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Abstract

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Keywords	environmental pollution; ISO 1996; measurement uncertainty; reflecting surface; health; road traffic noise
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Microphone position and noise exposure assessment of building façades

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ABSTRACT

The prevention or reduction of the exposure of the population to environmental noise is the fundamental objective of the European Noise Directive (END). To this end, strategic noise maps are considered as the basic tool and on-site measurements play an important role in its successful implementation. In this regard, the ISO 1996 standards are the reference for the measurement and assessment of environmental noise, but their application may be complex in many cases. It is therefore necessary to find urban scenarios in which the effects of the placement of the measuring equipment with respect to the façade on noise exposure levels can be analysed. In this study, an educational building was selected for an analysis of the differences in the weekly sound level from road traffic between a microphone flush-mounted on a plate at the façade and another placed between 0.5 and 2.0 m from it. The recommendations in Annex B of ISO 1996-2 were followed in the placement of the microphones. A broadband analysis shows that similar results were found for the four distances analysed, but that variations of up to 0.6 dBA above the reference value arose. An analogous study using frequency octave bands shows differences higher than 2 dB between the measured configurations for bands under 250 Hz. Based on the distance range given in ISO 1996-2 for the position of a microphone in front of a reflecting surface, the results suggest that the most appropriate option for accurately assessing the sound level incident on the façade of buildings is to place the microphone at a distance of 2 m if the guidelines of the ISO 1996-2 standard can be met.

Keywords: environmental pollution; ISO 1996; measurement uncertainty; reflecting surface; health; road traffic noise.

1. INTRODUCTION

In situ noise measurements are taken into consideration in the European Noise Directive (END) [1] for the elaboration of strategic noise maps in relation to the exposure of the population to environmental noise. They are also recognised as essential by the Good Practice Guide [2] in the development and validation of computational methods for noise mapping. This guide states that measurements have many additional functions to fulfil in the successful application of the European Noise Directive (END) [1], and especially in the development of action plans and verification of the real effects of actions that are carried out [3-5].

Annex II of END [1] and its subsequent modification [6] propose the use of the series of ISO 1996 standards [7,8] for the measurement and assessment of environmental noise; these have recently been updated, and many works use them in the planning and development of outdoor noise studies [9-13].

The ISO 1996-2 standard [8] proposes certain corrections to be applied to measured sound levels to consider the effects of sound reflections on building façades [14]. Depending on the position of the microphone, three different scenarios are identified. Firstly, in the case of a microphone located at the façade of a building, an interesting issue is introduced in the new version of the standard [8]. The correction required to obtain a free field is 5.7 dBA if the conditions in Annex B are met; otherwise, this figure can reach 6 dBA. Secondly, if the microphone is between 0.5 and 2.0 m in front of the surface, the value of this correction is 3 dB. Finally, for the free-field position (the reference condition), no correction is applied.

The new version of the ISO 1996-2 standard [8] includes a new aspect with respect to the previous version [15] in relation to the calculation of the uncertainty associated with the selection of microphone location. A table is presented in Annex B that gives the uncertainty standard for corrections to the reflections of different microphone locations relative to vertical reflecting surfaces for a road traffic sound source. This topic has been the subject of study in many papers where road traffic is considered the main source [16-21], and also in cases where sound impacts on the façades of buildings at very different angles, for example in the case of aircraft noise [22]. Hall et al. [16], Quirt [17] and Jagniatinskis et al. [18] conclude that a value of 3 dB for the correction is usually suitable when the microphone is 2.0 m from the façade. Memoli et al. [19] reach a similar conclusion for microphone positions of between 0.5 m and 2.0 m from the surface, but in this case, deviations from the proposed value of up to about 1 dB are detected. Montes et al. [20] report several effects on corrections associated with parking lines. Finally, Mateus et al. [21] describe the possible influence of wind on the registered values for corrections in a case where the microphones were located at about 150 m from the sound source.

Some of these conditions have been analysed in previous studies [23,24], since this microphone location is frequently used in research about environmental noise [25,26] and in *in situ* measurements based on the ISO 11819-4 standard [27] for a modified version of the statistical pass-by method or the ISO 10847 standard [28] for the determination of insertion loss of outdoor noise barriers. Barrigón et al. [23] highlight disparities in the values obtained in this measurement configuration of up to 2 dB from the correction of 6 dB established by the previous version of the ISO 1996-2 [15] standard. In the same vein, Montes et al. [24] report a study in which the microphone was placed on a reflective surface using plates of different materials. The experimental values of the corrections varied at the different measurement points and were lower than 6 dB, reaching average values of up to 5.2 dB in one of the studied cases.

A-weighting is generally used in the assessment of the impact of environmental noise on the population. This means that low frequencies have a lower weight in the final value of the sound indicators than medium or high frequencies. However, it is well known that the behaviour of sound waves is highly dependent on the frequency, meaning that each octave band may show different behaviour depending on the location of the microphone. The use of A-weighting to assess annoyance in environmental noise has been analysed and reviewed in the literature. For example, in a study conducted by Schomer et al. [29], the loudness-level-weighted equivalent level was proposed for assessment of the annoyance from environmental noise. The results indicate that compared with the A-weighting, a loudness-level weighting can order and assess transportation noise sources more effectively. Nilsson et al. report that with similar A-weighted sound pressure levels, sounds with higher low-frequency levels were louder and more annoying than sounds with lower levels [30], or suggest that an evaluation of the annoyance-reduction efficiency of noise barriers should not only rely on the expected reduction in A-weighted sound pressure level but should also take into account the associated increase in the relative level of low-frequency sound [31]. Even in studies conducted in urban green areas, the linearly weighted equivalent level showed a better relationship with traffic noise annoyance than an A-weighted value [10]. The effects of low-frequency noise on humans have also been studied by various researchers. A review of low-frequency noise sources and their effects can be found in the work of Berglund et al. [32]. Another study shows that the prevalence of annoyance, disturbed concentration and rest was greater in areas with low-frequency noise exposure, and that the A weighting was a poor predictor of annoyance due to low-frequency noise [33].

Taking into account these aspects of the new version of ISO 1996-2 [8], the importance of the frequency weighting used to determine environmental noise levels and the role of *in situ* measurements in the assessment and management of environmental noise [1], this paper presents a broad study of the corrections proposed by this standard by means of one-week measurements for different positions of the microphone. A broadband analysis is first carried out in which the weekly measured values are analysed globally. The distribution of the correction values is then analysed to determine their variability according to the time of day and the measured sound level. Finally, a study in octave frequency bands of the corrections is presented in order to deepen the experimental knowledge of sound reflections and interference phenomena that take place in front of vertical surfaces in urban environments.

2. METHODOLOGY

This study was carried out at the Polytechnic School of the University of Extremadura (Cáceres, Spain). The measurement devices were located on the façade of a teaching area in the Common Building of the Polytechnic School, which has direct view of the N-521 road (Fig. 1). This is an acoustically sensitive building with educational use and is directly affected by one of the main access roads to the city [34-36].

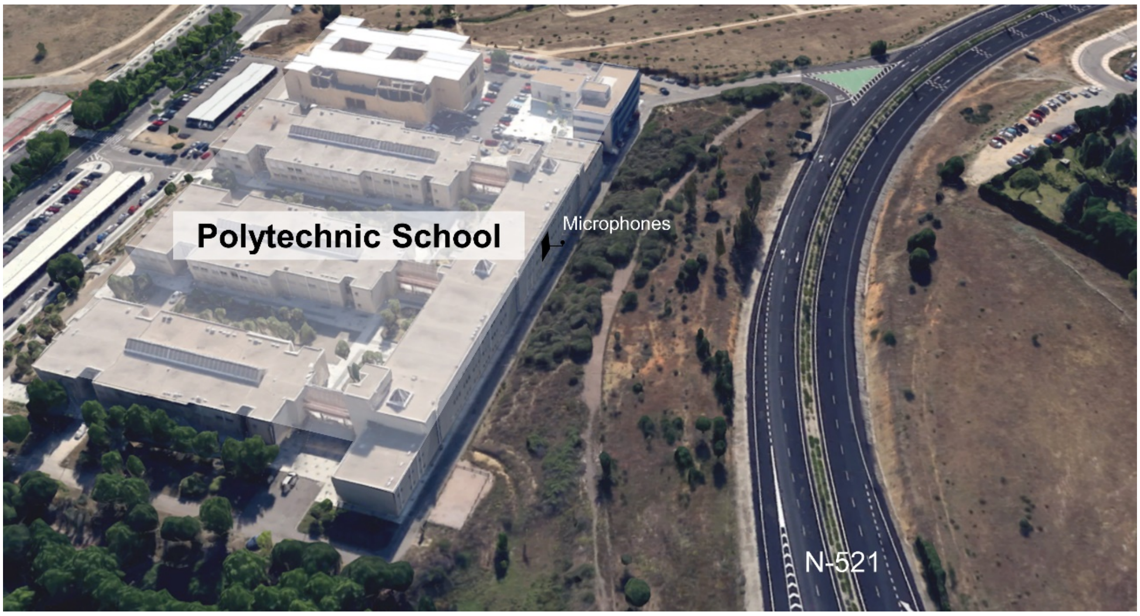
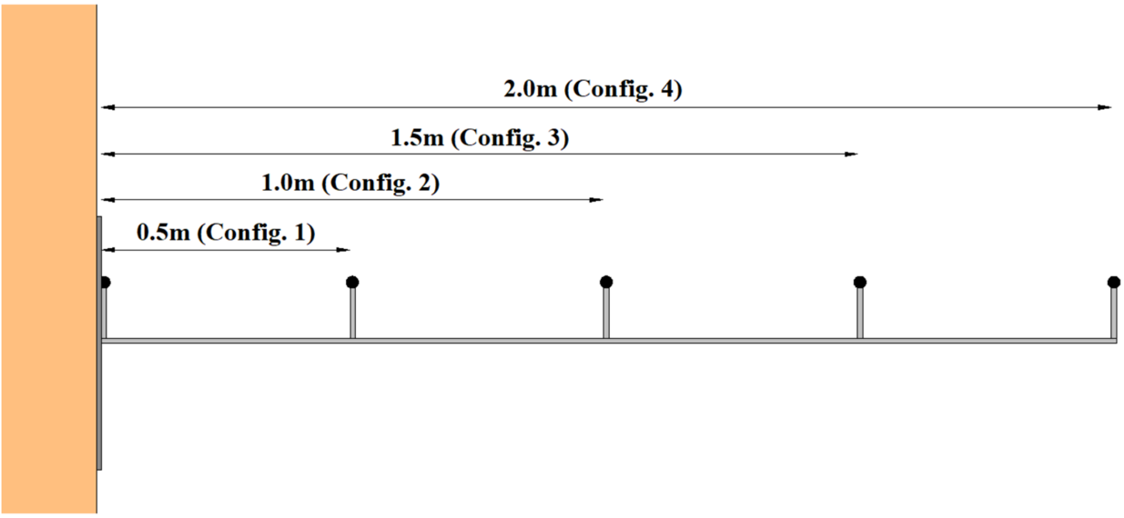


Fig. 1. Polytechnic School (Google Earth)

Two class 1 sound level meters (Brüel & Kjær type 2250 Light) were used to establish four different measurement configurations. In each of these configurations, the microphone of one of the sound level meters (façade microphone) was placed flush with the façade of the building on a 6-mm-thick metal plate with effective dimensions of 0.535 x 0.705 m. The microphone of the second sound level meter (mobile microphone) was placed at varying distances (0.5, 1.0, 1.5 and 2.0 m) from the façade (Fig. 2a). Both microphones were placed at a height of 7.75 m above the ground. Fig. 2b shows a photograph of configuration 4, in which one of the microphones is placed on the façade and the other one is 2.0 m away from it.

a)



b)

Fig. 2. (a) Diagram of the four configurations; and (b) photograph of configuration 4

Measurements of the sound levels were carried out with an integration time of one minute over the period of a week in each configuration. In this way, an analysis of the results for different integration time intervals was carried out. A detailed analysis of the time of the day at which each measurement was made and the values of the registered sound levels was also performed. Finally, a spectral analysis of the differences between the two microphones in each of the four configurations was performed. To this end, the octave bands included in the general frequency range defined by the ISO 1996-2 standard were considered.

The guidelines provided by the ISO 1996-2 standard in its normative part and Annex B [8] were used as a basis for placing the microphones: the characteristics of the façade and the measurement devices, the positions of the microphones and distances to the edges of the reflective surface, and the relationship of the distances between façade, microphone and sound source.

In addition to the sound levels registered, the meteorological conditions were monitored at one minute intervals to verify that the values were within the ranges recommended for the International Standards and thus discard their influence on the variability of the sound levels. The ANSI S12.18 [37] and ISO 1996-2 [8] guidelines were considered in the weather station location.

3. RESULTS AND DISCUSSION

This section presents an analysis and discussion of the results of measurements carried out using the procedure described in Section 2. A study of the broadband results is first presented in Section 3.1, in accordance with ISO 1996-2. A spectral analysis in octave bands is then carried out in Section 3.2.

3.1. Broadband results

3.1.1. Global differences

As previously indicated, four measurement configurations were analysed. In each of these configurations, one of the microphones was placed on the reflective surface (façade microphone) and the other at varying distances from the façade (mobile microphone): 0.5 m (configuration 1), 1.0 m (configuration 2), 1.5 m (configuration 3) and 2.0 m (configuration 4). Using measurements taken over one week, the difference in the equivalent sound level registered by façade microphone ($LAeq_{façade}$) and mobile microphone ($LAeq_{mobile}$) for an integration time of one hour was calculated for each configuration *i* (Eq. 1)

$$\Delta LAeq_i = LAeq_{façade} - LAeq_{mobile} \tag{1}$$

Fig. 3 shows the average and standard deviation of the sound level differences between the two microphones obtained in each measurement configuration. It can be seen in Fig 3 that the interval of variability in configuration 2 is smaller than in the rest. This difference in the variability interval may be mainly related to a greater uniformity in the equivalent sound level at nights, that do not reach values as low as the other monitoring weeks, and a lower occurrence of sound events other than traffic noise (main sound source).

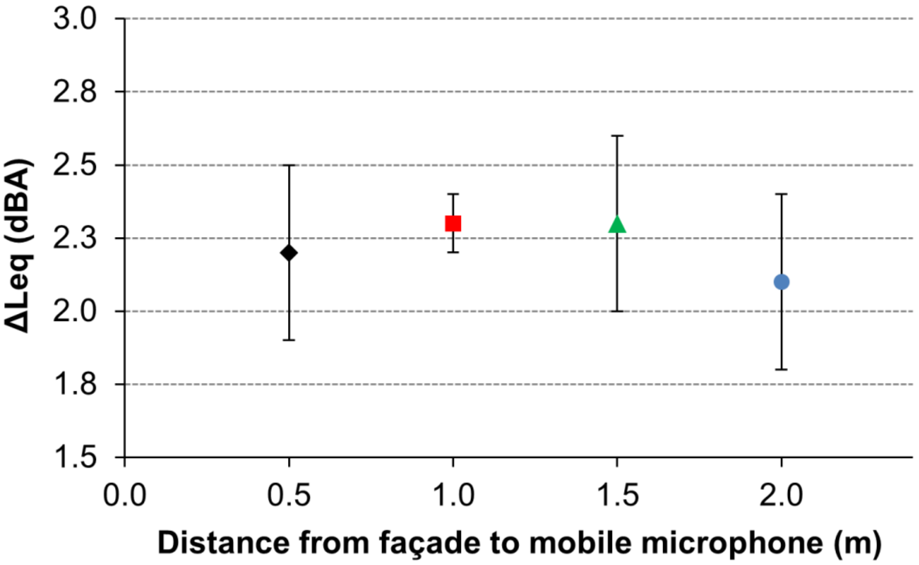


Fig. 3. Average and standard deviation of the differences in sound levels recorded by both microphones for each measurement configuration

As mentioned in the introduction, the ISO 1996-2 standard introduces certain corrections with respect to the free-field situation: 3 dBA for a microphone positioned at a distance of between 0.5 and 2.0 m from the façade, and 5.7 dBA for a microphone at a reflective surface (if the conditions of Annex B are met [23]). Therefore, since these conditions are fulfilled at this measurement point, the expected value for the difference in the equivalent sound level between the two microphone positions is 2.7 dBA (Eq. 1). Taking into account the average values shown in Fig. 3 for all the measurement configurations, variations of up to 0.6 dB are observed relative to the expected value. In view of the greatest value of 0.5 dB for the range indicated in Annex B of ISO 1996-2 for the standard uncertainty of corrections to the reflections of different microphone locations relative to vertical reflecting surfaces for road traffic noise incident from all angles, the average values of the differences between the equivalent sound levels obtained would be located at the lower limit, or even outside the specified range. From the standard deviations shown in Fig. 3, it can be seen that: a) the lower values are clearly below the expected range in three of the four measurement configurations; and b) the value of 2.7 dB is outside the range of variability found in any measurement configuration. However, if all sources of uncertainty included in the ISO 1996-2 standard (measuring system, meteorological conditions, etc.) were considered, the measurement uncertainty would be at least 1 dB. In any case, this variation with respect to the ISO 1996-2 standard indicates the need for future studies. It is important that studies are carried out using long-term measures and according to the requirements indicated in the standard. This would allow to compare results obtained at different sites, in order to conclude whether this bias is a feature of the site or of the ISO 1996-2 methodology.

An inferential statistical analysis comparing the average values between the different measurement configurations shows that the average differences found in the 2.0 m configuration (configuration 4) are statistically lower than in the other configurations (see Table 1).

Table 1. *P*-values for pairwise comparisons of configurations using a *t*-test for ΔLeq (dBA)

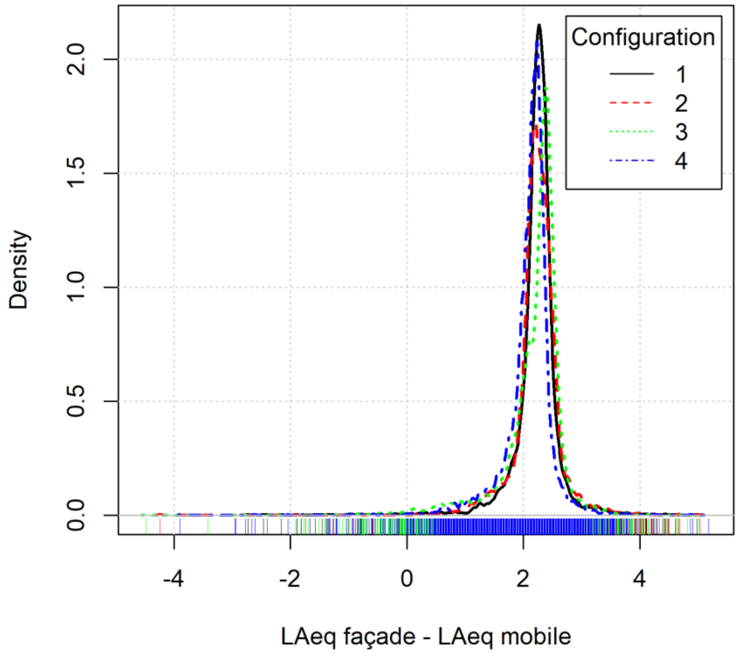
	Configuration	**1**	**2**	**3**
ΔLeq (dBA)	**2**	> 0.05	-	-
	3	> 0.05	> 0.05	-
	4	< 0.01	< 0.001	< 0.001

3.1.2. Distribution of sound differences

The average weekly sound levels were considered in the analysis carried out in the previous section, but these corrections may vary depending on the values of the sound levels and their temporality [38-45]. This aspect may be of interest in relation to the research line focused on dynamic noise maps [46-47]. A study of the statistical distribution of the differences in the sound levels measured by both microphones was carried out in order to analyse these possibilities, using an integration time of one minute, as used in the measurements. This allows to carry out a detailed analysis relative to both the time and the measured levels. It is therefore possible to find a structure related to the times at which the measurements were made or the values of the sound levels when the differences are analysed for a short integration time.

The distribution of the differences in sound levels was first analysed for each measurement configuration through the density function (Fig. 4). The values of the differences in sound levels are represented on the abscissa in Fig. 4, while the ratio of the values per unit variable (density) is on the ordinate. Therefore, if in a very small interval on the x-axis, for example, in a quarter of a dBA, there is more than a quarter of the data, more than 100% of the data per dBA unit is being reached in that area. When this occurs, the density exceeds the value 1.0 on the ordinate. It is possible to see from Fig. 4 that the density of the different measurement configurations exceeds the unit value in the range 2.0 to 2.5 dBA, meaning that the mode and the highest concentration of values of differences in sound levels between the two microphones for the different configurations are located in this range (Fig. 4).

a)



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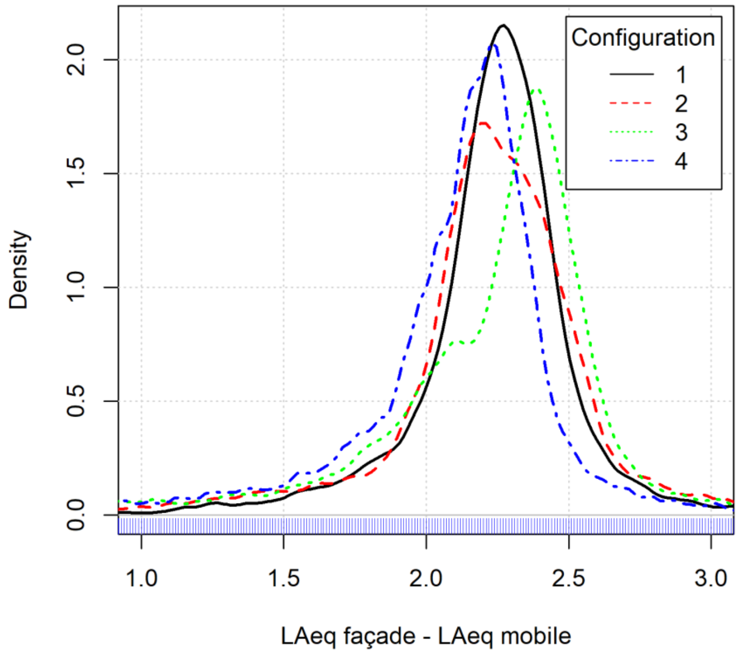

Fig. 4. Density of the differences in the sound levels registered by both microphones with an integration time of one minute over one week for each measurement configuration: a) 100% of the sound differences; b) sound differences between 1.0 and 3.0 dBA (95% of the data)

The distribution of the differences in sound levels for the different configurations seems similar (Fig. 4a). However, in a more detailed analysis in the range between 1.0 and 3.0 dBA (Fig. 4b), where more than 95% of the data were concentrated, differences between the different configurations can be observed. As a result, variations in the position of the maximum in the distribution and asymmetries can be seen.

In order to improve the understanding of these differences in the density of the different configurations (Fig. 4b), the distributions of the sound differences were then analysed based on the time interval (Fig. 5) and the value of the registered sound level (Fig. 6).

The differences in the sound levels measured by the two microphones in four intervals (1.0–1.5, 1.5–2.0, 2.0–2.5 and 2.5–3.0 dBA) are represented in Fig. 5 for each measurement configuration. As mentioned above, these intervals contain more than 95% of the total data. The ordinate in Fig. 5 represents the proportion of data in a given interval of differences considered that was measured in the time represented on the abscissa.

It should be noted that the frequency distributions shown in Fig. 5 are visually different depending on the range of differences considered (1.0–1.5, 1.5–2.0, 2.0–2.5 and 2.5–3.0 dBA) for all configurations. The range of time from 0:00 to 6:00 contains the lowest values of the differences between 1.0 and 2.0 dBA. The percentage within the 1.0 to 1.5 dB range is particularly notable. This result can be related to a previous study [18] that suggested that road traffic would cease to be the main source of noise during the night and that the sound level registered by microphones would correspond to urban background noise, which would influence the difference in the levels registered by both microphones. It should also be observed that the range 2.0 to 2.5 dBA is the most stable and uniform throughout the day for all configurations. In addition, it is interesting to note a small increase in the interval 2.5 to 3.0 dBA in the period of the day between 12:00 and 17:00. This is centred at 14:00 and corresponds to the period of the day with the highest traffic flow. This interval (2.5 to 3.0 dBA) also shows peaks at night, mainly in the configurations 1 (Fig. 5a) and 4 (Fig. 5d). In the latter configuration, the peak is higher than during the day. Finally, a comparison between the different measurement configurations shows that configuration 4 (Fig. 5d) has the most uniform distribution of differences throughout the day.

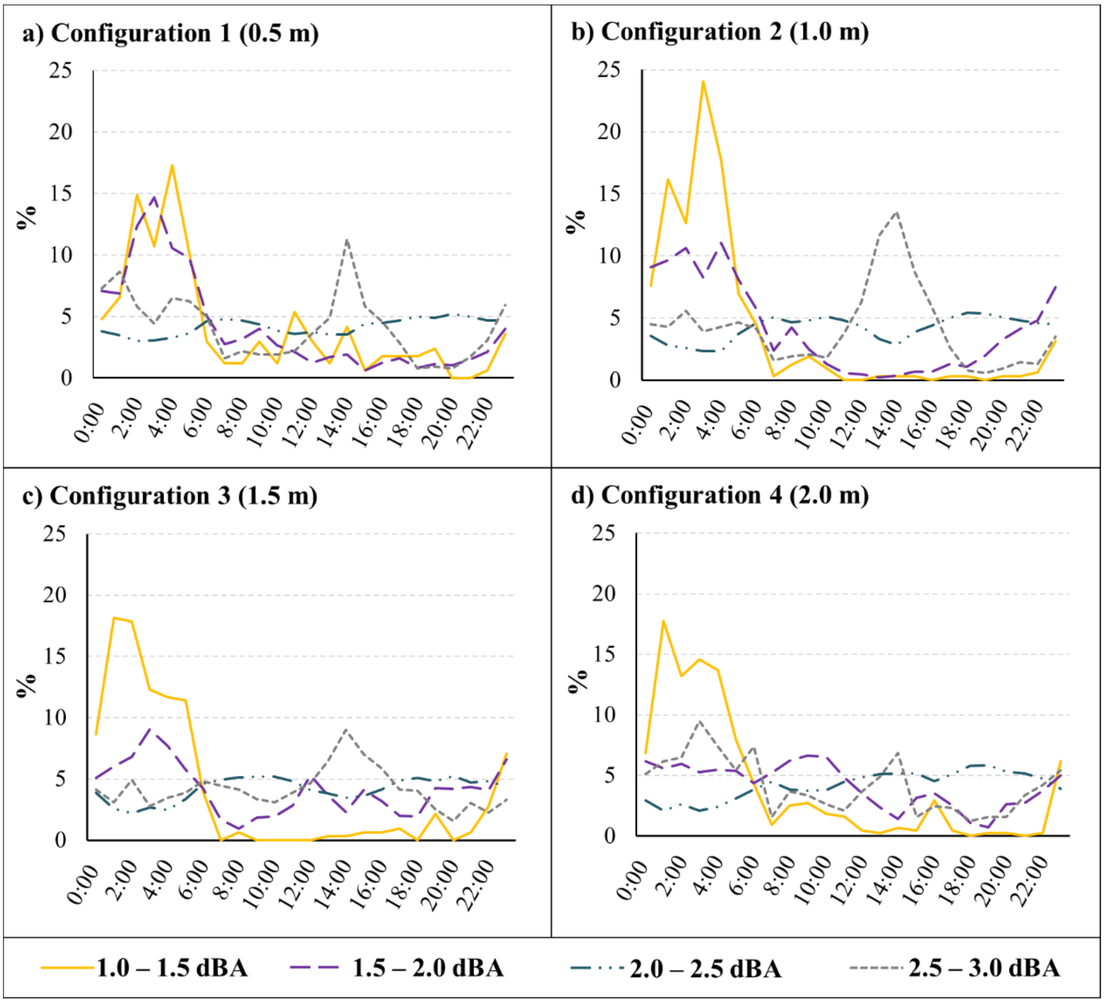

Fig. 5. Frequency distribution of the differences in sound levels registered minute by minute by both microphones with respect to the time interval of the day for each measurement configuration.

An analysis of the results in Fig. 5 suggests that the values of the measured sound levels may influence the differences found between both microphones. To analyse this possibility, Fig. 6 shows the proportion of data in the various ranges of sound level differences between both microphones (1.0–1.5, 1.5–2.0, 2.0–2.5 and 2.5–3.0 dBA), where the value of the sound level measured at the façade is represented on the ordinate.

Fig. 6 shows that for each of the measurement configurations, each difference interval (1.0–1.5, 1.5–2.0, 2.0–2.5 and 2.5–3.0 dBA) has a different frequency distribution depending on the values of the measured sound levels.

The differences in the range 1.0–1.5 dBA show a structure in which the greatest proportion of values fall into the range 30 to 45 dBA in all measurement configurations, reaching maximum values in the range 30–35 dBA. Between 30% and 50% of the measurements in which the difference between the two microphones is in the range 1.0–1.5 dBA are concentrated in this interval. These results are in accordance with those reported by Jagniatinskis et al. [18], and are related to the results shown in Fig. 5, in which the highest proportions of the lowest values of the differences in levels are registered from 0:00 to 6:00. In contrast, the range of differences 2.0–2.5 dBA shows a very high proportion in the range of measured values from 50–65 dBA in all measurement configurations. It also has a maximum in the range 55–60 dBA, with proportions varying between 40% and 50% of the data in the range of differences 2.0–2.5 dBA. Both intervals of differences (1.0–1.5 and 2.0–2.5 dBA) therefore show similar behaviour in all measurement configurations.

However, the difference ranges of 1.5–2.0 dBA and 2.5–3.0 dBA present a more variable frequency distribution than the previous ones depending on the sound level measured in the façade and the measurement configuration used. In particular, the range 2.5–3.0 dBA shows a behaviour that is similar to that shown in the range 2.0–2.5 dBA, but with significant percentages in the range of low measured values (30–45 dBA), especially in configuration 4 (Fig. 6d). This result seems to confirm those reported above, depending on the time of measurement; that is, low values of the sound levels can also cause differences in the range 2.5–3.0 dBA. On the other hand, the difference range 1.5–2.0 dBA contains high proportions for all configurations in the ranges 30–45 and 50–65 dBA.

If the results obtained for the different measurement configurations are compared, it can be seen that the extreme values of the range of differences (1.0–1.5 dBA) are typically found for low values of the measured sound levels in all configurations. In contrast, the highest values of the differences (in the range 2.5–3.0 dBA) are mainly found in the range of measured values of 50–65 dBA, although it is not negligible the proportion in the range of low sound levels (35–45 dBA) in configuration 4.

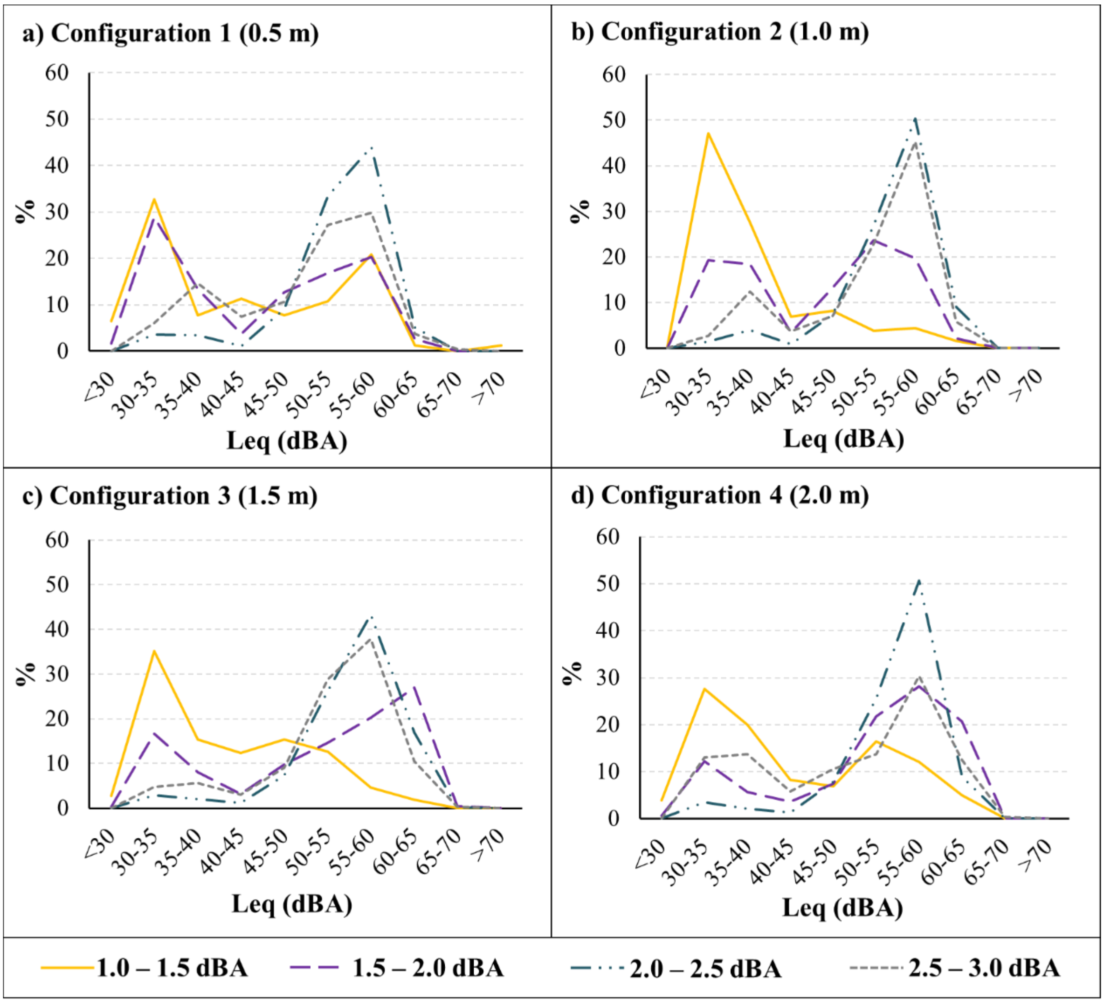

Fig. 6. Frequency distribution of the of the sound differences measured minute by minute over one week with respect to the sound levels measured at the façade for each measurement configuration.

Regarding the measurement with a microphone mounted on the façade, the broadband analysis revealed that measurements carried out with microphones at different distances from the reflecting surface differ from those indicated by the ISO 1996-2 standard. This analysis also demonstrated that the distance at which the microphone is placed influences the result. A detailed temporal analysis shows that the lower values of the differences in sound levels measured by both microphones are concentrated at night in all configurations. It also can be concluded that it is particularly configuration 4 shows the greatest temporal stability of the differences. Furthermore, when the differences are related to the values of the measured sound levels, it was clearly detected that the lowest values of the differences are found for the lowest sound levels (30–45 dBA). On the other hand, when the differences are around the distribution modes (Fig. 4), the values of the sound levels are in the range 50–65 dBA.

3.2. Spectral results

The general frequency range proposed by the ISO 1996-2 standard includes the octave bands between 63 Hz and 8 kHz. However, for the case in which a microphone is placed directly on a surface, Annex B of ISO 1996-2 indicates that a 6 mm microphone should be used for octave-band measurements if the frequency range is expanded above 4 kHz. Therefore, given that Brüel & Kjær 4950 microphones of the sound level meters used in this studio are 13 mm in diameter, a spectral study was carried out in octave bands between 63 Hz and 4 kHz (Fig. 7).

The spectrum of the differences between the two microphones used in each of the four configurations studied in the frequency range 63 Hz–4 kHz (Fig. 7) shows statistically significant differences between all pairs of configurations studied, as revealed by a multivariate analysis of variance (MANOVA) (Table 2).

Table 2. MANOVA for ΔLeq (dB) in octave bands between pairs of configurations

Configurations	**Pillai's value**	**F**	***P*-value**
1–2	0.95	815.78	< 0.001

1–3	0.90	363.06	< 0.001
1–4	0.83	210.26	< 0.001
2–3	0.86	265.57	< 0.001
2–4	0.66	83.32	< 0.001
3–4	0.63	71.13	< 0.001

If octave bands are independently examined (Fig. 7), several results of interest can be found.

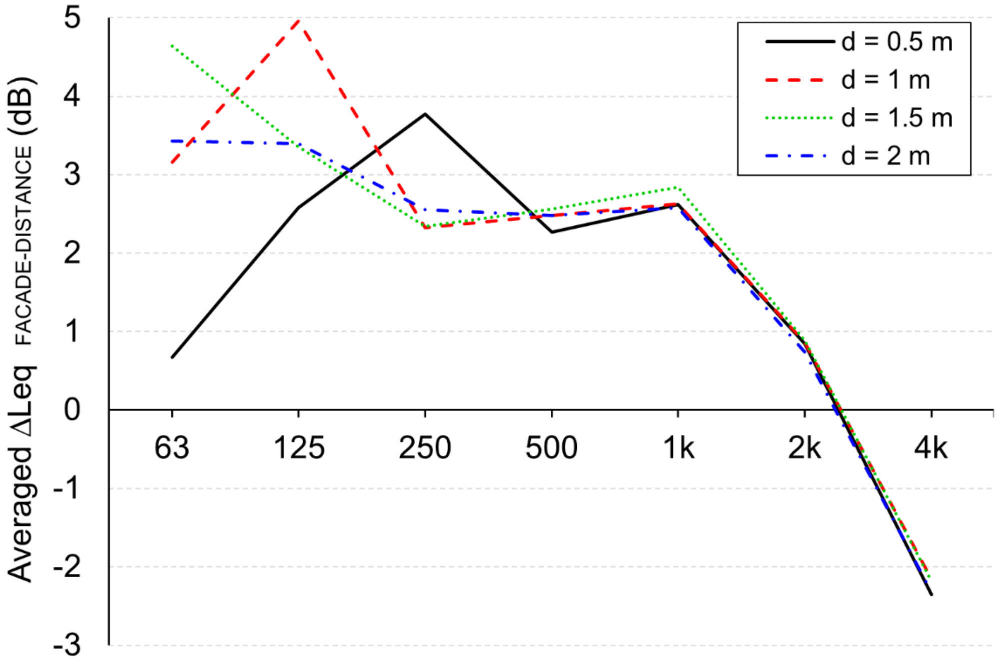

Fig. 7. Average difference in equivalent sound level between both microphones in frequency octave bands

When the high-frequency zone is evaluated, a very significant high negative in the differences between the two microphones can be observed at 4 kHz, regardless of the measurement configuration. In fact, this negative value indicates that the microphone located at a certain distance from the façade measures a higher sound level than that mounted at the façade. Since this result is the same for all four configurations, this minimum would be related to the existence of a destructive interference for a high frequency for the microphone located at the reflecting surface. In addition, it can also be noted that the value of the differences between the two microphones at a frequency band of 2 kHz is different in all configurations from the expected value of 2.7 dB based on the ISO 1996-2 standard. Therefore, both for the 4 kHz and 2 kHz bands, the location of a microphone at the façade would cause the incident sound levels for buildings to be assessed at a lower level than the real value, meaning that the doses of noise received at the façades at these frequencies would be underestimated. Variations in these frequencies influence the broadband levels in dBA that are used to determine the effects of sound exposure on the health of the resident population.

Table 3. *P*-values for pairwise comparisons of configurations using a *t*-test for ΔLeq (dB) in octave bands

ΔLeq (dB)	**Configuration**	**1**	**2**	**3**
63 Hz	**2**	< 0.001	-	-
	3	< 0.001	< 0.001	-
	4	< 0.001	> 0.05	< 0.001
125 Hz	**2**	< 0.001	-	-
	3	< 0.001	< 0.001	-
	4	< 0.001	< 0.001	> 0.05
250 Hz	**2**	< 0.001	-	-
	3	< 0.001	> 0.05	-
	4	< 0.001	< 0.001	< 0.001
500 Hz	**2**	< 0.001	-	-
	3	< 0.001	< 0.001	-
	4	< 0.001	> 0.05	< 0.001
1 kHz	**2**	> 0.05	-	-
	3	< 0.001	< 0.001	-
	4	> 0.05	> 0.05	< 0.001
2 kHz	**2**	> 0.05	-	-
	3	> 0.05	> 0.05	-

	4	> 0.05	< 0.001	< 0.001
4 kHz	**2**	> 0.05	-	-
	3	> 0.05	> 0.05	-
	4	> 0.05	> 0.05	> 0.05

Turning to the low- and medium-frequency range, from an analysis of the results shown in Fig. 7 it can be concluded that both destructive and constructive interference phenomena can occur at the microphone located at a certain distance from the façade depending on the selected distance. A destructive interference phenomenon is found for configurations 1, 2 and 3 at frequencies that depend on the distance between the microphone and the reflecting surface. At a distance of 0.5 m (configuration 1), a maximum value of the difference in the sound levels is obtained at 250 Hz. This maximum occurs at 125 Hz for configuration 2 and 63 Hz for configuration 3. For configuration 4, in which the microphone is located 2.0 m from the façade, this maximum does not appear. This result is related to that specified by the ISO 1996-2 standard in Annex B (informative) with regard to the appearance of coherence effects at low frequencies and the recommendation of a minimum distance of 1.6 m for measurements in octave bands. However, it is shown in Fig. 7 that for an octave band of 63 Hz at a distance of 1.5 m, detectable interference remains between the direct and reflected sound waves. On the other hand, a decrease in the differences can be seen at low frequencies in terms of the appearance of constructive interference. This is detected at 63 Hz in the case of configuration 1, and must be related to the existence of constructive interference at 0.5 m between the direct and reflected waves from the façade. These results are also linked to the interference effects of waves reported in research by Quirt et al. [17] and Hopkins et al. [48].

An analysis of the results for the frequency bands in Table 3 concerning the significance of the differences shows that: a) the low-frequency bands from 63 Hz to 500 Hz generally show significant differences in most of the comparisons we can make between pairs of configurations; b) in the medium-frequency bands between 500 Hz and 1000 Hz, the 500 Hz band shows a behaviour in terms of the significance of the differences that is similar to that at low frequencies when configurations are compared; and the 1 kHz band behaves in an intermediate way between the low- and high-frequency bands; c) in general, the high-frequency bands of 2 and 4 kHz do not show significant differences for the different configurations.

Based on the results of the above analysis of the spectrum of differences, prior works concerning the suitability of the use of A-weighting to assess the annoyance of environmental noise [29,31] and the possibility that A-weighting is a poor predictor of annoyance due to low-frequency noise [30,33], it is of interest to assess the influence of the range frequencies considered in the measurements, as indicated in ISO 1996-2 standard, and the use of weighting in the evaluation of continuous equivalent sound levels. Table 4 below shows the average difference in equivalent broadband sound levels for the different octave frequency band ranges, in dB, dBA and dBC.

If the same analysis is carried out by configuration, it can be observed that configuration 1 differs from the others in all low-frequency bands up to 500 Hz. Configuration 2 differs from configuration 3, and configuration 3 from configuration 4 generally at low and medium frequencies.

Table 4: Differences in equivalent broadband levels obtained at different frequency ranges and with different frequency weightings (Z, A and C)

Config.	**Frequency ranges for ΔLeq**		
	63–8000 Hz	**63–4000 Hz**	**125–4000 Hz**

	Z (dB)	A (dBA)	C (dBC)	Z (dB)	A (dBA)	C (dBC)	Z (dB)	A (dBA)	C (dBC)
1	1.5	2.2	1.5	1.5	2.2	1.5	2.6	2.2	2.6
2	3.1	2.3	3.1	3.1	2.3	3.1	3.0	2.3	3.0
3	3.6	2.3	3.5	3.6	2.3	3.5	2.7	2.3	2.7
4	3.0	2.2	3.0	3.0	2.2	3.0	2.6	2.2	2.6

It is worth noting that for A-weighting, there are no variations between the differences of the measured sound levels in both microphones for any of the configurations analysed when the 8 kHz or 63 Hz bands are eliminated (Table 4). In addition, a strong similarity between the results obtained using linear or C-weighting can be noted.

If now the linear and C configurations are analysed, Table 4 shows that removing the 8 kHz band has no detectable effect on the global level in any configuration when these weightings are used. This is undoubtedly associated with the low sound energy of the 8 kHz band in the measured noise spectrum. However, if the 63 Hz band is eliminated, an important effect arises, indicating that the sound energy in that frequency band is important for the measured noise. In configuration 1, the variation between the global values is greater than 1 dB, and this is probably associated with the existence of a constructive interference in the 63 Hz band for the microphone located 0.5 m from the façade. This variation is only 0.1 dB for configuration 2, probably due to the great weight of destructive interference for the microphone located at 1.0 m at a frequency of 125 Hz. For configuration 3, the difference is a decrease of slightly less than 1 dB, and this must be associated with destructive interference at that frequency in the microphone located at 1.5 m from the façade. Finally, a moderate decrease in the difference of 0.4 dB between microphones is still detected for configuration 4, due to the weight of this band in the global differences.

The variations in the low- and medium-frequency range shown in Fig. 7 are therefore transferred to the overall results using linear weighting. This effect is stronger in configurations 1 and 3. However, all the differences detected according to the considered spectral range do not appear when A-weighting is applied. Consequently, the attenuation due to the use of A-weighting in the weights of low frequencies eliminates the differences in the spectrum that arise when measurements are carried out at different distances from the façade. Therefore, if the evaluation of the noise doses received at low frequency is of interest and the use of C-weighting is adequate, the location of the microphone with respect to the façade may be of great relevance based on the effects that arise [32,33] or if the possible problems analysed in the introduction due to the use of A-weighting [10, 29-31] are taken into account.

Despite the important differences between the results obtained in this analysis of the noise spectrum for the octave bands in the range 63 Hz to 500 Hz, as a conclusion of this study it can be pointed out that for the measurement of traffic noise, given its spectrum and the effects of A-weighting, if somebody wishes to assess the overall noise level incident on the façade, the range 0.5 to 2 m indicated by the ISO 1996-2 standard for location of the microphone leads to similar results. In the present study, the differences between the façade and mobile microphones are found to be always in the low range of the error interval indicated by the standard.

If the spectral characteristics of the measured noise are different from traffic noise, the distance between the façade and the location of the microphone may become relevant. In this case, measurement at 2 m would be the best option, especially if low frequency noise is expected. In addition, in order to accurately assess the sound level incident on the façade, both in terms of the overall values and the spectrum, the effects detected in the measurements with a microphone mounted on the façade suggest that the most appropriate option is to place the microphone at 2 m from the façade, as well as meeting the indications given by the ISO 1996-2 standard.

4. CONCLUSIONS

An analysis was carried out in this study of the differences between the sound values measured in broadband and octave bands by a microphone placed at a certain distance from the façade (0.5, 1.0, 1.5 and 2.0 m) and another placed at the façade. Measurements were made over one week for each configuration following the guidelines of ISO 1996-2 standard for the microphone locations relative to reflecting surfaces (Annex B).

The following results were obtained from the broadband analysis of the differences in the measured sound levels:

a) Under the conditions of this study, average differences in sound levels experimentally determined were lower than the expected value of 2.7 dBA indicated by the ISO 1996-2 standard. These differences were found at the lower limit of uncertainty, or even outside the range indicated by the ISO 1996-2 standard. Considering the standard deviation, these average differences did not include the value of 2.7 dB.

b) An analysis of these differences and the sound levels recorded with the façade microphone showed that the smallest differences were found when the sound levels were lowest (30–45 dBA). However, the differences were around the average values when the measured sound levels were in the range 50–65 dBA.

c) It was detected in this study that the smallest differences (1.0-1.5 dB) between the sound levels measured by the microphone mounted on the façade and the microphone located at different distances are concentrated in the night time between 1:00 and 6:00, when the flow of vehicles decreases.

From the analysis of the differences in octave bands, the following conclusions can be drawn:

a) Significant differences were found between the configurations in terms of octave bands. Variations greater than 2 dB were obtained in the bands of 63, 125 and 250 Hz, which were associated with constructive or destructive interference phenomena depending on the distance from the microphone to the façade. It is therefore important that the measurement configuration is taken into account in the assessment of the doses of noise in low frequencies.

b) Destructive interference phenomena were detected at the façade microphone in the octave bands of 2 and 4 kHz. This indicates that the dose of noise received would be underestimated at these frequencies for this measurement location.

c) For traffic noise, the use of A-weighting eliminates the effects of the differences in the spectrum when the global results are analysed. However, if a C-weighting is used, the variations in the spectrum are transferred to the broadband noise.

Finally, considering the results of this work and the distance range established in ISO 1996-2 for the position of the microphone in front of the reflecting surface, a microphone location of 2 m from the façade can be considered the best option for an accurate evaluation of the sound level incident on the façade if the indications of the ISO 1996-2 standard can be met.

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