paper illustrates a comparison between the default procedure and the low-frequency procedure made on the same facade sound insulation measurement. It was found that SNQs values do not change when the low frequencies are included. Nevertheless, the uncertainties of SNQs measured with the low-frequency procedure are higher than the ones measured with the default procedure. Observing the one-third octave band results, it was found that the low-frequency procedure reduces sound insulation values and increases measurement uncertainties in the low frequency range, in particularly at 63 Hz. A possible cause can be found in the procedure itself, which requires to take into account the highest sound pressure levels from corner measurements instead of the average levels from the default procedure, even if in the presence of high background noise peaks. Such condition highly affects sound in-

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sulation measurements especially at low frequencies, where ordinary sound sources do not usually have a linear response and the sound field is non-diffuse. For such reason, an alternative procedure based on average corner measurements was investigated: values are closer to the default ones and the uncertainties decrease with respect to the low-frequency procedure. However, questions about the actual accuracy of the results obtained with the different tested methods are still open. Therefore, in the future, the actual necessity and reliability of the low-frequency procedure in non-diffuse field should be discussed and further investigated. With respect to reverberation times, at 63 and 80 Hz there are no differences considering the measurement of the 63Hz octave reverberation time and using this single value to represent the 50, 63 and 80 Hz bands or the 1/3 octave reverberation time; however, some small differences are noticeable at 50 Hz. High uncertainties, which influence the SNQs and depend on the sound source directivity and position, which are being investigated in further detail in the ongoing study, were found at 4000 and 5000 Hz.

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