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2aEA7. Calibration of smartphone-based devices for noise exposure monitoring: methodology, uncertainties of measurement and implementation

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Standardized noise exposure campaigns face challenges such as high cost of instrumentation and other difficulties associated with practical deployment in the field. Our ongoing research evaluates the suitability of an alternate solution based on smartphone sensing: the occupational noise exposure and its associated measurement uncertainties are estimated from a spatio-temporal analysis of smartphones' noise measurements and GPS data. This paper presents a laboratory free field calibration method for any noise dosimeter application on smartphone-based device. The proposed calibration procedure includes a frequency response linearization and an A-weighted sound level correction which is a function of the C-weighted minus A-weighted (C-A) noise levels values and A-weighted noise level. To ensure a realistic calibration, noise sources used during the measurement are based on the distribution of a referenced industrial noise database. The methodology of the measurements and the calculation of combined uncertainties associated with the measured correction values are detailed. The interpolation of calibration values and their implementation in an Android app, developed by the authors, is also presented.

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CALIBRATION OF SMARTPHONE-BASED DEVICES FOR NOISE EXPOSURE MONITORING: METHODOLOGY, UNCERTAINTIES OF MEASUREMENT AND IMPLEMENTATION

Context

Noise-induced hearing loss is the most common work-related injury in Canada and the United States. In the US, the estimated annual cost for workers' compensation for hearing loss disability is 242 million dollars [1]. In order to reduce hazardous noise from the workplace, hearing loss prevention programs that include noise assessments are recommended; however, these campaigns aren't without disadvantages. Standardized noise exposure campaigns face challenges such as high cost of instrumentation and other difficulties associated with practical deployment in the field. Our ongoing research evaluates the suitability of an alternate solution based on smartphone sensing: the occupational noise exposure and its associated measurement uncertainties are estimated from a spatio-temporal analysis of smartphones' noise measurements and GPS data. In order to assess the accuracy of the noise measurements and the uncertainties associated with the field measurements, the first step is to investigate and evaluate the initial smartphone application calibration procedure. The calibration of most of the sound level meter smartphone applications available on distribution platforms depends on manually adjusting the sensitivity when comparing the readings to those made with a professional sound level meter. Despite the fact that all apps come pre-calibrated, the correction value is often unique and independent to each phone model which makes the field calibration an essential step in the process. The NoiseTube app [2] approach depends on a model-dependent calibration correction. The database, implemented in the application, provides correction values for each smartphone model that was tested in laboratory. This approach is particularly valuable when working with Android™ operating system applications as the latter is compatible with multiple phone models. This paper presents a laboratory free field calibration method for any noise dosimeter application on smartphone-based device. The proposed procedure includes :

- a frequency response linearization
- an A-weighted sound level correction, that is function of the C-weighted minus A-weighted (C-A) noise levels values and the noise levels

First, the methodology and hypothesis of the measurements are detailed. Second, the analysis of frequency response linearization measurement is detailed. Third, the measured calibration correction values and the calculation of their associated uncertainties are presented. Fourth, the interpolation of calibration corrections values and their implementation in the Android™ app, developed by the authors, are introduced. Finally, future works and ongoing measurements are outlined in a discussion section.

Methodology and Hypothesis of the Measurements

Instrumentation Used

Measurements are currently taking place in a 211 m^3 semi-anechoic chamber at the École de Technologie Supérieure in Montreal (Canada). The reference system consists of a Bruel & Kjaer (type 4190) 1/2-inch free-field microphone [3] and National Instrument (NIPXI-1033) 24-Bit acquisition card [4]. The errors associated with the data acquisition and the digital conversion of the signal (quantization error, system noise, offset error,...) are assumed to be negligible. The calibration of the reference system is performed with an acoustical calibrator [5]. The smartphone-based device under test includes the following elements :

- a smartphone embedded microphone
- an Android application called WikiLeq, developed by the authors [6].

The WikiLeq app processes the signal from the microphone at the sampling frequency of 22050 Hz and calculates dB, dB(A) and dB(C) values every second, $L_{\text{eq,1sec}}$. Audio processing features available on Android devices such as automatic gain control are disabled. L_{eq} calculations, A and C weighting filters are implemented according to IEC 61672 [7] standard specifications.

Test Setup

As seen in Figure 1, a powered speaker is positioned on the floor in one corner and directed towards the ceiling with an approximate 45 degree angle with the horizontal. In order to limit reflections from the floor, fiberglass panels are placed on the floor between the speaker and the movable walls. With the ventilation and lighting set normally, the ambient noise was measured below 50 dB for any octave band, therefore its variations do not affect noise measurements. Both small variations in temperature and atmospheric pressure and variations of the microphones' placement during installation are assumed to have no impact on the noise level measurements. The reference microphone and the smartphone-based device are positioned side by side 1.5 meters away from the speaker and 1 meter away from the closed pyramid shaped ceiling piece. Both the microphone and the smartphone-based device were positioned with their microphone diaphragms pointing towards the speaker so that normal incident sound on the microphone membrane is considered.

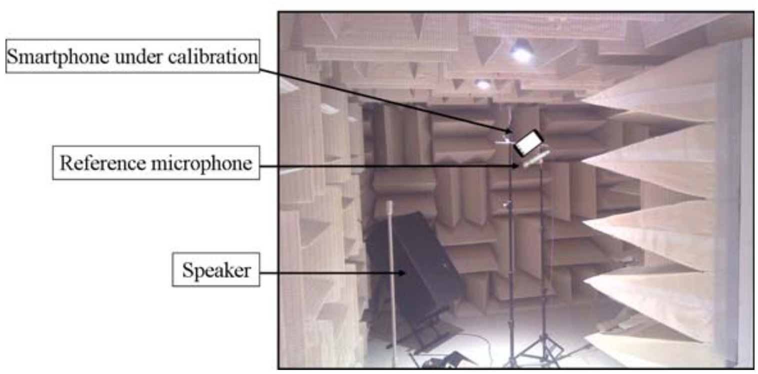

FIGURE 1: Setup of the calibration measurement in the anechoic chamber showing the smartphone under calibration, the reference microphone and the powered speaker

Frequency Response Linearization

The frequency response linearization consists of applying a digital filter on the smartphone microphone signal in order to correct its non-flat frequency response. A 30-second pink noise is emitted with a noise level of 85 dB(A) measured by the reference system. A frequency response of the transfer function with the phone signal as the input and the reference signal as the output is calculated using the dual channel FFT analysis. A finite impulse response filter (FIR) is then fitted to this frequency response and finally implemented in the Android app.

A and C-weighted noise level corrections

As shown in Eq.(1), A-weighted noise level correction values are the difference between the noise level, $L_{\text{eq,1sec}}$, measured by a reference system and the noise level measured by a smartphone-based device :

$$Lp_{\text{A,correction}} = Lp_{\text{A,ref}} - Lp_{\text{A,phone}}. \tag{1}$$

For a better readability, only the A-weighting values will be assessed through this paper while the similar calculations for C-weighting value can be performed. The overall correction values depend on the spectrum of the noise source emitted during the calibration measurements. To ensure a realistic correction, industrial workplace noise sources were chosen in accordance with the "NIOSH100" industrial noise database [8]. Three colored noise signals, source 1 , 2 and 3, shown in Figure 2, were created so their associated C-A value are the 20th, 50th and 80th percentile of the noise database distribution. As illustrated in Figure 3, C-A for sources 1,2 and 3 are respectively 0, 2 and 5 dB at

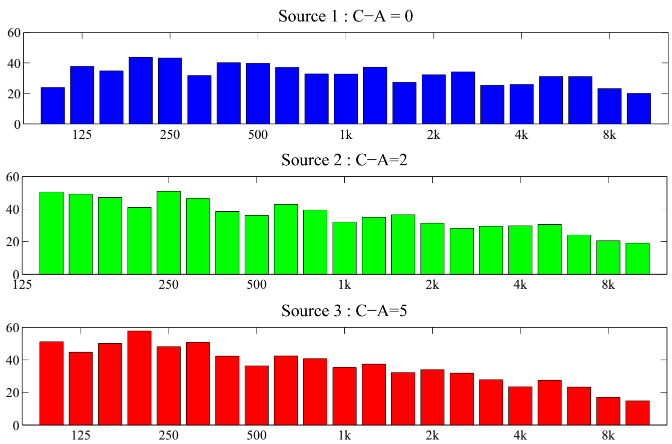

FIGURE 2: Noise spectrum of the Source 1, 2 and 3 with C-A value respectively 0, 2 and 5 dB at 85 dB(A)

85 dB(A) measured by the reference system. They slightly vary as the noise level increases and this effect is shown for phone measurements in Figure 7. As a comparison, C-A are around 2 dB for pink noise and -1dB for white noise. The stimulus signal is played 7 times in a row; at each play the noise level is increased by 5 dB. The measurement procedure is repeated 12 times under identical conditions. The range of noise levels assessed is from 75 dB(A) to 105 dB(A), measured with the calibrated reference measurement system.

Analysis of results

Frequency Response Linearization

Figure 4 shows the frequency response of the transfer function and the coherence function measured with a smartphone [9] and its embedded microphone. From this frequency response, a 40^{th} order FIR filter is designed, the main role of the filter is to compensate for the poor sensitivity of the smartphone microphone at low frequencies. The very low coherence after 4kHz illustrates the phase coherence problems that occur at high frequencies that maybe due to the distance between the microphones and an imperfect anechoic sound field.

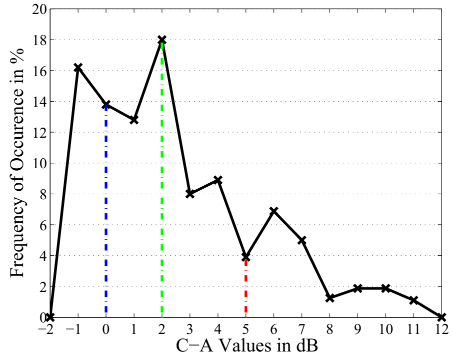

FIGURE 3: Histogram of the C-A values of NIOSH100 noise source database. The C-A of the noise sources used in this study are -1, 2 and 5 dB

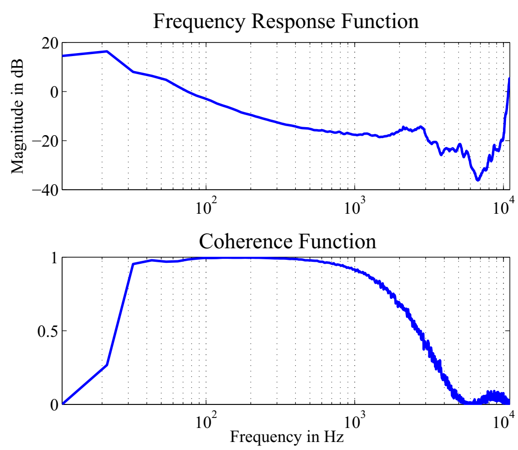

FIGURE 4: Frequency response function and coherence between a smartphone and the reference measurement system with dual channel FFT analysis

Calculation of the Combined Uncertainty Associated with the Noise Level Corrections Measurements

According to the Guide to the Expression of Uncertainty in Measurement [10] since the random variable $Lp_{\mathrm{A,ref}}$ is substracted to $Lp_{\mathrm{A,phone}}$ Eq.(1), the worst case of the combined uncertainty is when input quantities are considered uncorrelated. Therefore, the combined uncertainty associated with the measured correction value,$u_{Lp_{A,correction}}$, is expressed in (2). In this case, the uncertainties associated with the noise emitted and its propagation are assumed to be equal to zero.

$$u_{Lp_{A,correction}} = \sqrt{\left(\frac{\partial f}{\partial Lp_{A,ref}}\right)^2 \times u^2_{Lp_{A,ref}} + \left(\frac{\partial f}{\partial Lp_{A,phone}}\right)^2 \times u^2_{Lp_{A,phone}}} \tag{2}$$

where :

- $u_{Lp_{A,correction}}$ is the uncertainty associated with the measured correction value
- $u_{Lp_{A,ref}}$ is the uncertainty associated with reference measurement in dB(A) that will be detailed in step 1

- $u_{Lp_{A,phone}}$ is the uncertainty associated with the phone measurement in dB(A)that will be detailed in step 2

- $\frac{\partial f}{\partial Lp_{A,ref}} = 1$;
- $\frac{\partial f}{\partial Lp_{A,phone}} = -1$;

Step1 : Determination of the Uncertainty Associated with the Reference Measurement
$u_{Lp_{A,ref}}$ is a combined standard uncertainty calculated from different contributions listed below:

- $u_{ref.sensitivity}$ is the standard uncertainty associated with the reference microphone sensitivity
- $u_{ref.frequency}$ is the standard uncertainty associated with the frequency response of reference microphone. The microphone frequency response, given in the technical documentation, was numerically added to the three noise signals spectrum. The differences in dB between sources 1, 2 and 3 overall values and the sources with the added microphone response are obtained. The highest value is then chosen as the uncertainty.
- $u_{ref.calibrator}$ is the standard uncertainty associated with the calibration of the sound calibrator
- $u_{ref.calibration}$ is the standard uncertainty associated with the calibration of the reference microphone. Calibration factors are obtained from 12 repeated measurements. A standard deviation of 0.0045 dB is calculated from dB(A) and dB(C) values calculated by multiplying calibration factors to the measured signals.
- $u_{ref.repeatability}$ is the standard uncertainty associated with the repeatability of reference system measurements. The calculation is based on the experimental standard deviation for a series of twelve measurements.

Table 1 presents values for each contribution of $u_{Lp_{ref}}$ with its source and an estimation of $u_{Lp_{ref}}$

TABLE 1: Standard Uncertainty Associated with Reference Measurement, $u_{Lp_{ref}}$

Uncertainty	dB(A)	dB(C)	Source
$u_{mic.sensitivity}$	0.1	0.1	Manufacturer's specifications, [3]
$u_{mic.fr}$	0.04	0.02	Manufacturer's specifications, [3]
$u_{calibrator}$	0.025	0.025	Manufacturer's specifications, [5]
$u_{ref\_calibration}$	0.005	0.005	Measured
$u_{repeatability}$	0.06	0.06	Measured
$u_{Lp_{ref}}$	0.13	0.12	

Step 2 : Determination of the Uncertainty Associated with the Phone Measurement
$u_{Lp_{A,phone}}$ calculation is based on the experimental standard deviation for a series of twelve phone measurements. The smartphone's data acquisition and microphone imperfections are considered

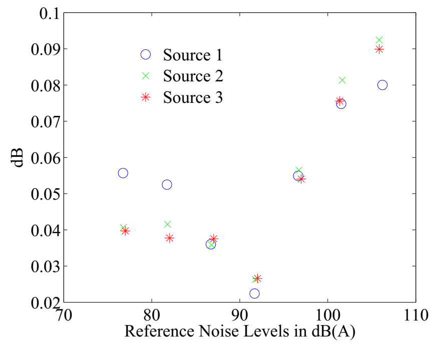

FIGURE 5: Uncertainty associated with the dB(A) phone measurement,$u_{Lp_{A,phone}}$ in dB

among the main sources of this experimental uncertainty. Figure 5 illustrates $u_{Lp_{A,phone}}$ for a smartphone [9] and its embedded microphone for the 3 noise sources and as a function of the reference noise levels.

The combined uncertainty associated with the measurement of A-weighting correction values, $u_{Lp_{A,correction}}$ are calculated using Eq.(2) for each combination of noise levels and noise sources. Figure 6 displays the measured correction values of a smartphone [9] with their associated expanded uncertainties which were obtained by multiplying the combined uncertainties by 2 for a level of confidence of approximately 95 percent.

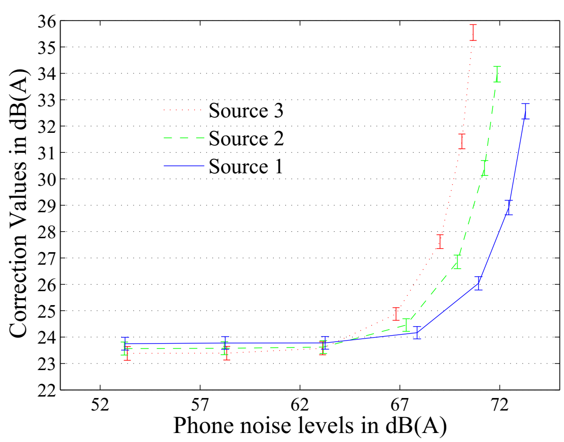

FIGURE 6: Correction values in dB(A) as a function of the phone noise levels and their associated expanded uncertainties in error bars

Interpolation of Calibration Corrections Values

Nonlinearity of the phone microphone signals at high noise levels creates shifts of C-A phone values. These shifts, shown in Figure 7 for sources 1, 2 and 3 are from a smartphone [9] and its embedded microphone measurements. The interpolation aims to generate correction values within the results of the calibration measurements and as a function of the phone noise level measurements, $Lp_{\text{A,phone}}$ and the phone C-A values, $C - A_{\text{phone}}$. A linear interpolation was considered as a first approach. Figure 8 illustrates the interpolated correction values calculated using a triangle-based linear interpolation method within a smartphone [9] calibration measurements. The interpolated

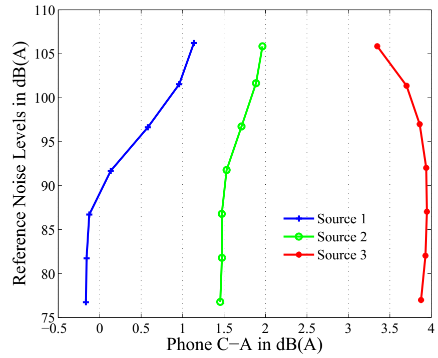

FIGURE 7: Reference noise levels in dB(A) as a function of phone C-A in dB(A)

values are implemented in the app as a lookup table that has $Lp_{\text{A,phone}}$ and $C - A_{\text{phone}}$ as input variables. Every second, a correction value, $Lp_{\text{A,correction}}$, is obtained from the lookup table and a $Lp_{\text{ A,calibrated phone}}$ is calculated using Eq. (3):

$$Lp_{\text{ A,calibrated phone}} = Lp_{\text{A,phone}} + Lp_{\text{A,correction}} \tag{3}$$

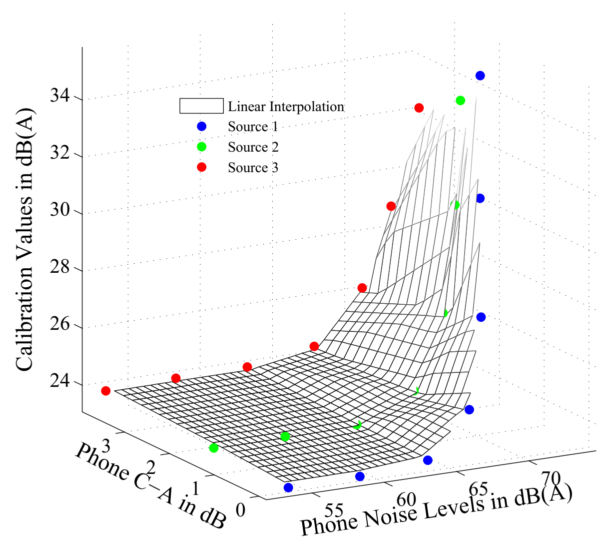

FIGURE 8: Interpolated correction values calculated with a linear interpolation and within the measured correction values for sources 1, 2 and 3

Discussion

The determination of the uncertainty associated with a calibrated phone measurement $Lp_{\text{ A,calibrated phone}}$ implies the calculation of uncertainty associated with the calculation of C- A noise levels and the uncertainty associated with the interpolation.The estimation of the uncertainty associated with the interpolation will be assessed using a Monte-Carlo approach within the values of $u_{Lp_{correction}}$. Ongoing measurements are currently conducted with several units of the same smartphone and headset microphone models. From these inter-model measurements, an uncertainty associated with inter-model variations will be assessed. Calibration measurements for "in-line" microphone on headphone cords and the microphone of a Bluetooth® earpieces are also currently assessed using the proposed procedure. The uncertainty associated with age drift is currently studied with future calibration measurements that will be performed with a 6 months and 1 year interval. Once the evaluation of the uncertainties associated with the laboratory measurements will be finalized, errors and uncertainties related to field measurements will be assessed. Although it was assumed in the laboratory measurements methodology that the temperature and atmospheric pressure were constants, uncertainties associated with variation in ambient temperature and variation in ambient pressure during field measurements need to be investigated. In industrial workplaces, the acoustic field characteristics differ significantly from a laboratory free field, the associated bias errors will be investigated with calibration measurements in a reverberant chamber and with regards to the directivity of the microphone and its placement on the workers' body.

Conclusions

A measurement methodology for the calibration of smartphone-based device was developed and the main measurements hypothesis were assessed. The proposed approach provides a calibration correction that takes into account the nonlinearity created by the devices' microphones at high noise levels. The noise sources used during the calibration measurements are based on the distribution of a referenced industrial noise database. A value of the standard uncertainty associated with the reference measurement system is estimated. Calculations of the uncertainties associated with the measurement of A-weighting correction are detailed. Interpolated correction values are calculated using a linear interpolation method within the measurements results. The correction values are then implemented in an Android app, developed by the authors, as a function of the phone noise level measurements and the phone C-A values.

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