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Evaluation of Measurement Uncertainties of the D_{2S} in Open-Plan Offices

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ABSTRACT

Measuring the acoustic performance of open-plan offices is an increasingly important issue for companies and employees. Indeed, it has been highlighted in several studies that noise in such workplaces reduces employees' performance and makes them be unsatisfied with their work environment. This is especially important for conversational noise. The ability of a room and its layout to reduce conversational noise can be assessed using acoustic indicators and in particular the D_{2S} (spatial decay of the A-weighted level of a speech signal when doubling the distance from the source on a line passing over workstations). This indicator is now widely used in the field because it is recommended by several national standards that give values to be achieved. However, to date, there are no studies that discuss the accuracy of a measurement in an office. The purpose of this presentation is to provide an analysis of the measurement uncertainties for this indicator. To that end, the measurement principle of D_{2S} will be presented as well as an analysis of uncertainties based on their theoretical developments. This analysis will be conducted using real cases (measurements) and simulated cases using a room acoustics software.

Keywords: Open-Plan Office, Uncertainties, D2S, Speech, ISO 3382-3

1. INTRODUCTION

Noise in open-plan offices represents one of the greatest issues for these workplaces. Indeed, it has been highlighted that the acoustic environment of open-plan offices reduces the employees' performance as well as their job satisfaction (1). Furthermore, among all noise sources, conversational noise has the biggest impact on performance (2) and constitutes the biggest source of annoyance caused by the acoustic environment (3,4). Therefore, it appears that the way the office (meaning the room and the furniture) influences conversational noise plays a major role in its acoustic quality.

The ISO 3382-3 (2012) standard (5) introduced an acoustic index which characterizes the spatial decay of speech across workstations: D_{2S}. More precisely, D_{2S} is defined as the decrease of the A-weighted level of a speech signal when doubling the distance from the source on a line passing over workstations. D_{2S} has then been used in many national standards (6,7) which prescribe required values.

Yadav et al. (8) evaluated the reliability and repeatability of the D_{2S}, but, to our knowledge, no study was devoted to the measurement uncertainties of this index. Therefore, the goal of this study is to evaluate such measurement uncertainties and to determine their influencing factors.

2. MEASUREMENT OF THE D_{2S} INDEX

2.1 Measurement principle

When measuring speech spatial decay, the first step is to determine a measurement path. This line must run from workstation to workstation, each of these workstations constituting a point of measurement. Two examples of paths are represented on the left-side of Figure 1. The ISO 3382-3 (2012) standard proposes a method to evaluate the A-weighted level that would have been measured at the different workstations if the noise emitted by the source had a speech-like spectrum (noted $L_{p,A,S}$ in the standard but called L_i thereafter). D_{2S} is then calculated as the slope of the linear

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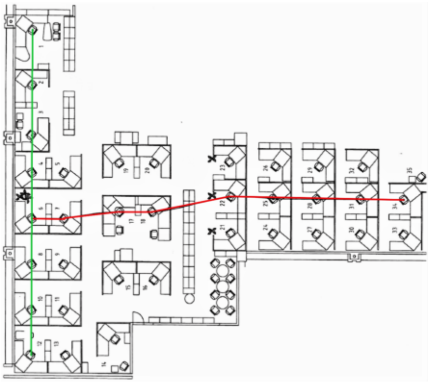
regression (using the least mean square method) of the A-weighted level of speech as a function of the distance from the source to the points of measurements (expressed on a logarithm scale – see the right-side of Figure 1). The calculation of D_{2S} given in the standard can be performed using equation 1.



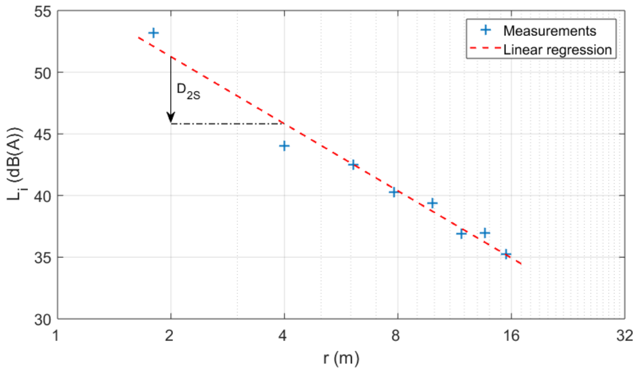


Figure 1: Examples of measurement paths from the ISO 3382-3 (left) and measurements realized in an open-plan office (right)

$$D_{2,S} = -\frac{N \cdot \sum\left(L \cdot \log_2(r)\right) - \sum L \sum \log_2(r)}{N \cdot \sum \log_2(r)^2 - \left(\sum \log_2(r)\right)^2} \qquad \text{(eq. 1)}$$

2.2 Measurements used for the study

For this study, D_{2S} values were measured in 8 open-plan offices, resulting in 21 paths of measurement. The 21 measured values are summarized in Figure 2. These values are comprised between 3.8 dB(A) and 7.4 dB(A) and their paths were constituted of 4 to 10 points of measurements in accordance with the ISO 3382-3 (2012) standard.

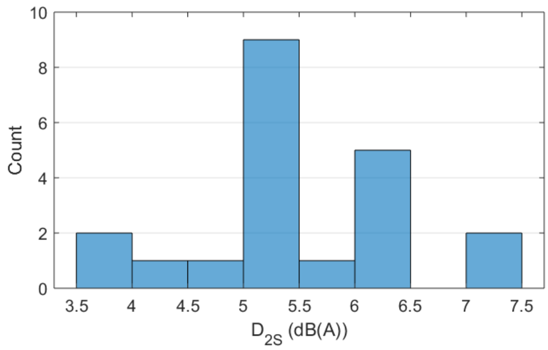


Figure 2: Measured values of the D_{2S}

3. EVALUATION OF THE MEASUREMENT UNCERTAINTIES

The Joint Committee for Guides in Metrology issued guidelines for the evaluation of measurement uncertainties (9). According to this document, the uncertainty made on the evaluation y of a measurand Y is obtained by combining the uncertainties of each input used to evaluate Y. In the case of D_{2S} (for a path constituted of N workstations), these inputs are composed of measurements of distances and sound pressure levels, resulting in equation 2 which enables to estimate the measurement uncertainty of the D_{2S}. The measurement uncertainty of the index depends on its first-order derivatives with respect to distances ($\partial D_{2S}/\partial r_i$) and speech levels ($\partial D_{2S}/\partial L_i$) but also on the measurement uncertainties of distances (σ_{r_i}) and speech levels (σ_{L_i}).

$$\sigma_{D2S}^2 = \sum_{i=1}^{N} \left(\frac{\partial D_{2S}}{\partial r_i} \cdot \sigma_{r_i} \right)^2 + \sum_{i=1}^{N} \left(\frac{\partial D_{2S}}{\partial L_i} \cdot \sigma_{L_i} \right)^2 = \sigma_{D2S}^2(\vec{r}) + \sigma_{D2S}^2(\vec{L}) \qquad \text{(eq. 2)}$$

This expression being the result of a first-order Taylor series approximation, guidelines precise that if the dependence of the measurand on inputs is significantly non-linear, it becomes necessary to include higher-order partial derivatives to the expression presented on equation (2).

3.1 Uncertainties due to the measurement of speech levels

To evaluate the uncertainties due to speech level measurements ($\sigma_{D2S}^2(\vec{L})$ in (eq. 2)), it is required to assess the uncertainties of speech levels measurements σ_{L_i} but also the partial derivatives of the D_{2S} with respect to L_i.

The derivative of the D_{2S} with respect to speech level, which expression is given by equation 3, does not depend on the level. Given the linearity of the D_{2S} with respect to speech level, the expression of $\sigma_{D2S}^2(\vec{L})$ is only composed of first-order derivatives and stays accurate regardless of the uncertainties made in measuring the speech level.

$$\frac{\partial D_{2S}}{\partial L_i} = -\frac{N \cdot \log_2(r_i) - \sum \log_2(r)}{N \cdot \sum \log_2(r)^2 - (\sum \log_2(r))^2} \qquad \text{(eq. 3)}$$

Speech levels are directly derived from measurements of octave-band levels. Therefore, the evaluation of their measurement uncertainties is based on the uncertainties of octave-band level measurements. The IEC 61672-1 (2002) standard (10) defines two classes of sound level meters based, in part, on tolerance limits for the measurement uncertainties of third-octave band levels. The measurement uncertainty of octave-band levels are defined from these limits, depending on the class of the sound level meter used to measure the D_{2S}. These limits are given in table 1.

Table 1 – Measurement uncertainties (σ_{oct} in dB) of octave-band levels for the two classes of sound level meters

Octave band	Class 1	Class 2
125 Hz	1.1	1.3
250 Hz	1.0	1.2
500 Hz	1.0	1.2
1000 Hz	0.8	0.9
2000 Hz	1.1	2.0
4000 Hz	1.1	2.0
8000 Hz	1.8	3.1

The measurement uncertainties of speech level is then evaluated with the same method as previously, resulting in the equation 4. In this case, the accuracy of the approximation has to be verified because the overall level is non-linear with respect to the octave-band levels.

$$\sigma_{L_i}^2 = \sum \left(\frac{\partial L_i}{\partial L_{i,oct}} \sigma_{oct} \right)^2 = \sum \left(\frac{10^{L_{i,oct}/10}}{10^{L_i/10}} \cdot \sigma_{oct} \right)^2 \qquad \text{(eq. 4)}$$

To assess the precision of this estimation, the result obtained using the equation 4 was compared to the one obtained from a Monte-Carlo method (11) on 137 measurements realized in several open-plan offices. This method consists in adding a random error on measured octave-band level. The dispersion of the overall levels obtained from this error sampling is equal to the real uncertainty.

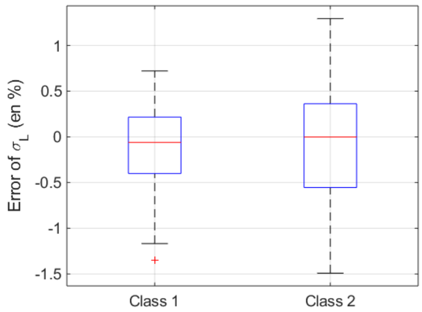


Figure 3: Error in the evaluation of σ_L for the two classes of sound level meters

The result obtained for this comparison are presented on Figure 3, for the two classes of sound level meters.

For both class of sound level meters, the evaluation of measurement uncertainties of the speech level made using (eq. 4) seems to be very accurate: the absolute value of the error was less than 2% for the 137 measurements realized in various open-plan offices.

In an effort to simplify the expression of $\sigma^2_{D2S}(\vec{L})$, some manipulation were made on equation 2. Equation 5 was obtained, where Var and Cov represent respectively the variance and the covariance of the variable(s).

$$\sigma^2_{D2S}(\vec{L}) = \frac{1}{N \cdot Var(\log_2(r))^2} \cdot Cov\left(\log_2(r) - \overline{\log_2(r)}, \left(\log_2(r) - \overline{\log_2(r)}\right) \cdot \sigma^2_L\right) \quad (5)$$

3.2 Uncertainties due to the measurements of distances

Evaluating the uncertainties in the D_{2S} evaluation caused by the measurements of distances $\sigma^2_{D2S}(\vec{r})$ requires to assess the uncertainties of distance measurements σ_{r_i} but also the partial derivatives of the D_{2S} with respect to r_i.

The derivative of the D_{2S} with respect to the distance is obviously non-linear and its expression is given by equation 6.

$$\frac{\partial D_{2S}}{\partial r_i} = \frac{-1}{\log(2)} \cdot \frac{N \cdot L_i - \sum L + 2 \cdot D_{2S}(N \cdot \log_2(r_i) - \sum \log_2(r))}{[N \cdot \sum \log_2(r)^2 - (\sum \log_2(r))^2] \cdot r_i} \quad (6)$$

To assess the distance measurement uncertainty, two hypotheses are made. Firstly, the error is assumed to follow a normal distribution centered on the true value of the distance to be measured. Secondly, the error is assumed to be independent of the distance. From these hypotheses, the distance measurement uncertainty is characterized by one parameter, the half-length of the 95% confidence interval, thereafter called d, following the expression given by equation 7.

$$\sigma_{r_i} = \sigma_r = \frac{d}{\sqrt{2} \cdot erf^{-1}(0.95)} \approx \frac{d}{1.96} \quad (7)$$

As D_{2S} is significantly non-linear with respect to the distances from the noise source, it is necessary to evaluated the accuracy of the expression of $\sigma^2_{D2S}(\vec{r})$ for different values of d. The uncertainties resulting from the distance measurement uncertainty were evaluated (using equations 2, 6 and 7) for 21 in situ measurements of D2S realized in various open-plan offices. These evaluations were compared to the real measurement uncertainties, estimated using a Monte-Carlo method (consisting in adding a random error to the measured distances). The result of this comparison presented on Figure 4.

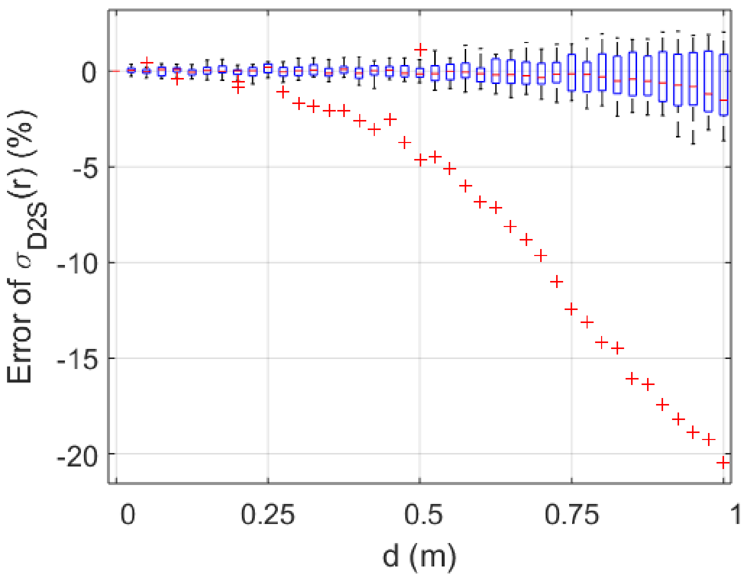


Figure 4: Error in the evaluation of $\sigma_{D2S}(\vec{r})$ for different d

Figure 4 indicates that as long as d stays below 50 cm, the evaluation of $\sigma_{D2S}(\vec{r})$ remains accurate (absolute value of the error below 5%). This limitation is not very restrictive because it is considered that with the current measuring equipment (laser range finder), it is easy, in an open office, to estimate the distance with an error of less than 50 cm.

In an effort to simplify the expression of $\sigma^2_{D2S}(\vec{r})$, some manipulations were made on equation 2. The result is presented in equation 8, where Var and Cov represent respectively the variance and the covariance of the variable(s).

$$\sigma^2_{D2S}(\vec{r}) = \frac{1}{N \cdot \mathrm{Var}(\log_2(r))^2} \cdot \frac{\sigma_r^2}{\log(2)} \cdot \mathrm{Cov}\left(\alpha - \overline{\alpha}, \frac{\alpha - \overline{\alpha}}{r^2}\right) \tag{8}$$

$$\text{Where } \alpha = L + 2 \cdot D_{2S} \cdot \log_2(r)$$

4. MEASUREMENT UNCERTAINTY OF D_{2S}

Finally, the total measurement uncertainty of D_{2S} was estimated using the abovementioned expressions for various values of d and for the two classes of sound level meters. Obtained values approximatively correspond to the half-length of the 95% confidence intervals of the corresponding measurement. The results are represented on Figure 5, in which each line correspond to a single D_{2S} measurement.

The principal observation that can be made from Figure 5 is that the expanded measurement uncertainty of D_{2S} remains of reasonable value: for both classes of sound level meters, it stays below 1 dB as long as the error made on distance measurement is less than 25 cm.

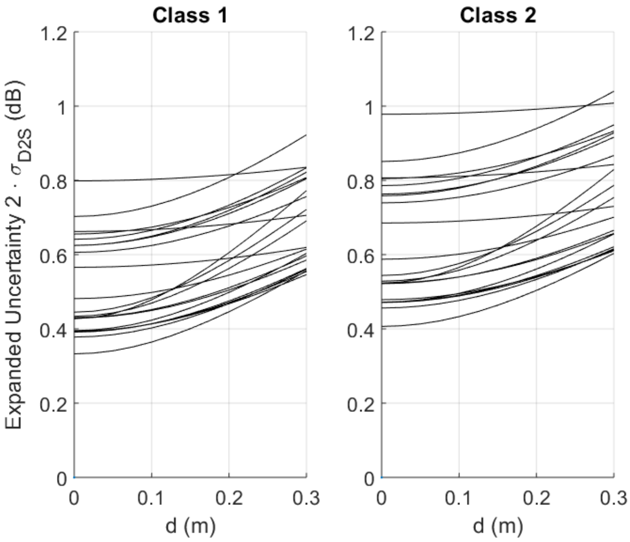


Figure 5: Expanded measurement uncertainty of D_{2S}

5. CONCLUSION

In this paper, a theoretical expression of D_{2S} measurement uncertainty was derived, depending on the measured speech levels and distances from the noise source. The validation of this expression was realized using a Monte-Carlo method on *in situ* measurements ranging from 3.5 dB(A) to 7.5 dB(A).

The first results indicate that the measurement uncertainty of D_{2S} is less than 1 dB(A) for both classes of sound level meters as long as the distance measurement uncertainty is less than 25 cm.

To complete this study, the expression of the D_{2S} measurement uncertainty must be validated on a wider range of D_{2S} and a parametric analysis will be carried out aiming to identify key factors that strongly influence the measurement uncertainty of the D_{2S}.

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