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# ON THE USE OF MOBILE PHONES AND WEARABLE MICROPHONES FOR NOISE EXPOSURE MEASUREMENTS: CALIBRATION AND MEASUREMENT ACCURACY

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# ON THE USE OF MOBILE PHONES AND WEARABLE MICROPHONES FOR NOISE EXPOSURE MEASUREMENTS: CALIBRATION AND MEASUREMENT ACCURACY

Romain DUMOULIN

## ABSTRACT

Despite the fact that noise-induced hearing loss remains the number one occupational disease in developed countries, individual noise exposure levels are still rarely known and infrequently tracked. Indeed, efforts to standardize noise exposure levels present disadvantages such as costly instrumentation and difficulties associated with on site implementation. Given their advanced technical capabilities and widespread daily usage, mobile phones could be used to measure noise levels and make noise monitoring more accessible. However, the use of mobile phones for measuring noise exposure is currently limited due to the lack of formal procedures for their calibration and challenges regarding the measurement procedure.

Our research investigated the calibration of mobile phone-based solutions for measuring noise exposure using a mobile phone's built-in microphones and wearable external microphones. The proposed calibration approach integrated corrections that took into account microphone placement error. The corrections were of two types: frequency-dependent, using a digital filter and noise level-dependent, based on the difference between the C-weighted noise level minus A-weighted noise level of the noise measured by the phone. The electro-acoustical limitations and measurement calibration procedure of the mobile phone were investigated. The study also sought to quantify the effect of noise exposure characteristics on the accuracy of calibrated mobile phone measurements. Measurements were carried out in reverberant and semi-anechoic chambers with several mobiles phone units of the same model, two types of external devices (an earpiece and a headset with an in-line microphone) and an acoustical test fixture (ATF).

The proposed calibration approach significantly improved the accuracy of the noise level measurements in diffuse and free fields, with better results in the diffuse field and with ATF positions causing little or no acoustic shadowing. Several sources of errors and uncertainties were identified including the errors associated with the inter-unit-variability, the presence of signal saturation and the microphone placement relative to the source and the wearer.

The results of the investigations and validation measurements led to recommendations regarding the measurement procedure including the use of external microphones having lower sensitivity and provided the basis for a standardized and unique factory default calibration method intended for implementation in any mobile phone. A user-defined adjustment was proposed to minimize the errors associated with calibration and the acoustical field.

Mobile phones implementing the proposed laboratory calibration and used with external microphones showed great potential as noise exposure instruments. Combined with their potential as training and prevention tools, the expansion of their use could significantly help reduce the risks of noise-induced hearing loss.

**Keywords:** noise exposure, noise dosimeter, mobile phone, calibration, acoustic noise measurement, noise level, wearable microphones

# VERS L'UTILISATION DE TELEPHONES ET MICROPHONES PORTABLES POUR LA MESURE DE L'EXPOSITON AU BRUIT: ETALONNAGE ET EXACTITUDE DE MESURE

Romain DUMOULIN

## RÉSUMÉ

Alors que la perte de l'audition liée au bruit est la première cause de maladie professionnelle dans les pays développés, les niveaux individuels d'exposition au bruit restent souvent inconnus et rarement évalués. En effet, les campagnes d'exposition au bruit normalisées ont pour principal désavantage le coût de l'instrumentation et les difficultés liées à leur mise en œuvre. Avec leurs capacités techniques avancées et leur omniprésence dans notre vie quotidienne, les téléphones portables représentent une opportunité de rendre la mesure d'exposition au bruit accessible. Cependant, l'utilisation des téléphones portables pour mesurer l'exposition au bruit reste limitée en raison de l'absence de procédures formelles pour leur étalonnage et les défis que représente la procédure de mesure.

Notre recherche a étudié l'étalonnage des téléphones portables pour mesurer de l'exposition au bruit avec le microphone intégré au téléphone et des microphones externes. La méthode d'étalonnage proposée intègre des corrections pour l'erreur associée au placement du microphone, et inclus deux types de corrections : dépendant de la fréquence avec un filtre numérique et dépendant du niveau de bruit basée sur la valeur du C-A (Niveau de bruit pondéré C moins niveau de bruit pondéré A). Les limites électro-acoustiques des téléphones portables et la procédure d'étalonnage ont été examinées. L'étude a également cherché à quantifier l'effet des caractéristiques de l'exposition au bruit sur l'exactitude des mesures avec des téléphones calibrés. Les mesures ont été effectuées dans des salles réverbérante et semi- anéchoïque avec plusieurs téléphones portables du même modèle, deux types de appareils externes (une oreillette et des écouteurs avec un microphone) et un mannequin acoustique.

La méthode d'étalonnage proposée a nettement amélioré l'exactitude des mesures de niveau de bruit en champs libre et en champs diffus, avec de meilleurs résultats en champs diffus et pour des positions de mannequin causant peu ou pas d'ombrage acoustique. Plusieurs sources d'erreurs et d'incertitudes ont été identifiées incluant les erreurs associées à la variabilité entre téléphones, à la saturation du signal, la position du microphone par rapport à la source et au porteur du microphone. Les mesures de validation ont mis en avant les limites de la méthode pour traiter la saturation du signal du microphone intégré au téléphone et amènent à plusieurs recommandations concernant les procédures de mesures incluant l'utilisation de microphones externes ayant une sensibilité appropriée.

Les résultats de l'étude fournissent les bases d'une méthode normalisée et unique d'étalonnage « d'usine » destinée à être mis en œuvre dans n'importe quel téléphone portable. Un ajustage défini par l’utilisateur a été proposé pour réduire les erreurs associées à l’étalonnage et au champ acoustique.

Les téléphones portables utilisés avec des microphones externes et incluant l’étalonnage en laboratoire proposé ont montré un grand potentiel en tant qu’un instrument de mesure de l’exposition au bruit. Combiné avec leur potentiel en tant qu’outils de formation et de prévention, l’augmentation de leurs utilisations pourrait considérablement aider à réduire les risques de perte d’audition due au bruit.

**Mot-clés :** exposition au bruit, dosimètre de bruit, téléphone portable, étalonnage, measure acoustique, niveau de bruit, microphone portable

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| A/D | Analog to Digital |
| ATF | Acoustical Test Fixture |
| FFT | Fast Fourier Transform |
| FIR | Finite Impulse response |
| HEG | Homogeneous noise Exposure Group |
| IIR | Infinite Impulse response |
| HPD | Hearing Protection Device |
| NIHL | Noise-Induced Hearing Loss |
| RFID | Radio Frequency Identification |
| RMS | Root Mean Square |
| SLM | Sound Level Meter |
| SPL | Sound Pressure Level |
| TF | Transfer Function |
| XML | Extensible Markup Language |

## LIST OF SYMBOLS

| | |
|---|---|
| $L_{eq}$ | Equivalent continuous sound level in dB |
| $L_{EX.8h}$ | A-weighted noise exposure level normalized over 8 hours |
| $L_p$ | Sound pressure level in dB |
| $p$ | Effective sound pressure in Pa |
| $p_{ref}$ | Reference sound pressure, 20 $\mu$Pa |
| $p_{rms}$ | Root mean square (RMS) sound pressure |

# INTRODUCTION

## Context

Despite the increasing presence of hearing conservation programs and noise exposure regulations, occupational noise-induced hearing loss (NIHL) remains a problem in developed countries. First, occupational NIHL is still the most common work-related injury in Canada and the United States. In the United States, around 30 million workers are exposed to hazardous noise and the estimated annual cost for workers' compensation for hearing loss disability is 242 million dollars according to NIOSH (2001). Second, the prevalence of NIHL among teenagers and young adults has increased and recent studies have brought to light NIHL risks in fields that were generally given less consideration such as the entertainment industry. Noise exposure assessments play a key role in the evaluation and prevention of NIHL. These assessments are used to ensure compliance with regulations and determine that hearing conservation programs are implemented including engineering and administrative actions, audiometric tests and provision of hearing protection devices (HPDs). Individual workers' noise exposure levels are still rarely known and infrequently tracked. This may be because standardized noise exposure campaigns require instrumentation that could be costly and are difficult to implement in the field. In complement to these procedures, informal noise surveys carried out with cheaper basic sound level meters do not hold metrological quality. Standardized noise exposure instruments, noise dosimeters and integrating sound level meters ensure the quality of the measurements as they meet standards' requirements for the main electro-acoustical characteristics including linearity, frequency response and directivity. However, their use by small companies, self-employed workers or the general public remain very limited. While Rabinowitz *et al.* (2011) states that, "monitoring daily occupational noise exposure inside hearing protection with ongoing administrative feedback apparently reduces the risk of occupational NIHL in industrial workers", recent technology used to monitor the daily at-ear noise exposure remains relatively expensive and difficult to access.

According to Ericsson (2013), there are about 1.6 billion people across the globe that have smartphones and the number is forecasted to reach 5.6 billion by 2019. The growth of mobile technology has led to the development of thousands of types of mobile phone applications, including apps that measure noise levels. Any mobile phone with an operating system that supports programmable applications could possibly be used as an noise exposure instruments since they already feature a built-in microphone and audio hardware components. This trend is in line with the emergence, from around 2005, of low-cost noise exposure instruments, called dose indicators, such as the NI-100® from 3M or the PocketEar® from SoundEar A/S, that provide a basic estimation of the noise dose with a limited quality and without meeting the standards' requirements. Using mobile phones for measuring noise exposure takes advantage of the ubiquity of mobile phones in people's lives: mobile phone users almost always have their mobile phones with them including at work and during recreational activities. Without any purchase of additional equipment, one can download and use a sound level meter (SLM) app very easily.

**Statement of the Problem**

Unlike standardized professional noise exposure instruments, a mobile phone's microphone and others hardware and software components have not been designed for measuring noise. While mobile phones have technical capabilities to measure noise levels, their widespread use for measuring occupational noise exposure is still limited due to the lack of formal calibration procedures and challenges regarding the measurement procedure. Moreover, design guidelines and standards that define the requirements of traditional noise exposure instruments hardly apply to mobile phone solutions. Standardized noise exposure instruments are linear (level independent) over a wide range of noise levels and have a flat frequency (frequency and level independent) response. Their *factory* calibration consists in determining the sensitivity level of the instrument based on a standardized calibration procedure. This traditional approach of a unique, frequency and level independent, calibration value, such as the sensitivity at 1 kHz, is not suitable for mobile phone-based solutions since an SLM app may be run on different mobile phones that have different microphones, hardware and software components with variable range of quality. The electro-acoustical limitations of the phones' audio recording chain require new calibration methods and/or the use of dedicated external hardware.

Standardized noise exposure measurements, defined in CSA (2013) or ISO (2008) can follow two main sampling approaches, both associated with a specific type of noise exposure instrument. The *full-day* approach consists in continuous measurements conducted with noise dosimeters over an entire work day. Noise dosimeters units are carried by the worker with the microphone located on top of the shoulder on the side of the most exposed ear. The *task-based* approach consists in several separate measurements taken during the tasks representative of the working day, conducted with SLMs and integrating SLMs. SLMs are placed at the location where the worker's head would be and they are either hand-held by an operator or fixed. New challenges related to noise exposure measurements with mobile phones could be identified as:

- Microphone positions recommended in the standards are not adapted for mobile phone built-in microphones;
- The calibrator used for field calibration is not adapted for mobile phone' built-in microphones;
- The measurement procedures associated with mobile phones are not adapted for long-term measurements;
- A mobile phone's audio recording chain is not suited for taking measurements of high levels of noise.

Therefore, tabulated data of uncertainties associated with the instrumentation and used for the calculation of noise exposure in standards such as CSA (2013) or ISO (2008), are not suitable for mobile phone measurements. Nevertheless, mobile phones have definitively technical advantages over traditional noise exposure instruments: they support programmable applications, they embed various technologies and sensors and they can provide a strong interactivity with the users. A mobile phone-based solution for measuring noise exposure may use these benefits to improve the quality of noise levels measurements.

**Background and Need**

There is a lack of research regarding the electro-acoustical limitations of mobile phones. Certain external microphones have been specifically designed for noise level measurements with mobile phones. They are intended to be used as sound level meters, using the *task-based* sampling approach in the case of noise exposure measurements. They aim to have better acoustics characteristics than the built-in microphones, especially regarding directivity and frequency response. A few of them also integrate a microphone preamplifier and analogue to digital (A/D) converters and even meet some of the ANSI and ISO Type-2 specifications. Although these external microphones improve the quality of the noise level measurements, their cost and their accessibility remains a barrier for widespread use of mobile phones for measuring noise exposure. Finally, the use of other type of external microphones, non-dedicated for noise levels measurements, such as headset in-line microphones or earpiece microphone, have not been investigated.

Most of the SLM mobile phone applications (apps) available through "app stores" (Google Play, Apple app store, Nokia Store) are designed and used for recreational purposes. They usually feature a basic sound level meter that displays noise levels without time integration or data logging. Since the most documented projects come from academics specialized in computer science, their research challenges were more focused on mobile sensing issues such as scalability, context-awareness or privacy, rather than noise measurements quality or compliance with regulations. A review of the existing apps shows that the most common factory default calibration consist in a single level and frequency-independent correction regardless of the phone model. More elaborated and accurate approaches consist in calibrating a mobile phone depending on the phone model or depending on a particular unit. The calibration algorithms, implemented in SLM apps to adjust mobile phone sensitivity can be either level-dependent, frequency-dependent or a combination of both approaches. Level-dependent algorithms consist in corrections applied on the to-be corrected phone sound pressure level (SPL) and frequency-dependent algorithms use filters to correct and flatten the frequency response of audio recording signals. While all calibration algorithms described in the literature are based on SPL corrections, neither frequency-dependent algorithms, nor a combinations of both frequency and level-dependent algorithms have been investigated in the literature.

In the only study found that discusses in detail factory default calibration of mobile phones, Stevens (2012) presents the different calibration paradigms and algorithms (section 1.2.1.4) and describes his proposed calibration approach for the *NoiseTube* app with the following characteristics:

- A phone model-dependent calibration; this author assessed that differences between individual units of the same model were small enough so that the calibration can be independent of the unit used;
- A level-dependent algorithm; a frequency-dependent calibration was found not relevant, as he assessed that the frequency response of the phone model he used was "flat enough";
- No field calibration; as he concluded that differences between two calibration measurements conducted with a five months interval with one mobile phone were, again "small enough"..

However, Stevens (2012)'s calibration approach presents several limitations:

- Calibration measurements were conducted with only one artificial white noise source, only in an acoustical free field environment;
- Only a few units of the one phone model were investigated during the calibration measurements;
- The microphone placement error due to body acoustical shadowing and reflections, the importance of which is discussed in detail in section 1.2.3, is not taken into account in the calibration compensations;
- The saturation of the audio recording chain at very high noise levels is not specifically considered: *NoiseTube* app was dedicated for measuring environmental noise sources with a range of noise levels of interest below 90 dB(A).

The few studies that evaluated the quality of mobile phone measurements, detailed in section 1.2.2, were based on noise levels comparisons of an existing app over measurements from a professional sound level meter. The work by Stevens (2012) with the *NoiseTube* app is the most extensive investigation. It shows good agreement between the phones and sound level meter measurements up to approximatively 95 dB(A). However, the measurements were conducted for one white noise spectrum and with only one particular phone unit and its built-in microphone. The review of the studies shows the lack of a common methodology to evaluate the quality of the mobile phone as SLM. The methodologies employed vary from the measurements in laboratory environments with artificial and recorded real-world noise sources to measurements in real-world conditions.

The use of mobile phones for occupational noise exposure measurements has not been studied yet. Although the SLM apps are designed to be used with the phone hand-held, this approach is hardly suitable for long-term continuous noise exposure measurements. There is a need for investigating the phones' microphone positions (including those of external microphones) and their impact on the measurement quality. Studies with noise dosimeters highlight that microphone placement error is one of the main source of errors. In the study about nonstandard microphone positions for noise dosimeters, Byrne and Reeves (2008) showed the impact of the acoustic field on the microphone placement error: the overall errors due to microphone placement were minor in a diffuse field whereas in a free-field, the errors depended greatly on the microphone position, the noise source location and the noise spectrum. In short, it appears that the quality of a real-world mobile phone noise level measurements relies on:

- The characteristics of the phone's hardware and software audio components;
- The quality of the SLM app including the calibration algorithm and the quality of the calibration measurements;
- The characteristics of the "real-world" environment and the errors associated with the use of the phone, such as the microphone placement error.

**Purpose of the Study**

The cost and the usability of standardized noise exposure instruments limit their widespread use in both occupational and recreational noisy environments. Mobile phones can easily act as sound level meters however the quality of the current solutions have not been sufficiently investigated and proved to justify their use for professional noise exposure measurements. The purpose of this study was to investigate the calibration of mobile phone-based solutions for measuring noise exposure. First, this study investigated the frequency response and the level linearity of mobile phones employed with built-in microphones and with external microphones. Second, a factory default calibration measurements including frequency response and noise levels measurements was investigated. The particularity of the proposed calibration approach, especially for wearable external microphones, was to consider the microphone placement error in the calibration corrections. The primary goals of investigation were:

- The design guidelines for factory default calibration algorithms;
- The impact of the noise characteristics (acoustic field, noise spectrum) and microphone placement on the calibration measurements.

Third, laboratory validation measurements were conducted by varying the noise sources, the acoustical field, the microphone placements and the factory default calibration parameters in order to evaluate how those factors affect the accuracy of calibrated mobile phone measurements. The measurement precision of the calibrated measurements was evaluated together with the uncertainties associated with the repeatability and the inter-phone unit variability.

An Android-based app that was developed by the author. It implemented the designed frequency and level-dependent calibration algorithms, calculated phone noise levels and recorded audio signals. Measurements were carried out in reverberant and semi-anechoic chambers with several mobiles phone units of the same model, two types of external devices (an earpiece and a headset with an in-line microphone) and an acoustical test fixture (ATF). The range of noise levels investigated in the study, from 75 to 105 dB(A) was considered to be representative of the noise levels in industrial and recreational environments implying a high risk of hearing loss.

### Research questions

The main research question addressed in this study was: How should a mobile phones-based solution be calibrated for measuring noise exposure? The subquestions were the following:

- How should mobile phone's electro-acoustical limitations and noise exposure characteristics be taken into account in the design of a mobile phone factory default calibration?
- How does the accuracy of calibrated mobile phone noise exposure measurements depend on the noise characteristics?
- How could the accuracy of mobile phone measurements be improved?

### Significance of the Study

The study was the first research work to investigate a mobile phone calibration approach that integrates corrections for the microphone placement error and considers wearable external microphones. The results showed that the proposed calibration approach significantly improved the accuracy of the noise level measurements in diffuse and free fields. Limitations of the approach for handling the built-in microphone signal saturation led to the use of external microphones having more appropriate sensitivity. A user-defined adjustment was proposed to minimize the errors with the calibration. The results of the investigations provided the basis for a standardized and unique factory calibration method intended for implementation in any mobile phone.

Major technical contributions of the study bear on the design and implementation of a frequency response linearization with a digital filter and a noise level-dependent calibration algorithm as a function of the C-A. It includes:

- a Java™ and Android-based app software;
- Matlab scripts for the analysis of the phone measurement files, the design of a FIR filter and the interpolation of noise level corrections.

## Roadmap

Chapter 1 presents a literature review that addresses areas related to the development a mobile phone-based solution for measuring noise exposure: the design of a mobile phones as SLMs, the studies regarding the accuracy of mobile phones as SLMs and research related to the accuracy of noise exposure measurements in real world environments. Chapter 2 describes the methodology of the study including the noise measuring app developed by the author, the mobiles phones and external microphones used during the study, the procedures of both calibration and validation measurements, and finally, the design and implementation of calibration algorithms. Chapter 3 presents all the results of the study. It includes the study of the electro-acoustical limitations of mobile phones and external microphones, the results associated with the design and implementation of the calibration algorithms and the results of the laboratory calibration and validation measurements. Chapter 4 summarizes and discusses the major findings of the study. The basis of a mobile phone calibration methodology is described and it also presents the main sources of errors and uncertainties identified in the study within methods to minimize the errors. Finally, recommendations for future works and longer-term projects are discussed.

## Definitions and terminology

The definition of the following concepts, written by the author, clarify some of the terminology used in this thesis.

- *Noise exposure instruments* refers to the instrumentation recommended to use to measure noise exposure: noise dosimeters (referred to as personal sound exposure meters in certain standards) and the integrating-averaging sound level meters (SLMs);
- *Noise exposure measurements* corresponds to A-weighted noise level measurements conducted with noise exposure instruments;
- *Noise exposure assessment* corresponds to a procedure that aims to determine the overall noise exposure. It includes a work analysis, the noise exposure measurements follow-

ing a specific sampling strategy and the analysis and presentation of the measurements results;

- *Mobile phone* is synonymous with smartphone (for the purposes of this thesis), it corresponds to a mobile phone that has an operating system with the capability to support programmable applications;
- *Overall A-weighted error* is the A-weighted noise level measured with the phone minus the A-weighted noise level measured with the reference measurement system and conducted at the center-of-head with no ATF.

The terminology of the following concepts are used in this thesis. Their definitions are extracted from the International vocabulary of metrology, JCGM (2012):

- *Measurement accuracy*: closeness of agreement between a measured quantity value and a true quantity value of a measurand. The concept 'measurement accuracy' is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error;
- *Measurement trueness*: closeness of agreement between the average of an infinite number of replicate measured quantity values and a reference quantity value. Measurement trueness is not a quantity and thus cannot be expressed numerically, but measures for closeness of agreement are given in ISO 5725, ISO (1998);
- *Measurement precision*: closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions;
- *Measurement error*: measured quantity value minus a reference quantity value;
- *Measurement repeatability*: measurement precision under a set of repeatability conditions of measurement;
- *Measurement uncertainty*: non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used;

- *Calibration*: operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication;
- *adjustment of a measuring system*: set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured;
- *Validation*: verification, where the specified requirements are adequate for an intended use;
- *Correction*: compensation for an estimated systematic effect;
- *Sensitivity of a measuring system*: quotient of the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured.

Returning to the concept of accuracy, according to ISO 5725-1, ISO (1998), it consists of the combination of measurement trueness (as defined in ISO 5725-1) and measurement precision, as illustrated in Figure 0.1. Noise level descriptors and noise level-associated terminology are defined and explained in Annex II, including the definition of the sound pressure level, the frequency weightings A and C and the equivalent continuous sound level, also referred to as $L_{eq}$.

**Limitations**

The very limited number of devices being tested (four units of the same phone model, one earpiece and one headset) prevented the generalization of some of the findings to a larger set of mobile phones models. The use of an ATF with the external microphones measurements, as compared to human subjects, limited the results interpretation regarding the investigation of the microphone placement error. Validation measurements were conducted in controlled laboratory environments during a short period of time, thereby, several uncertainties and errors have not been investigated in this study, such as the error due to the instrumental drift caused by aging or the errors associated with measurements in "real-world" environments (contributions

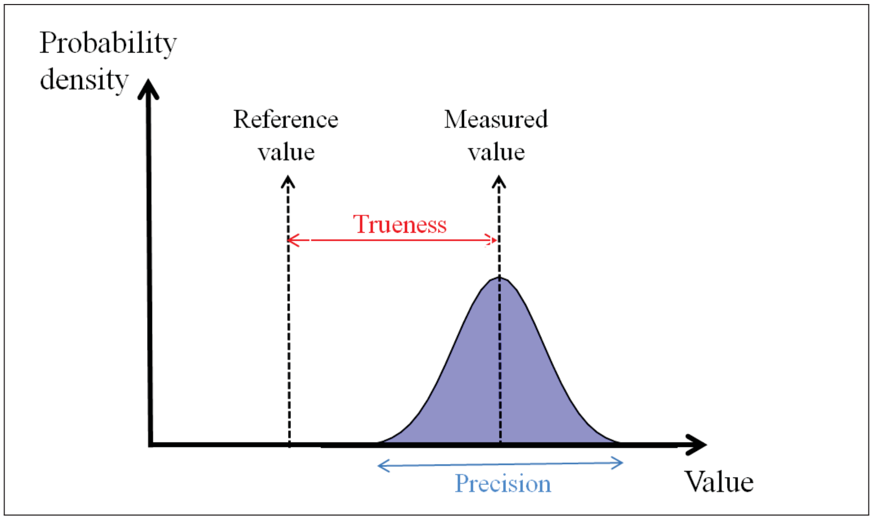


Figure 0.1 Concept of Accuracy based on the trueness and the precision concepts, as defined by ISO 5725-1, ISO (1998)

from wind, the microphone rubbing on clothing,etc.). This study did not investigate the noise exposure assessments or the overall measurement uncertainty that includes for example the uncertainties associated with the sampling of the measurements.

# CHAPTER 1

# LITERATURE REVIEW

## 1.1 Introduction

Noise exposure assessments play a key role in the evaluation and prevention of NIHL. These assessments are used to ensure compliance with regulations and determine that hearing conservation programs are implemented including engineering and administrative actions, audiometric tests and provision of hearing protection devices (HPDs). NIHL is the number one occupational disease, individual workers' noise exposure levels are still rarely known and infrequently tracked.This may be because standardized noise exposure campaigns require instrumentation that could be costly and are difficult to implement in the field. Standardized noise exposure instruments, noise dosimeters and integrating sound level meters ensure the quality of the measurements as they meet standards' requirements for the main electro-acoustical characteristics including linearity, frequency response and directivity. However, their use by small companies, self-employed workers or the general public remain very limited. Unlike standardized professional noise exposure instruments, a mobile phone's microphone and others hardware and software components have not been designed for measuring noise. While mobile phones have technical capabilities to measure noise levels, their widespread use for measuring occupational noise exposure is still limited due to the lack of formal calibration procedures and challenges regarding the measurement procedure. Design guidelines and standards that define the electro-acoustical requirements of traditional noise exposure instruments hardly apply to mobile phone solutions.

The literature review will address three areas related to the development a mobile phone-based solution for measuring noise exposure. The first section will address research related to the design of a mobile phones as SLMs. It covers a survey of the hardware and software components that are involved in the design of mobile phones as SLMs and a review of the current factory default calibrations approaches including the algorithms and the measurements procedures. The second section focuses on studies regarding the accuracy of mobile phones as SLMs. Finally, the third section will discuss research related to the accuracy of noise exposure measurements in real world environments with an emphasis on the sources of errors and uncertainties. Figure 1.1 presents the relations betweens sections of the literature review depending on the three areas of research.

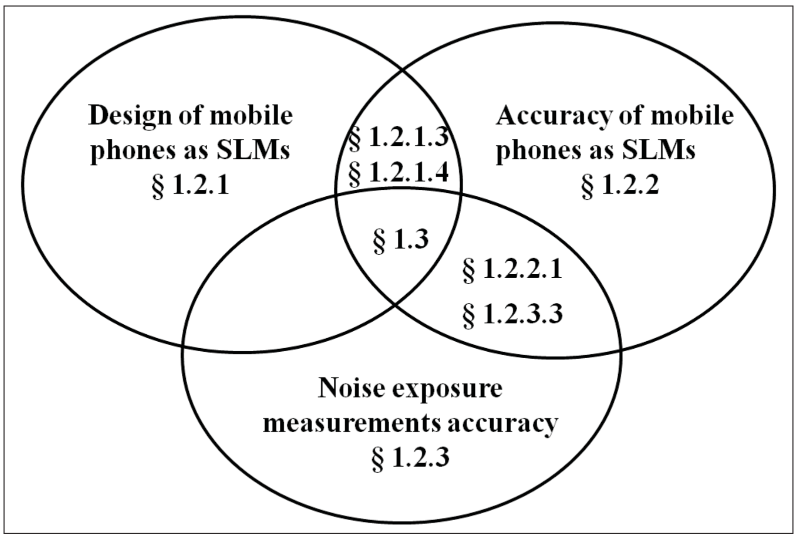


Figure 1.1 Sections of the literature review depending on their relation with the study's areas of research

## 1.2 Body of the review

### 1.2.1 Design of mobile phones as a SLM

#### 1.2.1.1 Audio recording chain

**Overview**

The audio recording chain includes all the phone's hardware and software components involved in the recording of an audio signal. With the noise levels calculating from the recorded audio signal, the audio recording chain has an significant impact on the quality of the phone measurement. Figure 1.2, adapted from Stevens (2012), illustrates the different components of an audio recording chain, as mentioned by Stevens (2012), "labels in italics signify that the parameters or properties of the component in question are unknown or uncontrollable from the perspective of the app" and the boxes with a dashed outline represent components which may or may not be present on a particular device, and whose presence may be undetectable from the perspective of the app".

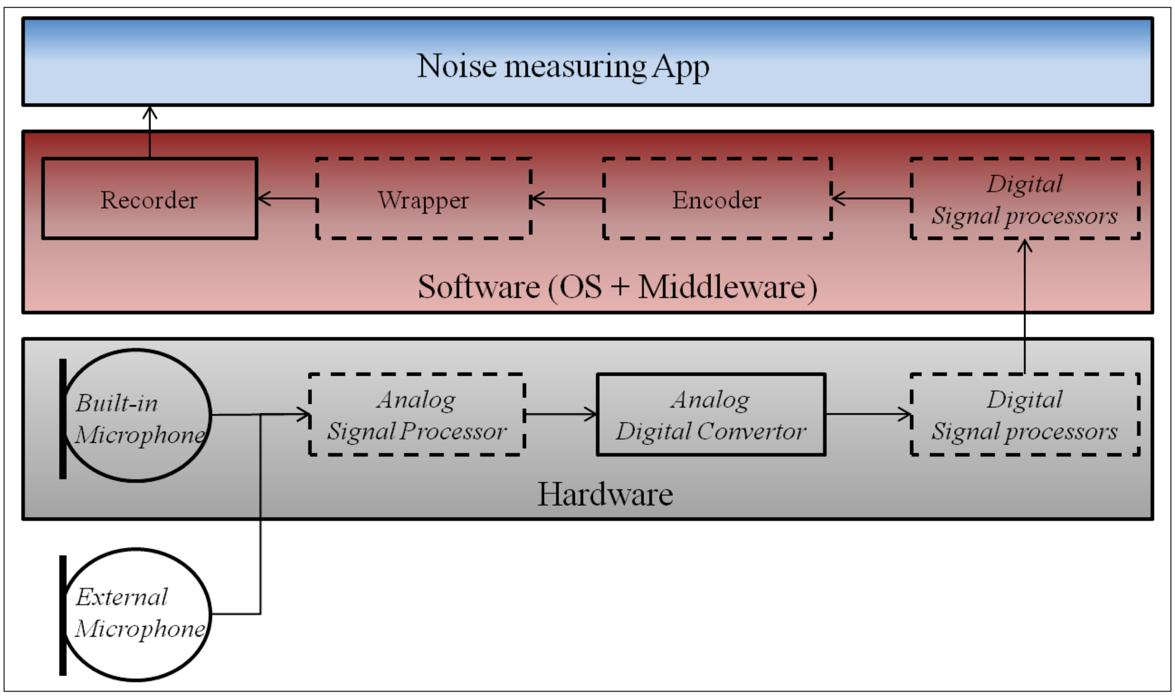


Figure 1.2 Hardware and software components of the audio recording path of mobile phones

Built-in microphones in mobile phones were originally electret condenser microphones (ECM). According to Akustica (2011), ECM present two main limitations: their large size and their non-homogeneous electro-acoustic characteristics, such as the nominal sensitivity and the background noise level. Since the 2010s, MicroElectrical-Mechanical System (MEMS) microphones have become the preferred microphone solution for mobile phones. They are smaller than ECMs and highly homogeneous in phase and sensitivity response. Based on the informations provided by manufacturers, MEMS have a good omni-directional response with a dynamic range of around 120dB, a signal-to-noise ratio around 60 dB and a flat frequency response from 60-100 Hz to 15-20 kHz. Microphones in mobile phone are very rarely documented and it usually requires a mobile phone tear-down, as outlined on Ifixit.com (2013), to determine the microphone models used within a given phone. However, the microphone characteristics alone without the entire phone's audio recording chain is of little use: the microphone sensitivity is affected by hardware components such as the A/D converter and the microphone frequency response is affected by the placement of the microphone inside a mobile phone. The only microphone characteristic to consider remains the inter-unit variability of the microphone sensitivity, given in the microphone data sheets with a standard deviation in dB or with minimum and a maximum sensitivity values.

Instantaneous voltage output from the microphone is converted by the A/D converter in samples. The sampling rate, and format of the digitalized audio stream are specified through the audio framework of the phone's operating system that manages the hardware and software components of mobile phones. For SLM apps that use 16-bit PCM (Pulse-Code Modulation) audio bit depth such as NoiseSpy, Kanjo (2009) or *NoiseTube*, Stevens (2012), instantaneous voltage output from the microphone is converted in samples signed short values between - 32768 and + 32767 where + 32767 represents the maximum positive voltage and - 32768 represents the minimum negative voltage. In addition to the basic microphone signal conditioning and A/D conversion, mobile phones also integrate specific audio processing such as automatic gain control, noise suppression, echo canceler and equalization. According to Android (2013), Automatic Gain Control (AGC) "normalizes the output of the captured signal by boosting or lowering input from the microphone to match a preset level so that the output signal level is virtually constant". The presence or the absence of these features depend on the manufacturer and the operating system requirements, as detailed later in section 1.2.1.5. The audio processing features are sometimes controllable from the application depending on the hardware implementation and the access provided by the operating system of the phone. At the software level, illustrated in Figure 1.3, several objects handle the audio processing: the encoder and the wrapper tackle the encoding and formating of the audio stream into digital data and the recorder allows the phone applications to control and specify parameters of audio recording signal, such as the format, the sampling rate or the bit depth.

#### 1.2.1.2 External microphones

Built-in microphones can be bypassed using external microphones, plugged into the analog audio input of the phone, the micro USB port (for Android-based smartphones) or the dock connector (for iOS-based devices). External microphones are integrated in a large variety of device such as headset, headphones and Bluetooth™ear-piece. External microphones specifically designed for phone acoustic measurements aim to offer better directivity and the frequency response than built-in microphones at a fraction of the cost of professional noise exposure instruments. For example, the MicW® i436 is an external electret microphone that connects to the mobile phone with an audio connector (Figure 1.3). Although Studiosixdigital states that there is no improvement in frequency response with MicW® compared to the iPhone built-in microphone, Faberacoustical (2012b) highlights its flat frequency response and its omni-directionality that is supposedly designed to meet the Class 2 standard for sound level meters. One other advantage highlighted by Faberacoustical (2012b) is that the microphone size allows a field calibration with a sound calibrator and an adapter.

Other external measurement microphones come with hardware components that bypass a significant portion of mobile phone audio recording path. The iTestMic® microphone by StudioSixDigital integrates a microphone preamplifier, A/D converters, and USB digital audio interface. It is designed for iOS-based devices as it uses a dock connector interface (Figure 1.3) and according to Studiosixdigital, it meets ANSI / ISO Type-2 specifications for frequency response, linearity, and directional characteristics.


Figure 1.3 Pictures of external microphones : MicW® i436 microphone from MicW (2013) on the left and iTestMic® microphone from Studiosixdigital on the right

#### 1.2.1.3 Audio processing in SLM apps

This section presents the main audio processings employed in SLM apps to calculate noise levels excluding the factory default calibration processing described in detail in the following section (§ 1.2.1.4).

The main components of SLM apps are the audio decoder, the filter component, the noise level calculator including the calibration algorithms. In traditional noise exposure instruments, noise exposure metrics, detailed in Annex II, are calculated using either only hardware components for analog instruments or a combination of hardware and software components in digital instruments. Annex III provides an overview of the audio processing that leads to the calculation of noise metrics in sound level meters (SLMs), integrating sound level meters and noise dosimeters. In SLM apps, the calculation of noise metrics mimics the calculation of noise metrics in the noise exposure instruments through digital audio processing implemented in the code of the SLM apps. The calculation of the noise metrics in SLM apps is rarely detailed in commercial apps. The open source code source of the *NoiseTube* app, Stevens (2012), and WideNoise app, WideTag (2014) allow one to analyze in detail the noise calculation algorithms used.

The audio decoder component process the signal from the A/D converter. The filter component implements the A and C frequency weighting (Annex II). The filters used in the *NoiseTube* app are Infinite Impulse Response (IIR) filters implemented in the programming language Java™. The filters are designed to meet the requirements of the international standard IEC (2002). According to Stevens (2012), the "A-weighting filter [of the *NoiseTube* app] meets the tolerance limits for Class 1 SLMs at all frequencies except those between 10 and 12.5 kHz".

The noise level calculator computes noise levels from the filtered signals. The SLM apps that feature time integrating implement a memory buffer and an algorithm that average samples in the buffer. In the *NoiseTube* app, the A-weighted equivalent continuous noise level, $L_{A,1sec}$, in dB(A), is implemented using the equation 1.1 with $p_{ref}$, the reference sound pressure of 20 $\mu$Pa, $p_A$, the A-weighted effective sound pressure being measured and $f_s$, the sampling frequency.

$$L_{A,eq1sec} = 20\log_{10}\left(\frac{\sqrt{\frac{1}{f_s}\sum_{i=1}^{f_s} p_A^2(i)}}{p_{ref}}\right) \tag{1.1}$$

Most of the SLM apps available on the "app stores" (Google Play, Apple app store, Nokia Store) feature a basic sound level meter that displays noise levels in A-Weighting decibels with a Fast or Slow time weighting and without time integration ($L_{eq}$ values) or data logging. Among eleven apps specifically intended for environmental noise monitoring, only 4 measure A-weighted decibels, 7 are not calibrated. The integrating time of the noise level value is very variable from one app to another: 0.5 second $L_{eq}$ for *NoiseMap*, Schweizer *et al.* (2011), 1 second $L_{eq}$ for *NoiseTube*,Stevens (2012), *Ear-Phone*, Rana *et al.* (2010) or *SoundOfTheCity*, Ruge *et al.* (2013), 5 seconds for *WideNoise*, WideTag (2014).

The user calibration feature in most of the SLM apps takes advantage of the user involvement and the phone's user interaction to improve the quality of the SLM app. It consists in the manual adjustment by the user of the phone noise levels. Rana *et al.* (2010) developed an algorithm, implemented in the *Ear-Phone* app, that takes advantage of sensors embedded in the phone (proximity sensor, inertial sensors, magnetometer sensor and GPS receiver) in order detects the phone's location (palm, pocket and bag or belt) during noise level measurements. It improves the quality of noise exposure measurements since measurements that are detected as measured in the pocket or the bag are not take into account in the noise exposure calculation. With the exception of the user calibration approach and the detection of phone's location, currently overlook SLM apps take very little advantage of mobile phone user-interaction and mobile technologies in order to improve the quality of noise exposure measurement.

#### 1.2.1.4 Factory default calibration of mobile phones

**Existing approaches**

Unlike standardized professional noise exposure instruments, mobile phones' microphone and others hardware and software components have not been designed for measuring noise. Standardized noise exposure instruments are linear (level independent) over a wide range of noise levels and have a flat frequency (frequency and level independent) response. Their *factory* calibration consists in determining the sensitivity level of the instrument based on standardized calibration procedure. This traditional approach of a unique, frequency and level independent, calibration is not suitable for mobile phone-based solution since a SLM app may be run on different mobile phones that have microphones, hardware and software components with variable range of quality.

The calibration of mobile phone intends to compensate for the systematic errors due the phone's microphone and others components of the phone's audio recording path including hardware and software components. There are 3 mobile phone calibration paradigms: a single calibration for all devices, a calibration specific to a particular model and a calibration specific to a particular device unit. One can assume that SLM apps with a single calibration for all the phones are necessarily less accurate than apps with a model-dependent or unit-dependent calibration. The model-dependent or device-dependent calibration approaches remain rare: in the most extensible study about mobile phone calibration, Stevens (2012) surveyed only 4 apps that had calibration settings depending on phone models. Initially SLM apps are calibrated with a factory default calibration hard-coded into the application with calibration values from either one specific phone model or for one "average"device. The technical approach developed by Stevens for both model-dependent and unit-dependent calibration consists in a database of calibration values for several phone models or devices contained in the app. Everytime the app is launched, the phone model name is detected and the database is queried to determine if it contains the model's calibration values. If yes, the calibration values associated with the phone model are retrieved and used when implementing the calibration algorithm.

The calibration algorithms are used to adjust mobile phone sensitivity, they can be level-dependent, frequency-dependent or a combination of both. Level-dependent algorithms consist in corrections applied on the to-be corrected phone SPL and frequency-dependent algorithms use filters to correct the frequency response of audio recording signals. At the time of writing, no frequency-dependent calibration algorithms have been documented in the literature. Stevens (2012) recommends the use of digital filtering techniques with finite impulse response (FIR) or infinite impulse response (IIR) filters whose coefficients would be calculated from calibration measurements, however no algorithm was tried out. In a study investigating the accuracy of iOS SLM apps (reviewed in section 1.2.2), Brown and Evans (2011) highlights the use of a frequency-dependent algorithm for the factory default calibration of the app Real Time Analyzer by Studiosixdigital (2013a). The frequency-dependent algorithm compensates for the Iphone® built-in high pass filter. However Studiosixdigital (2013a) does not describe the calibration algorithm .

Calibration of the *NoiseTube* app, developed by Stevens (2012) used a level-dependent algorithm and can be either model-dependent or device-dependent. It is based on the following assumptions:

- "instances of the same model behave sufficiently similar to warrant, for general purposes, the correction of measurements using calibration points determined for the model, rather than the individual device";
- The frequency response of the mobile phones used in the study are "flat enough" and a frequency calibration is not relevant regarding the expertise required and the design time of a filter;

- "microphone characteristics remain stable over time, or at least do not change enough to necessitate recalibration, such as is done with professional SLMs".

The results of the measurements intended to validate these assumptions are discussed in the section 1.2.2.

**Existing Level-dependent calibration algorithms**

According to Stevens (2012), most of SLM apps factory default calibration are based on a level-dependent trimming algorithm and a few apps use a scaling algorithm or a combination of trimming and scaling.

In the trimming algorithm, one constant offset, $\Delta_{phone}$, is added to phone's uncorrected noise levels. $\Delta_{phone}$ is the difference between the reference noise level and the uncorrected noise level at one specific reference noise level.

$$L_{p,calibrated} = L_{p,uncalibrated} + \Delta_{phone} \tag{1.2}$$

Figure 1.4, adapted from Stevens (2012), shows a phone's noise levels calibrated using the Trimming algorithm with a $\Delta_{phone}$ calculates at a reference noise level of 85 dB(A).

In the scaling algorithm, one constant factor, $S_{phone}$ are multiplied to phone's uncorrected noise levels. $S_{phone}$ is the ratio between the reference noise level and the uncorrected noise level at one specific reference noise level.

$$L_{p,calibrated} = S_{phone} \times L_{p,uncalibrated} \tag{1.3}$$

Figure 1.4 shows a phone's noise levels calibrated using the scaling method with a $S_{phone}$ calculates at a reference noise level of 85 dB(A).

The combination of scaling and trimming algorithms consist in phone's uncorrected noise levels that are added to one constant offset and multiplied by one constant factor. Unlike the scaling and the trimming algorithms which require one calibration point (a pair of mobile phone noise level and its corresponding reference noise level) the scaling-trimming method requires at least two calibration points. The factor and the offset are respectively the slope and the y-intercept of the linear equation between the two calibration points.

$$L_{p,calibrated} = S_{phone} \times L_{p,uncalibrated} + \Delta_{phone} \tag{1.4}$$

Figure 1.4 shows a phone's noise levels calibrated using the Scaling-Trimming algorithm with calibrations points at 50 and 85 dB(A). In the 3 previous algorithms, the offset and the factor remain constant regardless of the noise level, the systematic errors are only compensated at noise levels used for the calculations of the offsets and ratios, which are, in the case illustrated in Figure 1.4, the reference noise level of 85 dB(A) for the scaling and the trimming algorithms and reference noise levels of 50 and 85 dB(A) for the combination of scaling and trimming.

Stevens (2012) presents a linear interpolation algorithm which aims to handle the systematic errors depending on the noise level. It uses multiple linear equations calculated from two consecutive calibration points. For each noise level value to calibrate, the algorithm select two calibration points, from a set of measured calibration points, whose phone noise levels include the phone noise level "under calibration". A factor and an offset values are calculated by solving the linear equation between these two calibration points and the calibrated noise level is calculated using Equation 1.4. Theoretically, this algorithm results in a perfect compensation of systematic errors with the calibrated mobile phone levels that match the "perfect fit" line, as illustrated in Figure 1.4.

**Calibration measurements**

At the time of writing, the study by Stevens (2012) was the only one that describes calibration measurements. Factory default calibration measurements conducted by Stevens (2012) aim to measure calibration points at different noise levels. Measurements took place in an anechoic chamber with reference system that included a measurement microphone, an acquisition station and the PC running a data acquisition software. The microphone and the mobile phones were

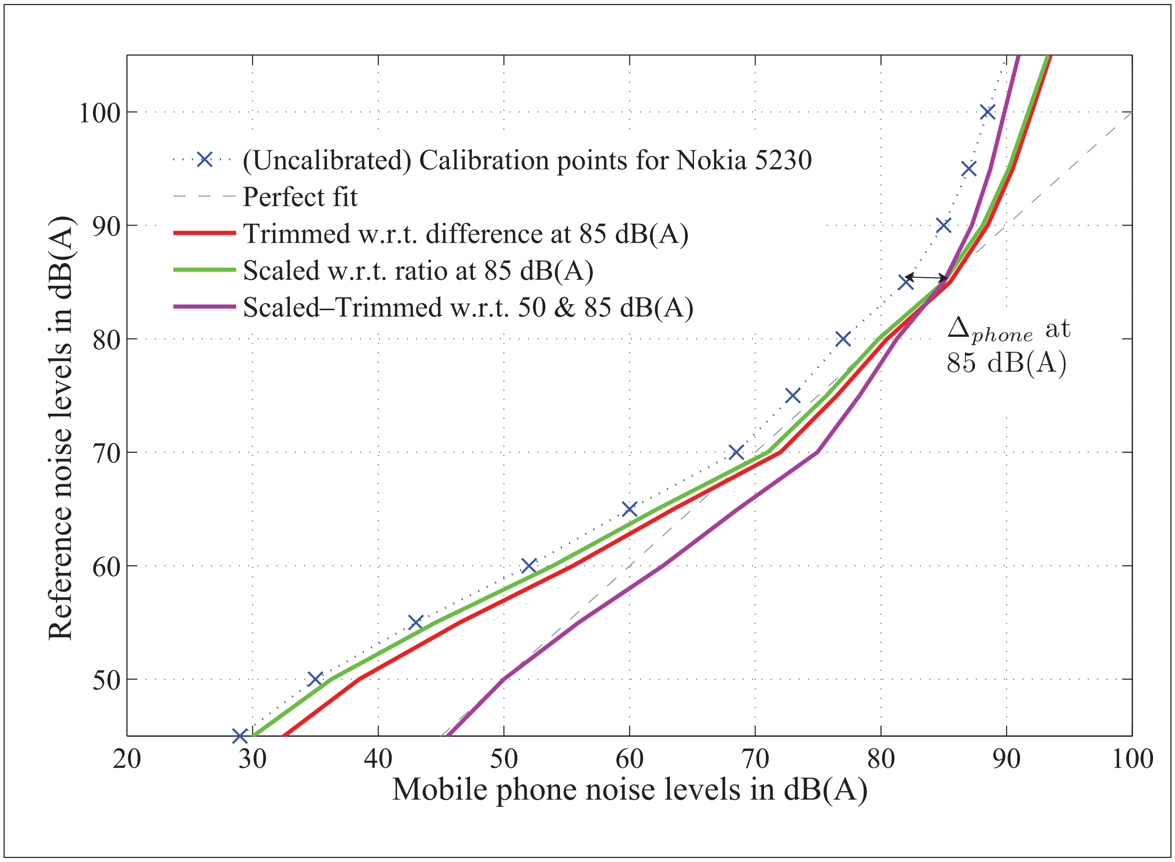


Figure 1.4 Existing calibration methods found in related work, numerically computed for a Nokia 5230 mobile phone, adapted from Stevens (2012)

both directed towards a loudspeaker and from the same distance. A 1 minute white noise signal was played at 16 noise levels ranging from 30 to 105 dB(A) which result in a 16-minutes measurement. The measurement was conducted for 11 units of the same mobile phone model, a Nokia®5230s. Figure 1.5, extracted from Stevens (2012), illustrates the measured calibration points and the phone's model generic calibration points calculated from all the calibration points. Since calibration measurements were conducted without anybody holding the phone, the calibration approach does not take into account the microphone placement error due to body acoustical shadowing and reflections, as discussed in detail in section 1.2.3. Finally, no study investigates calibration measurements conducted in a diffuse field.

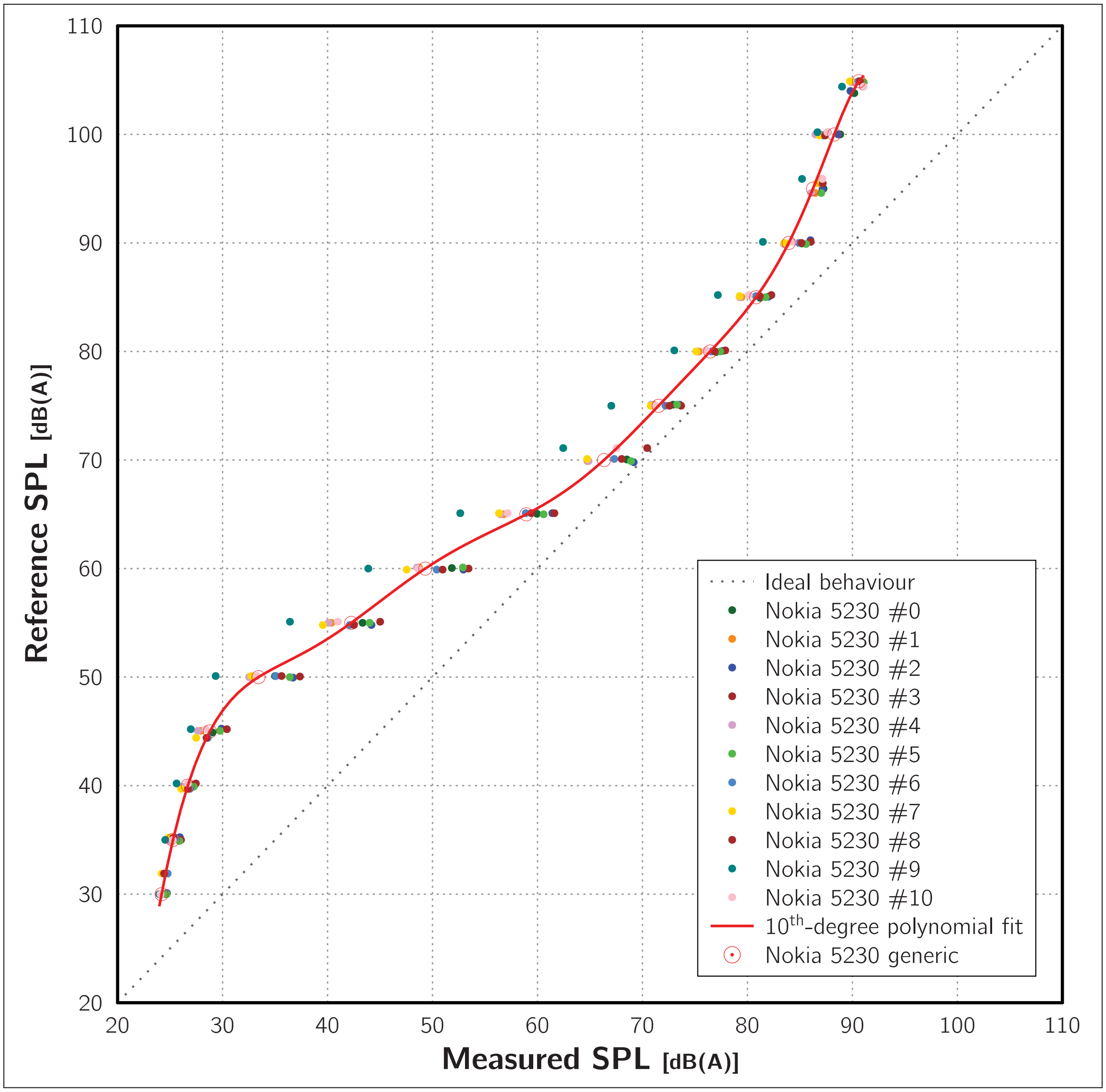


Figure 1.5 Calibration points for our 11 Nokia 5230 handsets (based on white noise calibration), plus the "average" calibration points for a generic Nokia 5230. Reproduced with the permission from Stevens (2012)

#### 1.2.1.5 Specifics of the operating systems

Unlike the iOS operating system, used in Apple devices (iPad®, iPhone®, and iPod Touch®), Android is used in many different mobile phones devices: according to OpenSignal (2012), there were in 2012, almost 4 000 distinct Android-based devices from almost 600 distinct brands such as Samsung, HTC, Motorola and Sony Ericsson.

Discrepancies in the hardware and software used in those devices imply large variety of audio characteristics among the Android-based devices. While the same SLM app is designed for several phone models, the design of an Android-basd SLM app that would provide accurate measurements regardless of the phone model is very challenging. Figure 1.6 shows calibration measurements extracted by the author from the calibration database of the *NoiseTube* app. Noise levels were measured with the *NoiseTube* app (without calibration) on several mobile phones and compared to noise levels measured with a reference system (mainly a professional sound level meter). It highlights the variability of audio recording characteristics between several (uncalibrated) Android-based phone models.

The requirements of the Android compatibility program by Google (2013), of which an extract is quoted below, aims to decrease the variability between devices by recommending audio recording requirements for Android-based devices including flat frequency response of the audio recording chain, specific values for the audio input sensitivity, the linearity and the total harmonic distortion.

> "The device SHOULD exhibit approximately flat amplitude versus frequency characteristics; specifically, $\pm 3$ dB, from 100 Hz to 4000 Hz.Audio input sensitivity SHOULD be set such that a 90 dB sound power level (SPL) source at 1000 Hz yields RMS of 2500 for 16-bit samples.PCM amplitude levels SHOULD linearly track input SPL changes over at least a 30 dB range from -18 dB to +12 dB re 90 dB SPL at the microphone.Total harmonic distortion SHOULD be less than 1% for 1kHz at 90 dB SPL input level."

Even though, these recommendations are intended to improve the audio recording of Android-based phones, they would also decrease the discrepancies of performance between phones' noise level measurements. While these recommendations are not mandatory, Google (2013) notes that the requirements may become mandatory in a future Android version.

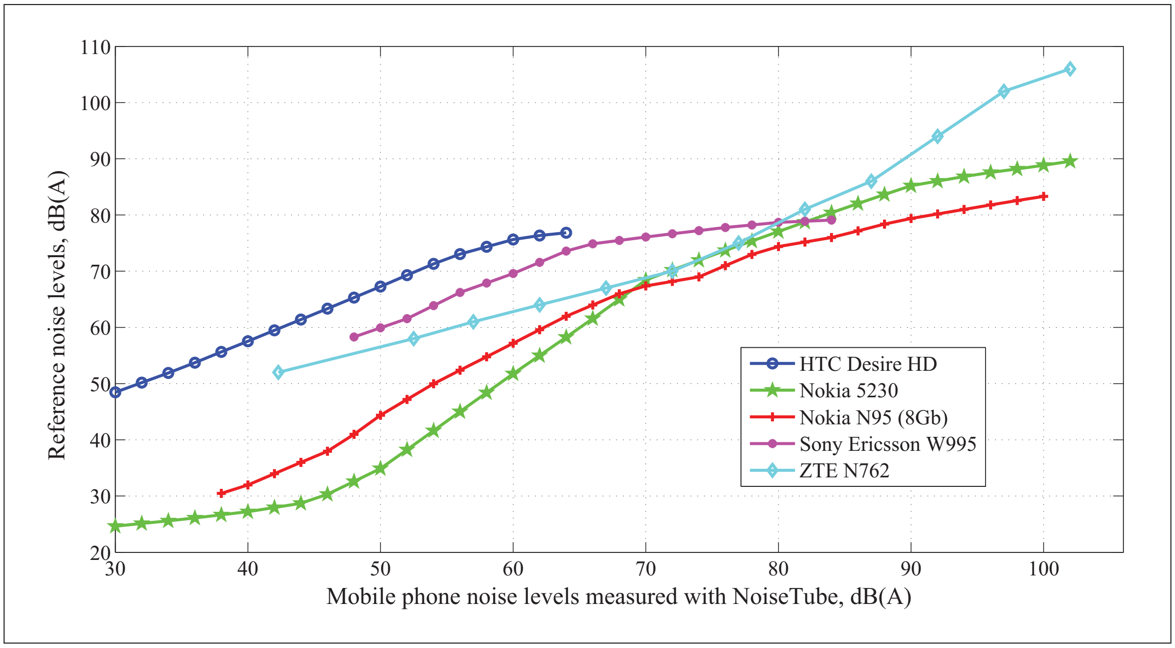


Figure 1.6 Differences between (uncalibrated) Android mobile phones for noise levels measured with NoiseTube app. Data are extracted by the author from the NoiseTube app calibration database

Android audio framework provides the *MediaRecorder.AudioSource* class, Google (2014), that allows one to define among the various audio source available: the microphone audio source only or the microphone audio source processed for different purposes such voice communication or voice recognition. It is worth noting that the microphone audio source is not necessarily the pure microphone signal as audio pre-processings can be inserted by default in hardware and middleware components of the audio recording path (Figure 1.2).

With a small number of possible devices using iOS apps (7 iPhone® and 5 iPod Touch® models), apps developers can more easily customize noise measuring apps for each device and take into account of the different electro-acoustical characteristics of each model for calibration. Faberacoustical (2012a) evaluates the frequency response of several iOs devices with the built-in and headset microphones and shows:

- Important variation of the frequency response range between the iPhone (1st generation), iPhone 3G and iPhone3Gs, as highlighted in Figure 1.7;

- The presence of an high-pass filter with the low-frequency roll-off starting at 250 Hz, implemented in several Apple® mobile phones and affected both built-in microphone and headset recordings, as highlighted in Figure 1.8.

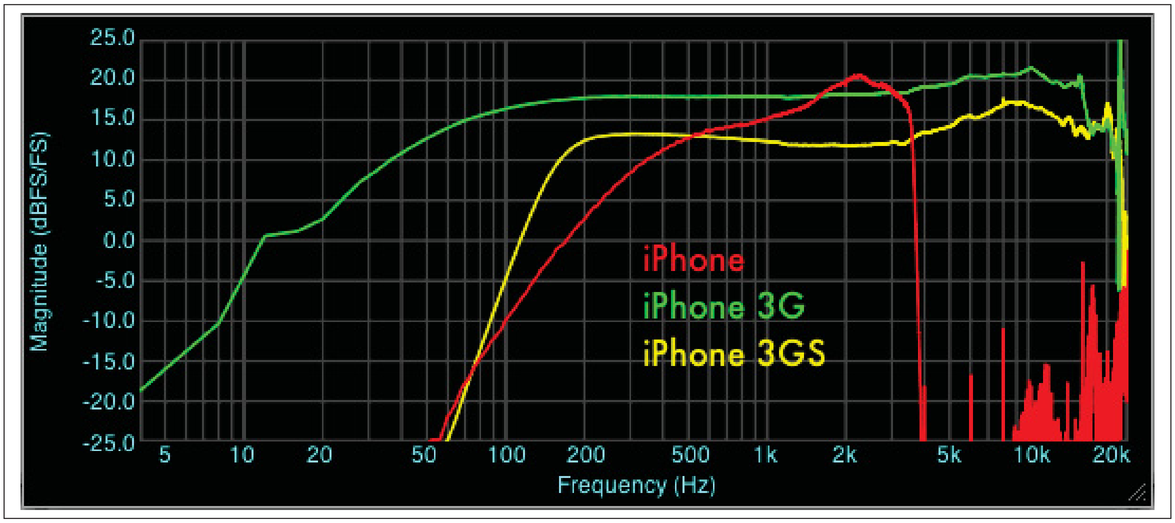


Figure 1.7 Built-in iPhone Microphone Frequency Response Comparison. Reproduced with the permission from Faberacoustical (2009)

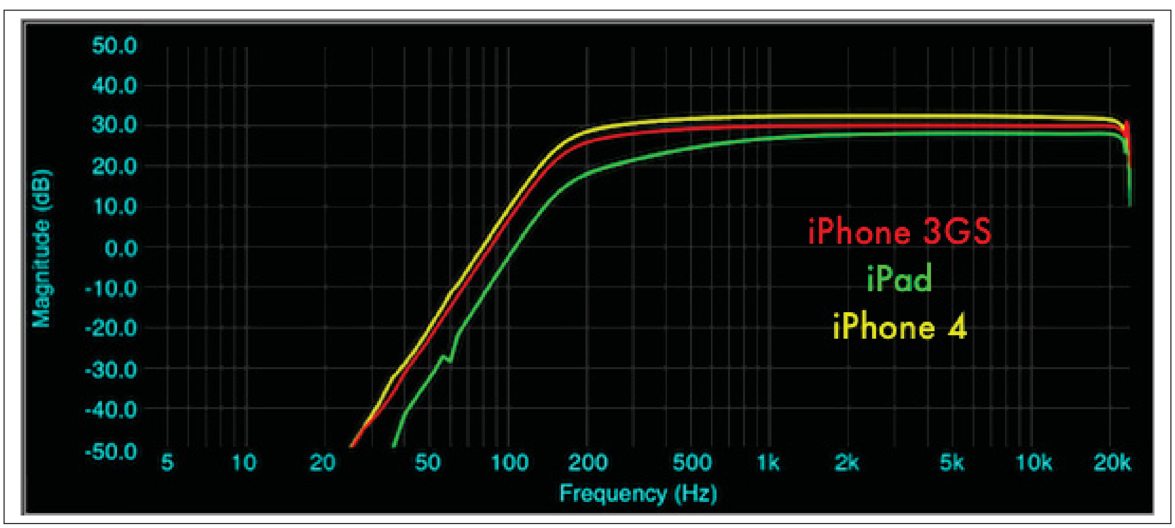


Figure 1.8 iPhone 4 Headset Microphone Frequency Response Comparison. Reproduced with the permission from Faberacoustical (2009)

With the iOS 5, released in 2011, the audio framework, Core Audio, provides an audio session category called "Measurement" which allows to disable the limiter and control the input gain of the built-in microphone. With the iOS 6, released in 2012, the audio framework allowed to disable (in measurement mode) the high pass filter that was implemented on recordings with the headset and built-in microphones. Regarding the variability of built-in microphones within the same model, according to Studiosixdigital (2013b), built-in microphones of iOS devices "tend to be very consistent from one unit to the next". As stated by Faberacoustical (2012a) shortly after the released of iOS 6, this improvement to iOS 6 "will significantly improve the quality of acoustical measurements that can be made with the iPhone, iPad, or iPod touch, without requiring a dock connector accessory for audio input".

### 1.2.2 Accuracy of mobile phones as SLMs

This section focuses on the accuracy of mobile phones used as SLMs. First the accuracy of standardized noise exposure instruments are discussed. It includes an overview of the main electro-acoustic characteristics, the sources of errors due to the instrumentation and the methods of evaluation to assess the performance of such instruments. Second, studies that have evaluated mobile phones as SLMs are presented.

#### 1.2.2.1 Performance of standardized noise exposure instruments

The performance of noise exposure instruments is ensured by their compliance with standards and their qualification for a type classification referred to as Class or Type. The type classification summarizes the overall measuring performance of an instrument. Class/Type-1 is more accurate and precise than Class/Type-2. Table 1.1 resumes the International Electrotechnical Commission (IEC) and American National Standards Institute (ANSI) standards for noise exposure instrumentation.

There are three levels of evaluation tests that aim to verify the compliance of the requirements:

Table 1.1 International and american noise instrumentation standards

| | |
|---|---|
| **Noise dosimeter** | ANSI 1.25 1991: Specifications for Personal Noise Dosimeters, ANSI (2007a). |
| | IEC 61252: 1993, Electroacoustics - Specifications for personal sound exposure meters, IEC (1993) |
| **Sound Level Meter** | ANSI S1.4: 1983-Specifications for sound level meter (ANSI (1983)), ANSI S1.43: 1997-Specifications for Integrating-Averaging Sound Level Meters, ANSI (2007b). |
| | IEC 61672- Electroacoustics, Sound level meters, Part 1: Specifications, IEC (2002), part 2: Pattern evaluation tests, IEC (2003a), part 3 : Periodic tests |

- The "pattern evaluation" which is conducted by national metrology laboratories. It verify the compliance of the requirements for the complete range of evaluation tests in order to provide the calibration certification to instruments' manufacturers;
- The "periodic verification" which is, according to Campbell (2014), "an annual or bi-annual examination by an accredited laboratory where a sub-set of the pattern evaluation tests are performed to confirm that the instrument is still within its original calibration limits";
- The field calibration which is the check of the instrument performance on the field by its operator ensure. It requires the use of a sound calibrator, conformed to the requirements of calibrator standards such as IEC (2003b) or ANSI (1997).

The main electro-acoustic characteristics tested during the "pattern evaluation" and "periodic verification" tests are:

- The frequency response, defined by Goelzer *et al.* (2001) as, "the deviation between the measured value and the true value as a function of the frequency". It mainly relies on the frequency response of the microphone;
- The dynamic range which is the range of decibels over which a noise meter measures noise levels linearly and within specified tolerances. As stated by Goelzer *et al.* (2001),

the range is restricted at low levels by the electrical noise of the instrument and at high levels by "the signal distortion caused by overloading the microphone or amplifiers";

- The directional characteristics which correspond to an instrument's property to measure noise from various directions. The standards provide tolerance for maximum allowable deviation of specific sound-incidence angles based on a reference direction. When a dosimeter is worn on a person, the directional characteristics are impacted by the person themself and the location of the microphone;
- The pulse range which is defined in ANSI (2007a) as "difference in decibels between the peak signal level of a tone burst and the level of continuous low level signal specified by the manufacturer".

Overall, the standards' requirements for noise exposure instruments are an omni-directional response over a large frequency range, a dynamic range of at least 50 dB (from 80 dB to 130 dB), an accurate response for frequency weightings A and C (which implies a flat frequency response of the instrument), a good response to short-duration signals and a low sensitivity to environmental conditions such as temperature, radio-frequency electromagnetic fields, relative humidity, static pressure and vibrations. The requirements for the frequency and directional characteristics in the american standard for personal noise dosimeters, ANSI (2007a), corresponds to the tolerances for a Type-2 sound level meter defined in ANSI (2007b) . Generally, the requirements of the IEC an ANSI standards are compatible however they may differ in some details. For example, IEC (2003a) specifies that sound level meters are calibrated or an acoustic free field while ANSI (2007a) requires a random incidence calibration. Earlier versions of the SLM standard IEC (2002) provided the basic accuracy of class 1 and class 2 SLMs: $\pm 0.7 dB$ and $\pm 1 dB$ respectively. Since these values are specific to a one reference level and frequency for specific laboratory conditions, and because, according to Campbell (2014), "these conditions hardly ever exist in relation to a practical noise measurement, they [the values of accuracy] are not very helpful and so they do not appear in the more recent version of the standards".

More specifically to noise dosimeters, according to Giardino and Seiler (1996), the main errors associated with electro-acoustical characteristics of the device are the frequency response error, the sensitivity error and the linearity error. The A-weighting frequency response error is mainly due to the instrument's microphone frequency response. It is defined by Giardino and Seiler (1996) as:

$$a_j = A_j(m) - A_j \ (dB) \tag{1.5}$$

where:

- $a_j$ is the A-weighting frequency response error of the noise dosimeter in the $j$th frequency band in dB;
- $A_j(m)$ is the measured A-weighting value of the noise dosimeter in the $j$th frequency band in dB;
- $A_j$ is the true value of the A-weighting value in the jth frequency band in dB.

Tests evaluating the A-weighting frequency response error according to IEC (2003a) are conducted in an anechoic room with pure tone signals from 200 Hz to 8000 Hz and a signal level at 1 kHz set as a reference sound level. The linearity error is defined by Giardino and Seiler (1996) as "the deviation in the ability of the instrument to indicate an output equivalent to a known input over a 30-dB range above the criterion level" where the criterion level, also called the permitted exposure level, is the steady noise level permitted for a full eight-hour working day. The sensitivity error is the deviation of the instrument at the criterion level. In calibration tests, the errors are evaluated using coupler system and a pure tone signal at 4 kHz. Finally, impulse noise is also a source of errors associated with the noise dosimeter characteristics: noise dosimeters are not designed for measuring impulse noise. NIOSH (2008) mentions that "no instrument is capable of characterizing exposure or hazard on the market". Kardous *et al.* (2005) mentioned the noise dosimeters limitations for measuring impulse noise because of theirs limited frequency response and a limited peak detector dynamic range.

#### 1.2.2.2 Evaluation of the performance of mobile phones as SLMS

No standard describes or recommends electro-acoustical requirements specifically for mobile phones used as SLMs or noise dosimeters. However, existing standardized tests have been performed to evaluate the performance of a SLM app used together with an external microphone. According to the test reports provided by Studiosixdigital (2013c), an iPad®2 using the AudioTools 5.5 with an external audio interface iAudioInterface2 and an AudioControl CM-145 measurement microphone, have successfully passed the Class 1 periodic tests of ANSI S1.4-1983 and IEC 61672-3, IEC (2003c), for the weighting networks tests, the linearity test, the time averaging test and the impulse test. The SLM app was only used as a "noise metric calculator" since the external microphone and audio interface tackle most of the audio recording processing. The test results showed that the computation of the measurement metrics and the filters included in the app were adequate for a Type-1 Sound Level Meter.

The studies that have evaluated the quality of mobile phone measurements and described in this section, were based on noise levels comparisons of one existing app over measurements from a professional sound level meter. The goal behind most of these studies was more to investigate the performance of a specific SLM app than investigate the capability of mobile phones to measure accurately noise levels.

SafetyAwakenings (2013) assessed the accuracy of 30 iOS SLM apps with one iPad® and its built-in microphone. Noise levels for various sound sources were measured by the apps and compared with the readings of a calibrated Type-2 sound level meter. For each app, the factory default calibration setting was used. Each of the 4 types noise sources (pure tone signals of 1 kHz and 8 kHz, a 30-second sound recording, and a prerecorded explosion) were played at one noise level. The measurement environment is poorly described as SafetyAwakenings (2013) only mentions that the measurement did not take place in an acoustical laboratory. The analysis of the measurements shows that only 3 apps out of 30 have results similar to the sound level meter readings. Table 1.2 contains the differences in dB(A) between the sound level meter readings and the noise levels measured with the 3 best iOS apps. Among the 30 apps, 13 apps were considered "inadequate" which clearly demonstrates the need for rigourous mobile phone app calibration procedure.

Table 1.2 Difference, in dB, between the sound level meter readings and the noise levels measured by the 3 best iOS apps, extracted from SafetyAwakenings (2013)

| **Sound sources** | **Type-2 SLM Noise level in dB** | **Differences in dB** | | |
|---|---|---|---|---|
| | | SPLnFFT (app) | SoundMeter+ (app) | SPL Meter (app) |
| Pure tone (1 kHz) | 88.5 | 0.4 | 2.8 | -0.2 |
| Pure tone (8 kHz) | 94.3 | -0.4 | 8.0 | 6.8 |
| 3- second noise | 82.2 | 0.2 | 0.3 | n/a |
| Explosion | 87.6 | 0.1 | 3.1 | 0.1 |

Brown and Evans (2011) investigated the accuracy of the iOS apps SignalScope Pro by Faberacoustical (2013) and Real Time Analyzer by Studiosixdigital (2013a) for one iPhone®3GS device and its built-in microphone. One-third octave bands noise levels, overall and A-weighted noise levels measured by the SLM apps were compared to the readings of a calibrated professional Type-1 sound level meter. Measurement were conducted in real-world conditions with real-world noise sources. Brown and Evans (2011) showed that, unlike SignalScope Pro by Faberacoustical (2013), Real Time Analyzer implements a frequency-dependent calibration with a boost at low frequencies to compensate for the high-pass filter applied on the Iphone®3GS. As shown in table 1.3, differences between the A-weighted noise levels in dB(A) measured by the SignalScope Pro app and the sound level meter readings were less than 4 dB(A) for the various real-world noise sources. Brown and Evans (2011) concluded that "caution is required in the measurement of noise levels below 40 dB(A), above 80 dB(A) or with significant low-frequency noise components." At the time of writing, there was no comparative study similar to Brown and Evans (2011) or SafetyAwakenings (2013) for Android SLM apps.

Table 1.3 Difference, in dB(A), between the sound level meter readings and the noise levels measured with the SignalScope Pro app with an Iphone®3GS, adapted from Brown and Evans (2011)

| **Noise source, dB - dB(A)** | **Type-1 SLM** | **SignalScope Pro app** | **Differ-ence** |
|---|---|---|---|
| | **in dB(A)** | | |
| Boardroom (145 m3) – road traffic and services noise, 1.7 | 38.8 | 39.4 | 0.6 |
| Quiet office, services noise, 1.2 | 49.6 | 45.8 | 3.6 |
| Compressor, 0.9 | 54.2 | 54.6 | -0.4 |
| Road traffic noise, -0.1 | 75 | 72.2 | -2.8 |
| Car horn ( 3 metres), -1 | 87.5 | 84 | -3.5 |

Santini *et al.* (2009) assessed the accuracy of noise levels measured with uncalibrated mobile phone. The measurements took place in a quiet room with 3 mobile devices and a Type-2 sound level meter located on a table. While the conclusions of the study do not provide any statistical analysis of the measurements, the major value of the study is the use of "real-world" sound sources (audio recording of a traffic jam) in a laboratory environment.

The work by Stevens (2012) on the quality of *NoiseTube* app was the most extensive investigation. Stevens (2012) conducted several measurements to test and validate the following assumptions on which the calibration of *NoiseTube* app was based:

- A phone model-dependent calibration;
- A noise level-dependent algorithm without frequency-dependent algorithm;
- No need for field calibration.

Based on the calibration measurements conducted with several units of the same phone model, whose methodology described in section 1.2.1.4, Stevens (2012) showed that, for the specific phones units he tested, the variations between individual units of the same model was small enough to validate to use a model-dependent calibration instead of calibration unique for each individual unit.

Based on measurements conducted with 27 pure tone signals, from 50 Hz to 20 kHz for sound levels from 60 dB to 90 dB, Stevens (2012) concluded that the frequency response of the phones he tested was "flat-enough" and a frequency-dependent algorithm was not necessary.

The stability of microphone characteristics over time was investigated with two calibration measurements conducted with a five months interval, with only one mobile phone unit. Although the drift was only 0.29 dB, Stevens (2012) recommended to conduct additional measurements with a longer time interval between the measurements and with more than one phone. Overall, Stevens's measurement procedure presents several limitations:

- Calibration measurements were conducted (in a laboratory environment) with only one artificial white noise source;
- Only a few units of one phone model were investigated in detail.

The validation of the *NoiseTube* app calibration was carried out by Stevens (2012) in laboratory and outdoor environments. The laboratory validation procedure consisted in measuring in an anechoic room white noise signals at 16 noise levels with one phone unit. The phone noise levels were then compared to the readings from a reference system. It is worth noting that the calibration algorithm implemented in the phone unit was specific to this particular phone unit, which means that the same phone unit was used for calibration and validation measurements. This calibration approach remains always more accurate than a model-specific approach that is based on an average of calibration points measured with several units of the model. According to the measurements results, shown in Figure 1.9, Stevens (2012) highlighted an average absolute error of around 1 dB, that drops below 0.6 dB for noise levels below 100 dB(A). Figure 1.9 also clearly shows the limitation of the calibration algorithm at high levels starting at 95 dB(A) due to saturation of the phone's audio recording path. Frequency response of the calibrated phone was assessed using pure tones of different frequencies and levels. Stevens (2012) reported that the calibrated mobile did not meet the IEC (2002) frequency response requirements for Class 2 SLMs. The results of the outdoor validation are presented in the following sections as the quality of the phone noise level measurements in "real-world" conditions are discussed.

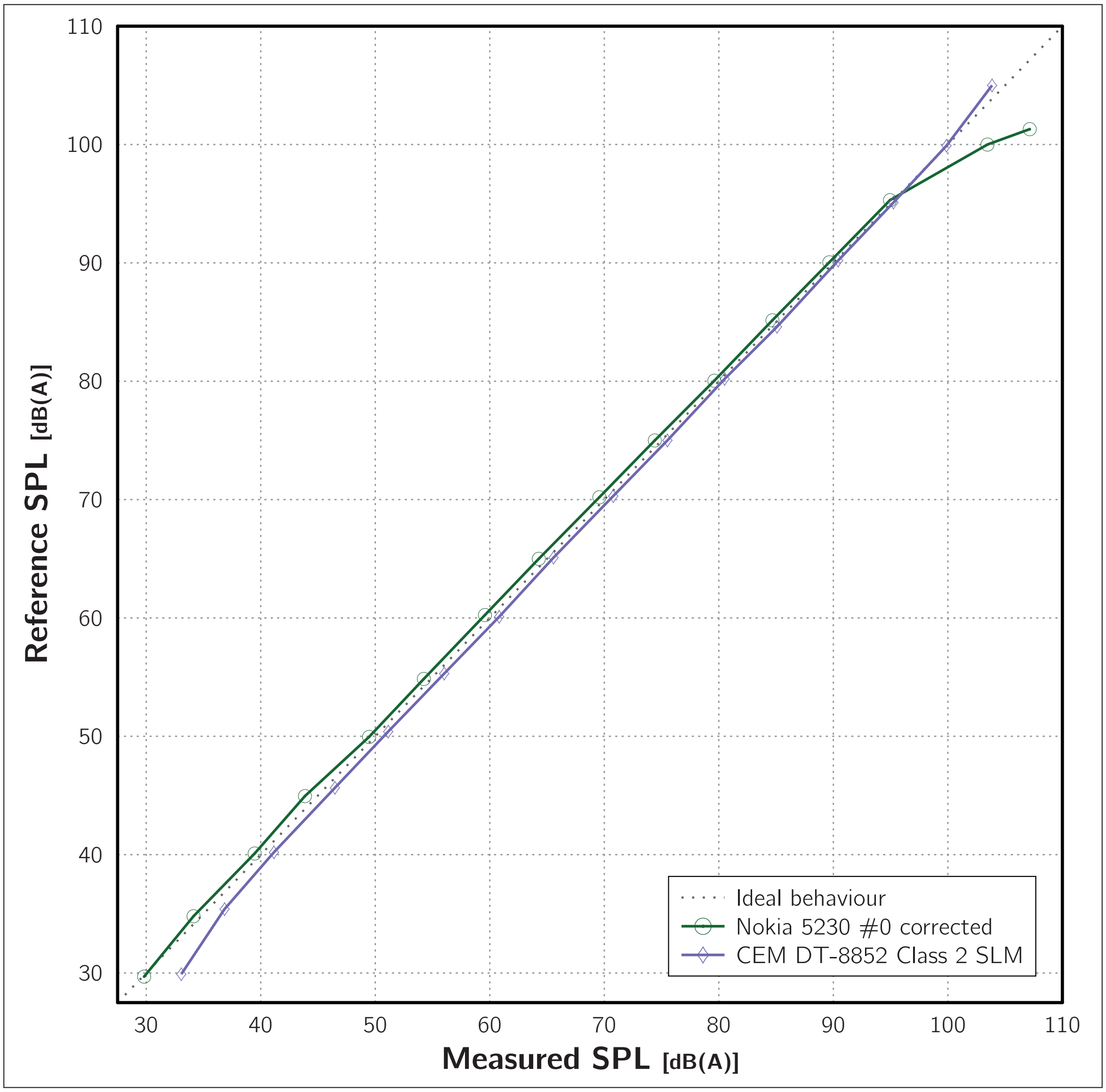


Figure 1.9 Validation measurements for white noise made by the calibrated Nokia 5230 #0 and a professional SLM. Reproduced with the permission from Stevens (2012)

In conclusion, the discrepancies between the measurement methodologies highlight the lack of standardized methodology to evaluate the accuracy of mobile phones as SLMs. The methodologies employed vary from measurements in laboratory environments with artificial noise sources to measurements in real-world conditions. A very limited number of phones models have been investigated (iPad®2, iPhone®3GS, Nokia® N95 8GB, Nokia®5230s), always with the built-in microphone and only with one phone unit of each model. Stevens (2012) provided the most extensive investigation about mobile phones as SLMs, however the study investigated only one phone model (and its built-in microphone) and followed a procedure with several limitations.

### 1.2.3 Noise exposure measurements accuracy with regards to the use of mobile phones

In the first part of this section, the main sources of errors and the uncertainties associated with noise exposure measurements with standardized noise exposure instruments are presented. A second subsection focuses on the microphone placement error and on nonstandard microphone positions with studies mostly conducted with noise dosimeters. Finally, a third subsection discusses the very rare projects and studies where mobile phones were used for noise exposure measurements.

#### 1.2.3.1 Overview of the noise exposure measurement sources of errors and uncertainties

Unlike CSA (2013) or ANSI (1996), the international and french standards, ISO (2008) and AFNOR (2002), require that the measured noise exposure is presented with an overall measurement uncertainty (also referred to as the expanded uncertainty, U) added to the measured noise exposure levels. According to ISO (2008), the main sources of uncertainties of noise exposure assessment are:

- The sampling of the noise levels;
- The estimation of the task durations (only for the task-based measurement strategy);
- The instrumentation.

The uncertainty associated with the instrumentation includes:

- The standard uncertainty due to the instrumentation used;
- The standard uncertainty due to the microphone location during the measurement.

According to ISO (2008), the standard uncertainty due to the instrumentation used "can not be derived directly from the tolerance limits given in instrument standards IEC 61672-1 [IEC (2002)] and IEC 61252 [IEC (1993)]", as it "depends on the characteristics of the noise exposure and the environmental conditions". The standard uncertainty due to microphone location is associated either with the acoustic reflections due to worker's body (if dosimeters are used) or the difference of measurement location between the worker's head and the instrument location (if SLMs are used). According to Giardino and Seiler (1996), "the accuracy of an occupational noise exposure measurement, obtained by the use of a personal noise dosimeter, is commonly specified as being within $\pm$ 2.0 dB". Similar to the two types of uncertainties characterized in ISO (2008), Giardino and Seiler (1996) identified two groups of errors that affect the overall accuracy of a real-world noise dosimeter measurements: errors associated with the instrument characteristics, detailed in the section 1.2.2.1, and the microphone placement error, detailed in the following section. Table 1.4 presents the two standard uncertainties associated with the instrumentation given by ISO (2008) standard. The values are based on empirical data, however the standard does not reference any study or report.

Table 1.4 Standard uncertainties associated with instrumentation for the different instrument types, adapted from ISO (2008)

| **Instrument type** | **Standard uncertainty due to the instrumentation used (dB)** | **Standard uncertainty due to microphone location (dB)** |
|---|---|---|
| Class 1 Sound level meter (IEC 61672-1:2002) | 0.7 | 1 |
| Personal sound exposure meter (IEC 6125) | 1.5 | |
| Class 2 Sound level meter (IEC 61672-1:2002) | 1.5 | |

When the noise exposure measurements are conducted following the requirements of ISO (2008), the following sources of uncertainties are considered to be insignificant or already included in the noise level sampling:

- The false contributions from wind, airflows, impact on the microphone and the microphone rubbing on clothing;
- The lacking or faulty work analysis;
- The contribution from non-typical noise sources, speech, music, alarm signals and non-typical behavior. Ryherd *et al.* (2012) showed that the wearer's voice can increase the noise level measured by body-mounted noise dosimeters by 5 dB in medium-level noise environments.

Finally, another source of error associated with the "real-world"measurements concern the clothing of the noise dosimeter's wearer. Johnson and Farina (1977) investigated the effect of clothing on the A-weighted noise levels measured with a noise dosimeter microphone mounted on a shoulder. Variations of 2.4 and 1.4 dB(A) were observed between a "light cotton uniform" and a "simulated leather jacket" while measuring a falling spectrum noise (with a C-A of 11) and a pink noise (with a C-A of 2) respectively.

#### 1.2.3.2 Microphone placement error and nonstandard positions

The microphone placement required by the standard ISO (2008) for noise dosimeters and SLMs is summarizes in Table 1.5. In addition to these standardized microphone placements, others microphone locations for noise exposure measurements have been discussed and studied in the literature:

- In the devices for noise exposure monitoring, presented in the papers of Michael *et al.* (2011) and Mazur and Voix (2013), the microphones are integrated within an earpiece, inserted into the ear;

- Byrne and Reeves (2008) investigated nonstandard noise dosimeter microphone positions such as the microphone on a subject's chest and the microphone hanging from a subject's hard hat.

Table 1.5 Recommended location of the microphone adapted from ISO (2008).

<table>
<tr><th>Instrument</th><th>Microphone location</th></tr>
<tr><td>Noise dosimeter</td><td>On the top of the shoulder at the side of the most exposed ear: at least 0.1 m from the entrance of the external ear canal and approximately 0.04 m above the shoulder</td></tr>
<tr><td>Integrating Sound Level Meter</td><td rowspan="2">At the centre plane of the worker's head, on a line with the eyes, with its axis parallel to the worker's vision, and without the worker present. At fixed workstations: hand-held or fixed sound level meters<br>If the worker has to be present: at 0.1 m and 0.4 m from the entrance of the external ear canal and at the side of the most exposed ear.</td></tr>
<tr><td>Sound Level Meter</td></tr>
</table>

The microphone placement error is defined by Giardino and Seiler (1996) as "the difference between the measurement of the sound field perturbed by the test subject and the undisturbed sound field (no worker present) at the center-of-head position". The microphone placement error is caused by the body shadowing and reflections. Seiler (1982) showed that microphone placement error depends greatly on the frequency, the type of acoustic field (diffuse or free-field) and the angle between the sound source and the microphone position in free-field situations. In their study about the uncertainties associated with noise dosimeters measurements, Giardino and Seiler (1996) highlighted that the microphone placement error only is in general greater than all the errors associated with the instrument characteristics, they also proved that the accuracy noise dosimeter measurements is in the range of $\pm$ 2.0 dB(A) for situations when measurements are conducted in a diffuse field or when "the dosimeter microphone is placed at the shoulder of the worker's most exposed ear". Finally, two main conclusions were drawn:

- "when sampling occupations where the worker is mobile with respect to the noise source, the measurement errors approach those of diffuse field";

- "if the noise dosimeter microphone is consistently located at the most exposed ear side, the overall errors introduced into the noise dosimeter measurement are minimized".

Table 1.6 summarizes the results of Giardino and Seiler (1996) and shows how the acoustic field affects the estimation of the noise dose measurement; the microphone placement (located on the left shoulder) and the incidence angle mentionned in the table are illustrated in Figure 1.10. Concerning the effect of the acoustical field, according to Giardino *et al.* (1976), environments with little or no reflecting surfaces or with highly directional noise sources accentuate the microphone placement error.

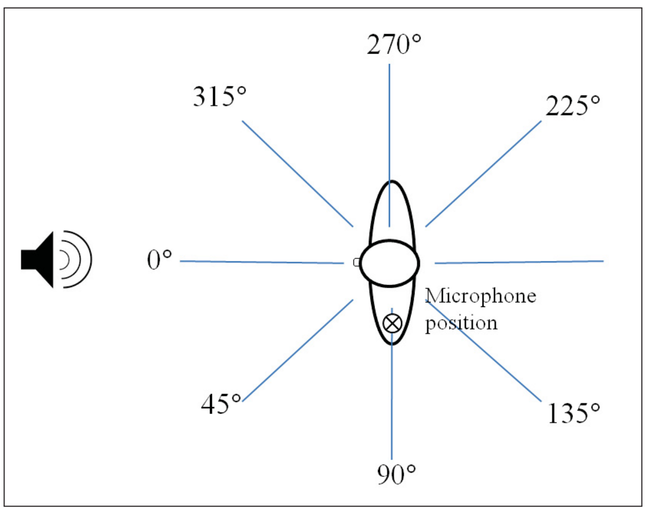


Figure 1.10 Incident angles for microphone placement, adapted from Giardino and Seiler (1996)

Table 1.6 Difference between the noise dose estimated from a real and ideal noise dosimeter, adapted from Giardino and Seiler (1996)

| **Diffuse field or incident angle (free-field)** | **Estimated dosimeter error** |
|---|---|
| Diffuse field | Overestimation by about 1 dB |
| 0° to 225° | Overestimation by as much as 3 dB |
| 270° to 315° | Underestimation by as much as 4.3 dB |

The study of nonstandard noise dosimeter microphone positions by Byrne and Reeves (2008) shows that, in general, the overall errors due to microphone placement are minor in the diffuse field. In the free-field, the errors depend greatly on the microphone position and supporting structure, the noise source location and the noise spectrum. In the diffuse field and for the microphone resting on subject's chest and the microphone dangling from hard hat, the A-weighted noise levels are overestimated by about 1 dB and slightly underestimated by less than 1 dB respectively. The A-weighted microphone placement errors in free-field, for a machinery noise spectrum, at various incident angles are illustrated in Figure 1.11. In order to minimize the microphone placement error, the Exposure Smart Protector, manufactured by doseBusters™, which is the device that were used in the Byrne and Reeves (2008) study, computes the noise exposure from the higher noise level received by one of two microphones, located at each side of the head. This approach differs from the unique shoulder-mounted microphone and according to Byrne and Reeves (2008) "provide a “conservative” estimate of a worker's actual noise exposure in a directional sound field."

#### 1.2.3.3 Mobile phone noise exposure measurements

Most of the apps specifically designed for occupational noise exposure feature a basic sound level meter functionality. A few apps provide an elaborated noise dosimeter feature with the calculation of the main noise exposure metrics, such as the SoundOfTheCity app, Ruge *et al.* (2013) for Android-based phone and the SoundMeter app by Faberacoustical (2013) for iOS-based devices, however, their measurement accuracy or precision are never documented. Moreover, these apps are mostly designed to be used with the phone hand-held and this approach becomes hardly suitable for long-term continuous noise exposure measurements.

Field validation of the *NoiseTube* app, conducted by Stevens (2012), remains, at the time of writing, the most extensible study that investigates phone noise exposure measurement in an real-world environment. It consisted in measuring noise levels during a walk in an urban area with a portable Type-2 SLM and the "device-specific" calibrated phone hand held. Although, the difference of noise levels over the overall 81-minutes walk, was less than 1dB, Stevens

(2012) hardly draw firm conclusions based on the measurement: first, over windy intervals, the phone noise levels were overestimated by 10 dB(A) and, second, most crucially, the two devices was not even measuring the same metrics. While the SLM was measuring 1-second noise level with an averaging time set as slow, $L_{A,S}$, every second, the *NoiseTube* app was measuring 1 second $L_{A,eq}$ every 2 seconds. Since the goal of the *NoiseTube* app is to measure outdoor environmental noise, the validation measurement took place in an urban environment where, according to Stevens (2012), the main noise source was the traffic noise. Thereby, the range of the measured noise levels was not completely representative of real-world noise exposure environments expected in industrial environments.

Rana *et al.* (2010) investigated the errors associated with real world mobile phone measurements with an in-house SLM app and four different phone placements: held in the hand, inside the trouser's pocket, on a belt case and in a bag. According to Rana *et al.* (2010), the sound source was "a chain of one second wide pulses of varying amplitudes". Following an undocumented measurement procedure, noise levels measured with a Type-2 SLM were compared to the readings of the SLM app. Rana *et al.* (2010) stated that their SLM app had an accuracy of $\pm$2.7 dB for the phone hand held, $\pm$3.1 dB with the phone in a trouser's pocket and $\pm$4.1 dB with the phone in a bag.

## 1.3 Summary of the literature review

The literature review explored three areas related to the calibration of a mobile phone-based solution for measuring noise exposure. The first section addressed research related to the design of a mobile phone as SLM. The second section focused on research about the accuracy of mobile phones as SLMs. Finally, the third section discussed research related to the accuracy of noise exposure measurements in real world environments with an emphasis on the sources of errors and uncertainties.

There is a lack of research regarding the electro-acoustical limitations of mobile phones. Some external microphones have been specifically designed for noise level measurements with mo-

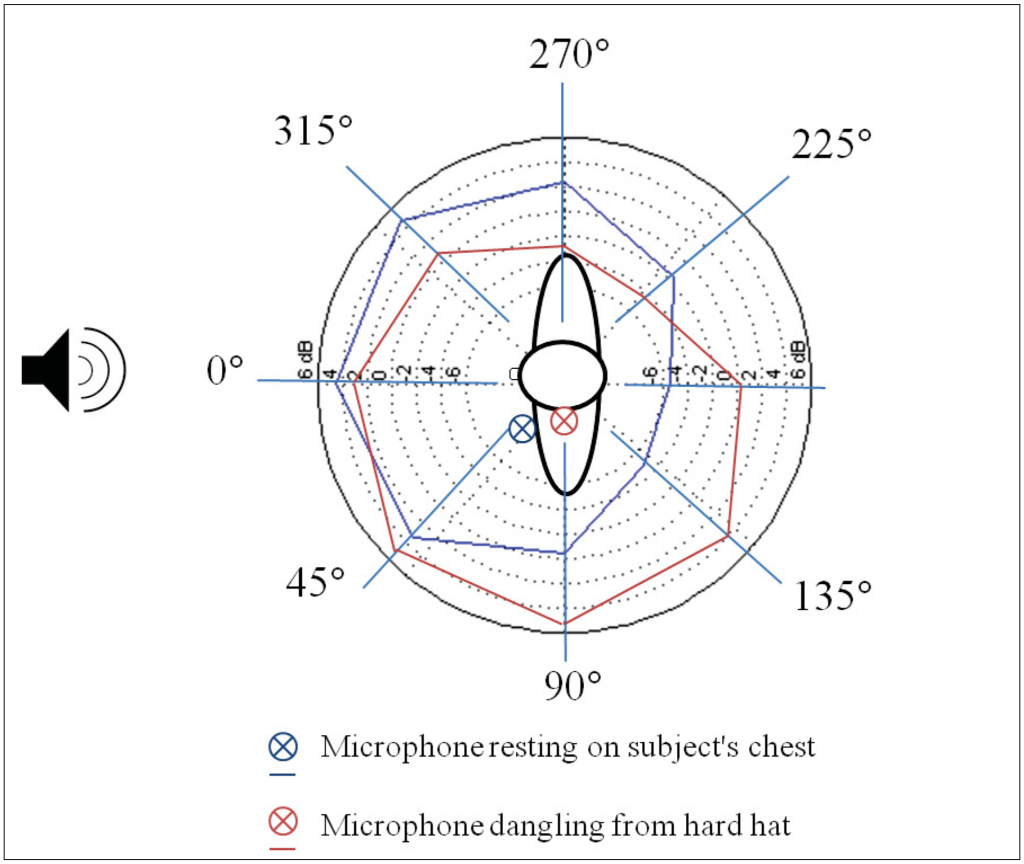


Figure 1.11    Mean A-weighted microphone placement errors (in dB) for the "Left-Chest" and "Left-Hanging"positions, adapted from Byrne and Reeves (2008)

bile phones. They are intended to be used as sound level meters, using the *task-based* sampling approach in the case of noise exposure measurements. They aim to have better acoustics characteristics than the built-in microphones, especially regarding directivity and frequency response. A few of them also integrate a microphone preamplifier and analogue to digital (A/D) converters and even meet some of the ANSI and ISO Type-2 specifications. Although these external microphones improve the quality of the noise level measurements, their cost and their accessibility remains a barrier for widespread use of mobile phones for measuring noise exposure. Finally, the use of wearable external microphones such as headset in-line microphones, have not been studied.

Most of the SLM mobile phone applications (apps) available through "app stores" (Google Play, Apple app store, Nokia Store) are designed and used for recreational purposes. The review of the existing apps shows that the most common factory default calibration consist in a single level and frequency- independent correction regardless of the phone model. More elaborated and accurate approaches consist in calibrating a mobile phone depending on the phone model or depending on a particular unit. A database of an SLM app calibration measurements shows the discrepancies in sensitivity of mobile phone models and highlight the need for a calibration that depends on the phone models. While all calibration algorithms described in the literature are level-dependent algorithms, based on SPL corrections, frequency-dependent algorithms, based on filters that correct and flatten the frequency response, have not been investigated in the literature. Regarding the calibration measurements, no study investigates measurements in a diffuse field or the impact of the acoustic field on the quality of the calibration. The most exhaustive study on factory default calibration of mobile phones found was conducted by Stevens (2012) and led to a calibration approach that has the following characteristics:

- A phone model-dependent calibration; this author assessed that differences between individual units of the same model were small enough so that the calibration can be independent of the unit used;
- A level-dependent algorithm; a frequency-dependent calibration was found not relevant, as he assessed that the frequency response of the phone model he used was "flat enough";
- No field calibration; as he concluded that differences between two calibration measurements conducted with a five months interval with one mobile phone were, again "small enough".

However, Stevens (2012)'s calibration approach presents several limitations:

- Calibration measurements were conducted with only one artificial white noise source, only in an acoustical free field environment;

- only a few units of the one phone model were investigated during the calibration measurements;
- The microphone placement error due to body acoustical shadowing and reflections, the importance of which is discussed in detail in section 1.2.3, is not taken into account in the calibration compensations;
- The saturation of the audio recording chain at very high noise levels is not specifically considered: *NoiseTube* app was dedicated for measuring environmental noise sources with a range of noise levels of interest below 90 dB(A).

The few studies that evaluated the quality of mobile phone measurements, detailed in section 1.2.2, were based on noise levels comparisons of an existing app over measurements from a a professional sound level meter. The goal behind most of these studies was more to investigate the performance of a specific SLM app than investigate the capability of the mobile phones to measure noise levels. The validation of the *NoiseTube* showed good agreement between the phones and sound level meter measurements up until approximatively 95 dB(A). However, the measurements were conducted for one white noise spectrum and with only one particular phone unit and its built-in microphone.

The discrepancies between the calibration and validation measurements methodologies highlight the lack of standardized methodology to calibrate mobile phone as SLMs. The methodologies employed vary from measurements in laboratory environments with artificial noise sources to measurements in real-world conditions.

The use of mobile phones for occupational noise exposure measurements has not been studied. While SLM apps are mostly designed to be used with the phone hand-held, this approach is hardly suitable for long-term continuous noise exposure measurements. There is a need for investigating the impact of the wearable external microphones positions on the accuracy of noise level measurements. Studies with noise dosimeters highlight that microphone placement error is one of the main source of errors. While studying nonstandard microphone positions for noise dosimeters, Byrne and Reeves (2008) showed the impact of the acoustic field on the microphone placement error: the overall errors due to microphone placement were minor in a diffuse field whereas in a free-field, the errors depend greatly on the microphone position, the noise source location and the noise spectrum. In short, it appears that the quality of a real-world mobile phone noise level measurements relies on :

- The characteristics of the phone's hardware and software audio components;
- The quality of the SLM app including the calibration algorithm and the quality of the calibration measurements;
- The characteristics of the "real-world" environment and the errors associated with the use of the phone, such as the microphone placement error.

First, there is a need to better understand electro-acoustical limitations of mobile phone including built-in and external microphones. Second, there a need to investigate the factory default calibration for mobile phones and external microphones including the following research topics:

- The design of level and frequency-dependent calibration algorithms;
- The measurement methodology, such as the effect of the microphone placement on calibration measurements.

Third, there is a need to investigate the sources of errors associated with phone noise exposure measurements and their accuracy with regards to the microphone placement and the noise characteristics.

This current study contributed to the existing research literature by investigating:

- The electro-acoustical limitations of mobile phones;
- The factory default mobile phone calibration for built-in microphone and external microphones;
- the evaluation of calibrated phone noise levels measurements accuracy.

# CHAPTER 2

# METHODOLOGY

Unlike standardized professional noise exposure instruments, a mobile phone's microphone and others hardware and software components have not been designed for measuring noise. While mobile phones have technical capabilities to measure noise levels, their widespread use for measuring occupational noise exposure is still limited due to the lack of formal calibration procedures and challenges regarding the measurement procedure. The review of literature highlighted a lack of research regarding the use of mobile phones for occupational noise exposure measurements. First, there is a need to better understand electro-acoustical limitations of mobile phones' built-in microphone and external microphones. Second, there a need to investigate the factory default calibration for mobile phones and external microphones including the following research topics:

- the design of level and frequency-dependent calibration algorithms;
- the measurement methodology such as the effect of the microphone placement on calibration measurements.

Third, there is a need to investigate the sources of errors associated with mobile phone noise exposure measurements and their accuracy with regards to the microphone placement and the noise characteristics. The following research questions were addressed in this study:

- How should mobile phone's electro-acoustical limitations and noise exposure characteristics be taken into account in the design of a mobile phone factory default calibration?
- How does the accuracy of calibrated mobile phone noise exposure measurements depend on the noise characteristics?
- How could the accuracy of mobile phone measurements be improved?

First, this study investigated the frequency response and the level linearity of mobile phones employed with built-in microphones and with external microphones. Second, a factory default calibration measurements including frequency response and noise levels measurements was investigated. The particularity of the proposed calibration approach, especially for wearable external microphones, was to consider the microphone placement error in the calibration corrections. The primary goals of investigation were:

- The design guidelines for factory default calibration algorithms;
- The impact of the noise characteristics (acoustic field, noise spectrum) and microphone placement on the calibration measurements.

Third, laboratory validation measurements were conducted by varying the noise sources, the acoustical field, the microphone placements and the factory default calibration parameters in order to evaluate how those factors affect the accuracy of calibrated mobile phone measurements. The measurement precision of the calibrated measurements was evaluated together with the uncertainties associated with the repeatability and the inter-phone unit variability.

An Android-based app that was developed by the author. It implemented the designed frequency and level-dependent calibration algorithms, calculated phone noise levels and recorded audio signals. Measurements were carried out in reverberant and semi-anechoic chambers with several mobiles phone units of the same model, two types of external devices (an earpiece and a headset with an in-line microphone) and an acoustical test fixture (ATF). The range of noise levels investigated in the study, from 75 to 105 dB(A) was considered to be representative of the noise levels in industrial and recreational environments implying a high risk of hearing loss.

The first section describes the acoustical test environments including: the acoustical laboratories, sound system, the reference measurement system, the noise sources and the effect of the acoustical environment on the reference measurements. In a second section, the noise measuring app, developed by the author, and the mobiles phones and external microphones used during the study are detailed. The third section describes the procedures of the calibration and validation measurements including the frequency response measurements and the noise levels measurements. Finally, the fourth section emphasizes the design and implementation of the frequency and level-dependent calibration algorithms.

## 2.1 Acoustical test environments and instrumentation

### 2.1.1 Acoustical environments and sound system

Measurements took place in the semi-anechoic and reverberant chambers at the École de Technologie Supérieure in Montreal (Canada) between November 2013 and January 2014. The dimensions (length, width, height) of the semi-anechoic chamber are 6.2 m x 7.4 m x 2.2 m. According to HGC (2011b), the chamber meets the requirements of the ISO standard 3745-2003 to a lower limiting frequency of 80 Hz, 1/3 Octave below the design goal of 100 Hz. The dimensions (length, width, height) of reverberant chamber are 7 m x 9 m x 3.5 m. The room meets the diffuse field requirements of the ISO standard 3741 at frequencies of 100 Hz and above, HGC (2011a). One Mackie HD1531 3-Way powered loudspeaker was used in the anechoic chamber, while 4 of them were used in the reverberant chamber. According to Mackie (2014), the loudspeaker features a frequency response (–3 dB) from 50 Hz to 18 kHz, a max SPL peak at 1 meter (measured with pink noise, in a free field before limiting) of 126 dB, an horizontal Coverage of $90°$ averaged and a vertical coverage of $40°$ averaged from 2 kHz to 10 kHz. Figure 2.1 presents the layout of the semi-anechoic and reverberant chambers drawn to scale and including the locations of the loudspeakers. The sound system included the powered loudspeakers and a 31-band equalizer.

### 2.1.2 Reference measurement system

The reference measurement system consisted of a Bruel & Kjaer® (type 4190) 1/2-inch free-field microphone, described in B&K (2013), a Bruel & Kjaer® (Type-2669) pre-amplifier, a Bruel & Kjaer (Type-2804) microphone power supply and a National Instrument® (NIPXI-1033) 24-Bit acquisition card, National Instruments (2014). The calibration of the reference

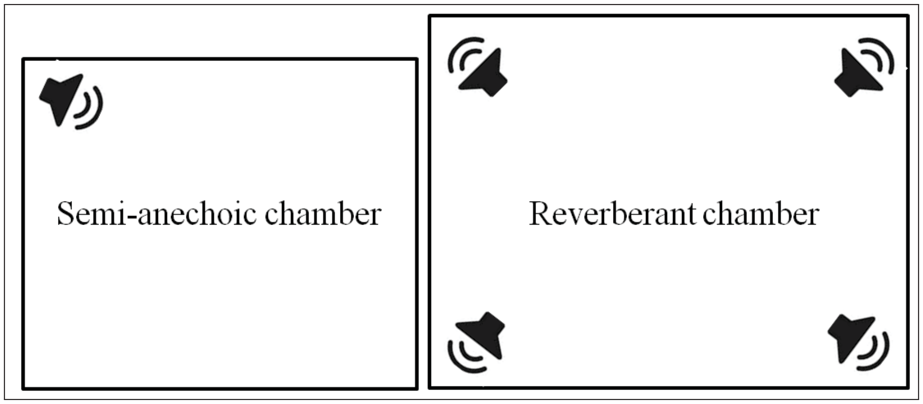


Figure 2.1 Layout of the Semi-anechoic and reverberant chambers drawn to scale including the locations of the loudspeakers

system was performed with an acoustical calibrator Bruel & Kjaer® Type 4231. A Bruel & Kjaer® Head and Torso simulator (type 4128C), referred to as the ATF, with a built-in ear simulator, was used for the measurements with the wearable external microphones. During the laboratory validation measurements, a Larson Davis® noise dosimeter (type Spark 706) was used with the acoustical calibrator Larson Davis® CAL200.

The uncertainties associated with the data acquisition and the digital conversion of the signal (quantization error, system noise, offset error,...) and with the sound system were assumed to be negligible.

**Uncertainty associated with the reference measurement**

$u_{Lp_{A,ref}}$ is the combined standard uncertainty associated with the reference measurement system, it is 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 noise signals spectrum used during the study

(sectionl 2.1.3). The highest increase in dB due to the adding of microphone response to the overall noise level calculated from the noise signals was 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 obtained by multiplying the 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 2.1 contains the values for each contribution of $u_{Lp_{ref}}$ with its source and an estimation of $u_{Lp_{ref}}$.

Table 2.1 Standard uncertainty associated with the reference measurement

| **Uncertainty** | **dB(A)** | **dB(C)** | **Source** |
|---|---|---|---|
| $u_{mic.sensitivity}$ | 0.1 | 0.1 | Manufacturer's specifications, B&K (2013) |
| $u_{mic.fr}$ | 0.04 | 0.02 | Manufacturer's specifications |
| $u_{calibrator}$ | 0.025 | 0.025 | Manufacturer's specifications |
| $u_{ref\_calibration}$ | 0.005 | 0.005 | Measured |
| $u_{repeatability}$ | 0.06 | 0.06 | Measured |
| $\boldsymbol{u_{Lp_{ref}}}$ | 0.13 | 0.12 | Calculated from the previous uncertainties |

### 2.1.3 Noise sources

First, this section presents the noise sources used during the investigation of the mobile phone electro-acoustical limitations and the calibration measurements. Second, additional noise sources used for the validation measurements are detailed.

**Factory default calibration noise sources**

With the objective of creating noise sources that correspond to realistic industrial noise sources; three audio signals were generated based on the C-A (C-weighted noise level minus A-weighted noise level) distribution of the "NIOSH100" industrial noise database, described by Gauger and Berger (2004) and illustrated in Figure 2.2. The three continuous and stable colored noise signals, Sources 1, 2 and 3, were designed so their C-A values correspond the 20th, 50th and 80th percentile of C-A values distribution, which are respectively 0, 2 and 5. Higher C-A values correspond to noise sources that have more low-frequency content than mid to high-frequency and as a comparison, the C-A value of the pink and white noise signals are approximatively 2 dB and -1 dB respectively. Figure 2.3 presents the spectral content of the three noise sources. For each noise source, a sequence was made out of seven signals of 30 seconds with the noise level increasing by 5 dB every time and with a 5-second silence between each signal, Figure 2.4 illustrates the sequence for Source 1 signals.

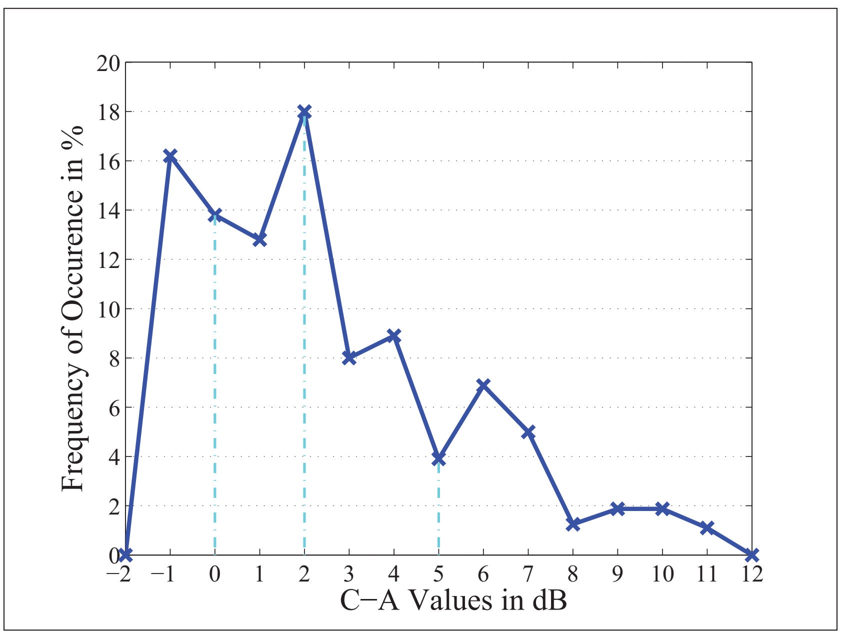


Figure 2.2 Histogram of the C-A values of NIOSH100 noise source database highlighting the 20th, 50th and 80th percentile of the C-A values distribution: 0, 2 and 5 respectively

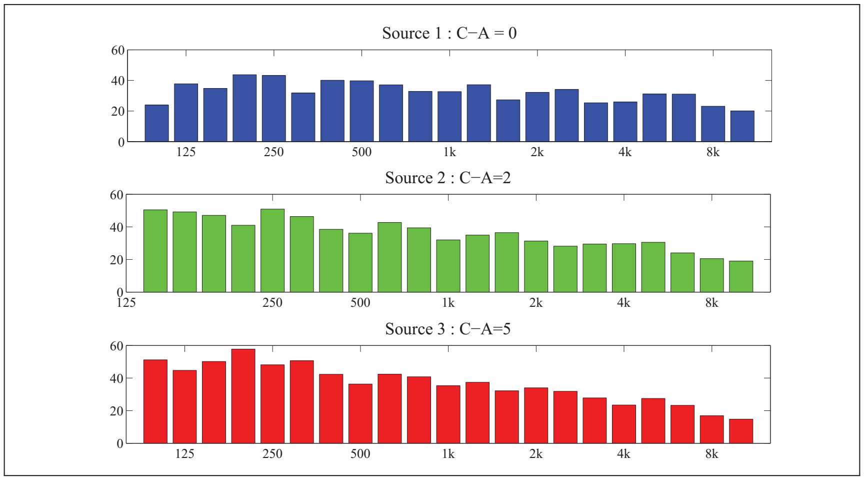


Figure 2.3 Noise spectrum of Sources 1, 2 and 3 with C-A value of 0, 2 and 5 respectively

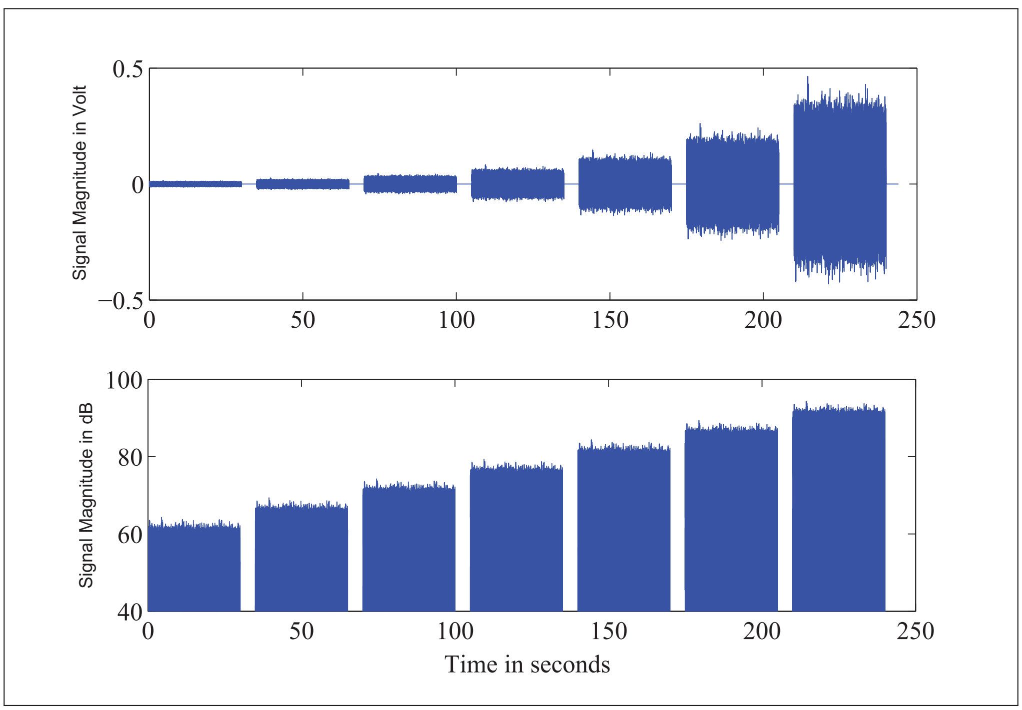


Figure 2.4 Sequence of 7 30-seconds signals of Source 1 with the noise level increasing by 5 dB every time and with a 5 second silence between each signal

### Validation noise sources

Noise sources with different characteristics than the Sources 1,2 and 3 were used for some of the validation measurements. Four noise sources were selected from the NOISEX-92 database, described byVarga (1993), which is a database that regroups audio recordings of industrial and military noise sources. In addition to the NOISEX-92 noise sources, a musical noise source, excerpt from the electronic music piece untitled "Harder, Better, Stronger" by Daft Punk (2001), was also used. The gain of the audio signals were normalized at similar noise levels. The noise sources from NOISEX-92 database are continuous noise with small noise level variations over the signal duration whereas the electronic music is a fluctuating signal that contains impulses. Table 2.2 summarizes the main characteristics of noise sources used for the validation measurements and Figure 2.7 shows the noise sources' frequency content.

Table 2.2 Main characteristics of noise sources used for the validation measurements

| **Name & reference** | **Description** | **Characteristics** | **Length in seconds** | **C-A values** |
|---|---|---|---|---|
| Factory1, Varga (1993) | plate-cutting and electrical welding equipment | Continuous with a level variation of 18 dB | 213 | 2.6 |
| Factory2 ,Varga (1993) | Car production hall | Continuous with a level variation 12 dB | 213 | 5.9 |
| Buccaneer,Varga (1993) | Cockpit noise in a buccaneer jet | Continuous | 213 | 0.9 |
| M109, Varga (1993) | Tank noise | Continuous | 213 | 7.9 |
| Daft Punk (2001) | Excerpt of an electronic music piece | Fluctuating and impulsive, 124 Beats Per Minute (BPM) | 120 | 4.5 |

### 2.1.4 Effect of the chambers' acoustical environment on the reference measurements

In the semi-anechoic chamber, the ambient noise was measured below 50 dB for any third-octave band with the ventilation and lighting set normally (Figure 2.5), therefore the ambient noise did not affect noise level measurements. In the reverberant chamber, the ambient noise was measured below 50 dB for any third-octave band with the ventilation and lighting set normally and the four loudspeakers turned on (Figure 2.6). In both chambers, variations in temperature and atmospheric pressure are assumed to have no impact on the noise level measurements. As illustrated in Figures 2.5 and 2.7, the frequency content, in third octave bands, calculated from noise sources audio signals differ from the frequency content measured with the reference system in the laboratory environments, mainly due to the acoustics of the anechoic and reverberant chambers and the limits at low frequencies of the sound system. Table 2.3 resumes the C-A values for the original Sources 1, 2 and 3 and Sources 1, 2 and 3 signals measured in the anechoic and reverberant chambers.

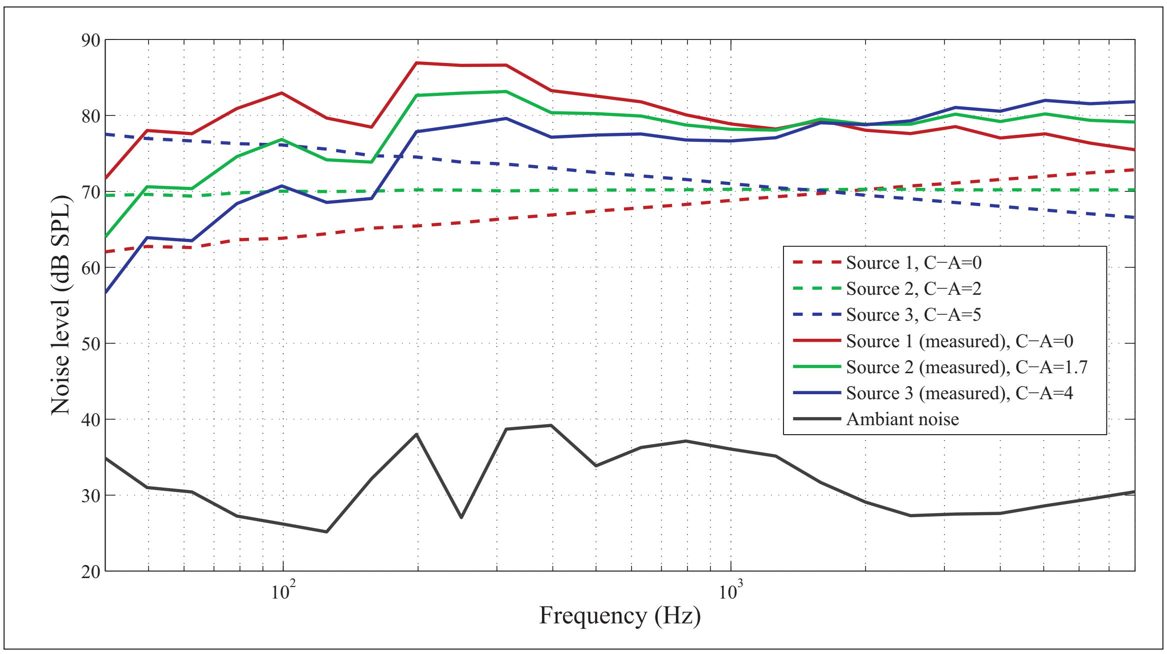


Figure 2.5 Frequency content of the ambient noise, the original signals of Sources 1, 2 and 3 and the measured Sources 1, 2 and 3 with the reference system in the semi-anechoic chamber

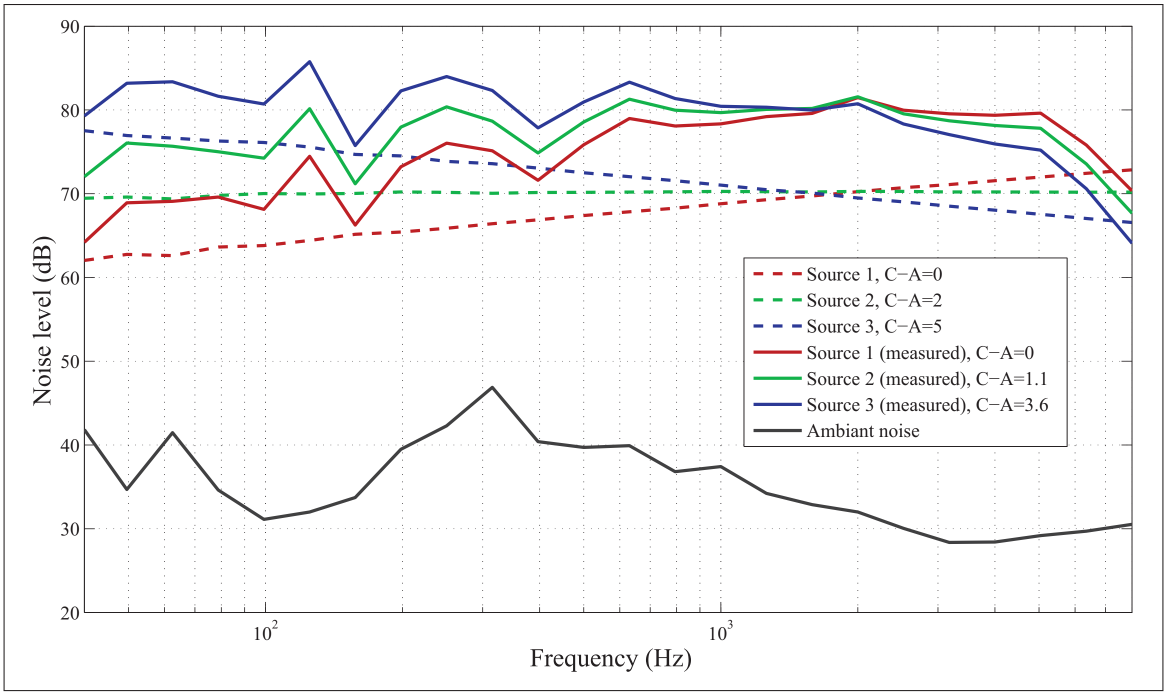


Figure 2.6 Frequency content, in third-octave bands of the ambient noise, the original signals of Sources 1, 2 and 3 and the measured Sources 1, 2 and 3 with the reference system in the reverberant chamber

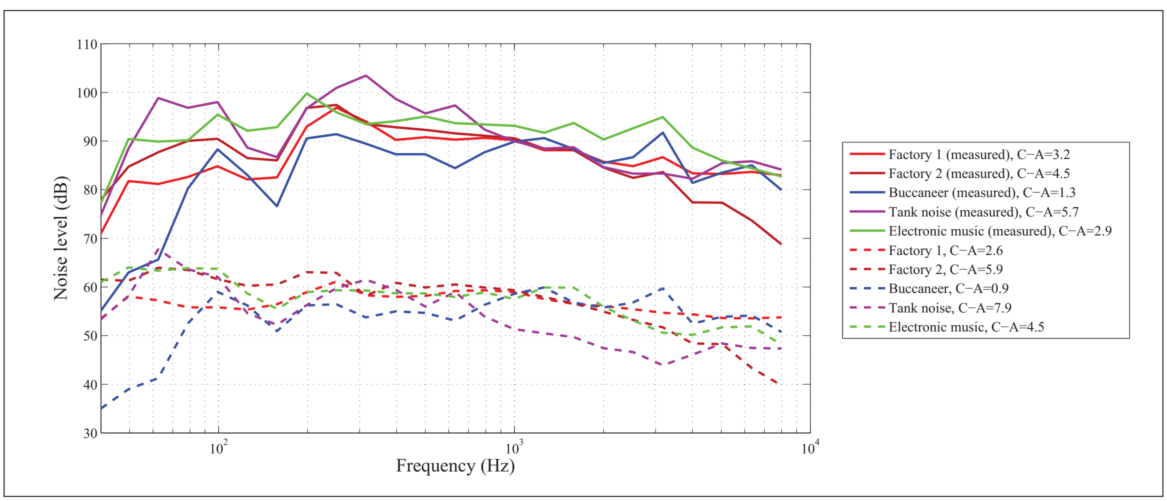


Figure 2.7 Frequency content, in third-octave bands of the original signals of the noise sources used for the validation and the measured noise sources with the reference system in the semi-anechoic chamber

Table 2.3 C-A values calculated for the original source signals and the measured signals in the anechoic and reverberant chambers

| | **Original (calculated)** | **Anechoic chamber (measured)** | **Reverberant chamber (measured)** |
|---|---|---|---|
| Source 1 | 0 | 0.2 | -0.2 |
| Source 2 | 2.0 | 1.9 | 1.1 |
| Source 3 | 5.0 | 4.2 | 3.6 |
| Factory1 | 2.6 | 3.2 | 2.2 |
| Factory2 | 5.9 | 4.5 | 4.2 |
| Buccaneer | 0.9 | 1.3 | 0.9 |
| Tank noise | 7.9 | 5.7 | 7.5 |
| Electronic Music | 4.5 | 2.9 | 3.4 |

## 2.2 Noise measuring app and devices under test

### 2.2.1 Noise measuring app

Android-based mobile phones have been chosen over iOS-base devices. The choice was determined by contextual and technical factors. First, Android is the most popular mobile phone operating system: according to ComScore (2013), Android-based devices represent the largest mobile phone market share, more that 50 percent of market share in the U.S. Second, as highlighted by Stevens (2012), "the [Android-based] devices come in a far wider price range than the iPhone" which allow to investigate entry-level mobile phones. Third, it provides an opportunity to evaluate the "acoustic" variability between a larger variety of model phones and, as discussed in section 1.2.1.5, that is the large variety of Android-based devices that makes mobile phone calibration more challenging.

An Android-based noise measuring app was developed with the (open-source) code of the *NoiseTube* Android app used as a starting point. Several functionalities that were needed for the noise measuring app were available in the code source of the *NoiseTube* app including:

- the A and C frequency weightings, implemented as digital infinite impulse response (IIR) filters and whose coefficients were designed to meet the specifications of IEC (2002);

- the calculation of time integrating noise levels;
- the formatting and storing of the measured noise levels in human-readable XML-based (Extensible Markup Language) format, that facilitated the measurement data analysis.

The noise measuring app was intended for devices that run Android versions equal or greater than v2.3.3 (referred to as the *Gingerbread* version). Figure 2.8 presents the audio processing steps and the associated Java™ classes involved in the noise measuring app developed for the study. Red boxes represent the components and classes that come from the *NoiseTube* Android app code source, texts in italics correspond to the Java™ classes or methods and boxes with a dashed outline (in the Software and Hardware parts) represent components which may or may not be present on a particular device and whose presence may be undetectable from the perspective of the app. The hardware and software components were recalled from Figure 1.3, described in section 1.2.1.1.

The *AudioRecord* Java™ class allows to specify the characteristics of the to-be-recorded audio signal. An instance of type *AudioRecord* is created (during the construction of the instance of type *SoundManager*) using the following code source where:

- *AudioSouce.MIC* is the microphone audio source provided by the operating system;
- *Utils.FREQUENCY* is the sampling rate of the audio signal, defined at 22050 Hz;
- *Utils.AUDIO_ENCODING* is the audio format: 16-bits PCM (pulse-code modulation).

```
audioRecord = new AudioRecord(MediaRecorder.AudioSource.MIC,
                 Utils.FREQUENCY, Utils.CHANNEL, ...
                     Utils.AUDIO_ENCODING, bufferSize);
```

The *IOStream* Java™ class manages the audio signal coming from the *AudioRecord* instance. It creates two audio streams: one intended for the creation 16-bit PCM audio file and one sent to the app's audio processing components for the calibration and calculation of noise levels.

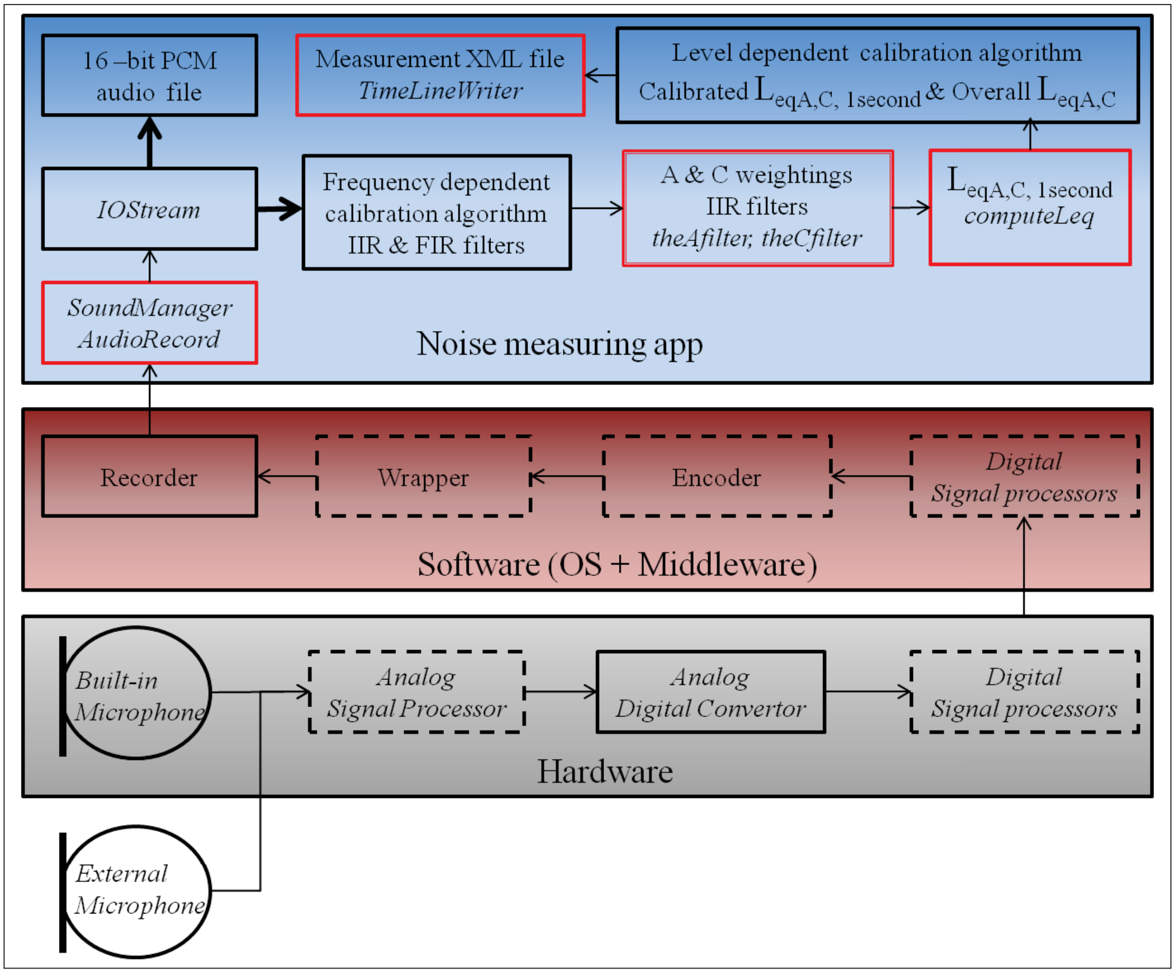


Figure 2.8  Audio processing components of the mobile phone and the noise measuring app, red boxes represent the components and classes that come from the *NoiseTube* Android app code source

The frequency-dependent calibration algorithm includes digital filters that aim to flatten the frequency response of the mobile phone. IIR and FIR digital filters were investigated during this study, as detailed in section 2.4.1.1. While the implementation of the IIR filters were based on *NoiseTube* Android app code source, the classes and methods for the implementation of FIR filters were developed by the author.

The A and C-weighings are implemented as IIR Filters whose coefficients were designed to meet the requirements from the IEC 61672 standard, IEC (2002). The methods and classes are based on *NoiseTube* Android app, the implementation is documented bySteven (2012). The

FIR filters are applied on the measured signal, as illustrated in the code source Java™ below, using the *apply* methods of the *theAfilter* and *theCfilter* classes, with *arr_ samplesCal* the measured audio signal.

```
arr_samples_A = theAFilter.apply(arr_samplesCal);
arr_samples_C = theCFilter.apply(arr_samplesCal);
```

The *computeLeq* Java™ method is used to compute A and C-weighted continuous noise level every second, referred to as, $L_{\mathrm{eq,A,1sec}}$ in dB(A), and $L_{\mathrm{eq,C,1sec}}$ in dB(C). The implementation used for the $L_{\mathrm{eq}}$ calculations was based on the *NoiseTube* Android app code source. The calculation of the $L_{\mathrm{eqA,1seq}}$ is based on Equation 1.1 and implemented in the *computeLeq* method whose the code source is presented in the box below.

```
private double computeLeq(double samples []) throws Exception
{
//samples.length = sampling rate (samples contains exactly 1s of audio)
double sumsquare = 0.0d, leq;
for(int i = 0; i < samples.length; i++)
//samples[i]  correspond to  the effective sound pressure
sumsquare += samples[i] * samples[i];
//implementation of the calculation of the equivalent continuous ...
    noise level
//where the constant part of the equation is 93.9794....
leq = (10.0d * MathNT.log10(sumsquare / samples.length)) +
93.97940008672037609572522210551d;
return leq; }
```

While the *NoiseTube* app is calibrated using a level-dependent linear interpolation algorithm, described in section 1.2.1.4, new level-dependent algorithms were implemented in this study. and described in detail in section 2.4.2. Finally, the calibrated A and C-weighted noise levels together with a "timestamp" and informations about the phone model are stored on the memory of the phone in a XML format file. Table 2.4 resumes the main audio characteristics of the noise measuring app.

Table 2.4 Main "audio" characteristics of the noise measuring app

| | |
|---|---|
| Sampling rate | 22050 Hz |
| Audio file format | 16-bit PCM Audio |
| Noise level descriptors | $L_{\text{eq,A,1sec}}$ and $L_{\text{eq,C,1sec}}$ |
| A,C weighting | According to IEC 61672 specifications, IEC (2002) |
| Display resolution | 0.1 dB |

### 2.2.2 Mobile phones and external microphones

The set of mobile phones being tested included four mobile phones of the N762 model by ZTE Corporation®. The ZTE N762 mobile phone, illustrated in Figure 2.9, is an entry-level Android-based phone: it was first released in Canada (in December 2011) at 149 Canadian dollars ($ CAD). The phones came from different manufacturing lot and had different usage histories as one mobile phone was purchased new in December 2011 and the three others were bought second-hand from different individual sellers between December 2011 and April 2012. In order to evaluate the audio processing of the phone's hardware and software components without the effect of the built-in microphone, an adapter cable that connects the phone's audio input to the power supply of the measurement microphone was used.

The external microphones investigated in this study were:

- The in-line microphone of an Apple iPhone®3G Stereo headset;
- A Sonomax® earpiece that was a part of the individual dosimetric hearing protection device developed by Mazur and Voix (2013) and illustrated in Figure 2.10. The earpiece integrates an electret condenser microphone microphone located on the exterior earpiece face plate and encircled in red in Figure 2.10. Figure 2.12, extracted from Sonion (2009), presents the frequency response of the earpiece microphone. According to

Sonion (2009), the sensitivity of the microphone at 1kHz is between -36.5 and -30.5 dB (ref. 1V per Pascal) which correspond to an inter-unit variability of 3 dB (ref. 1V per Pascal).

While the Apple headset is designed to be plugged into the audio input of mobile phones, the Sonomax® earpiece was intended to be plugged on a belt-pack. Thereby, a phone adapter cable was developed so the earpiece can be plugged into the phone' audio input and the phone operating system detects the presence of an external microphone. In order to decrease the earpiece's microphone sensitivity, a voltage divider, that attenuates the gain of the audio signal by around 9 dB, was integrated in the adapter cable. The electronic schematic of the adapter cable is illustrated in Figure 2.11.

Figure 2.9 Unit of ZTE N762 mobile phone with the adapter cable plugged into the phone' audio input and the built-in microphone encircled in red

While the evaluation of mobile phones and their built-in microphones were conducted with the phones attached to a microphone stand, the evaluation of external microphones included the use of the ATF. As illustrated in Figures 2.13 and 2.14, the Sonomax® earpiece and the Apple iPhone®3G Stereo headset were fitted within the built-in ear simulator whereas the standardized noise dosimeter microphone was located at the standardized position: on the top of the shoulder at 0.2 m from the entrance of the external ear canal and approximately 0.04 m above the ATF's shoulder.

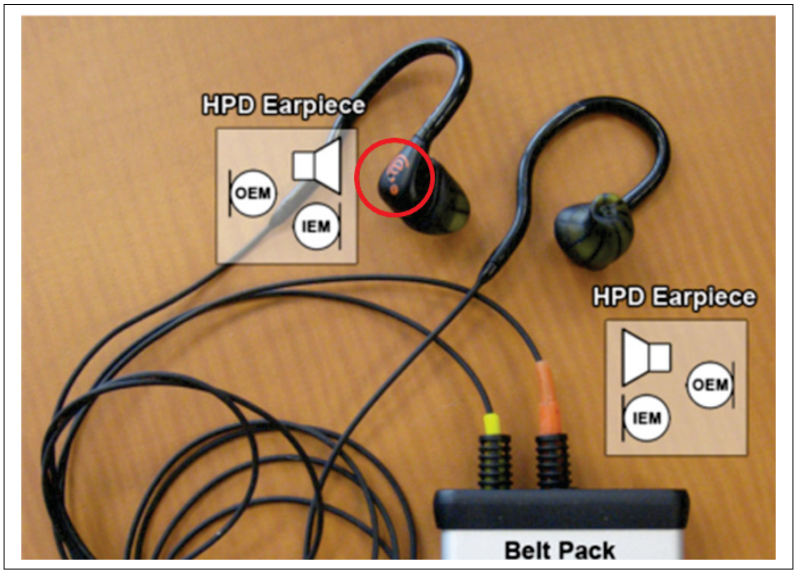


Figure 2.10  Sonomax® earpiece from the individual dosimetric hearing protection with the emplacement of the microphone encircled in red adapted with the permission from Mazur and Voix (2013)

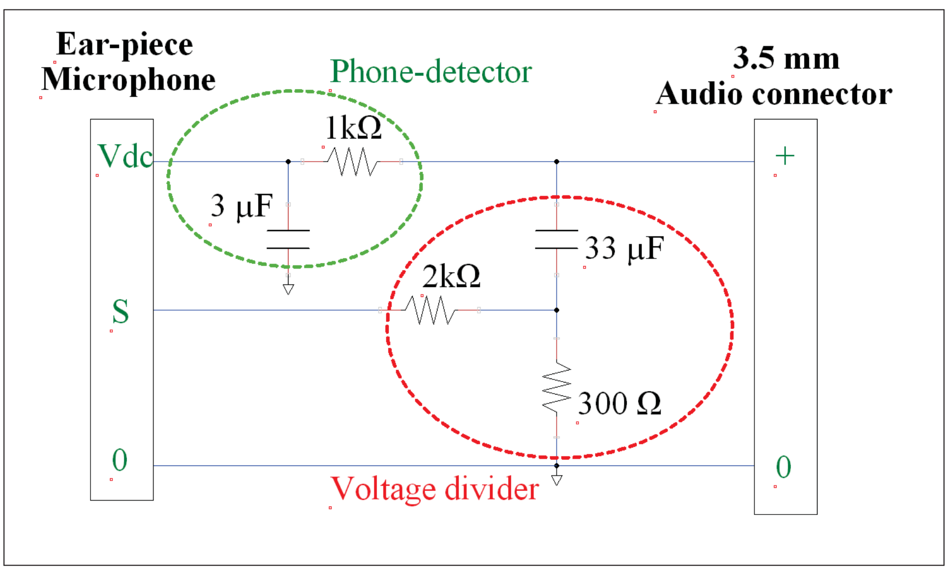


Figure 2.11  Electronic schematic of the adaptor cable with the circuit of the voltage divider and the phone-detector

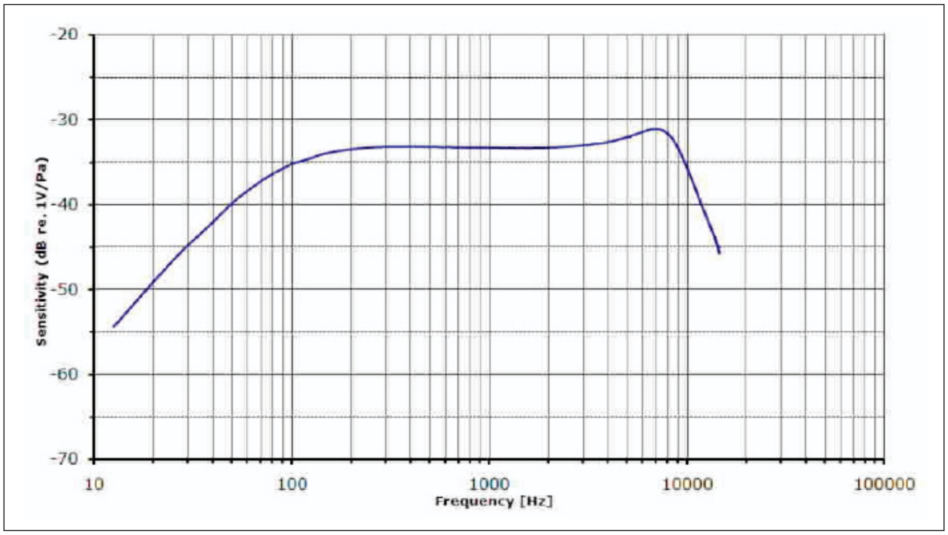


Figure 2.12 Frequency response of the Sonomax® earpiece microphone, extracted from Sonion (2009)

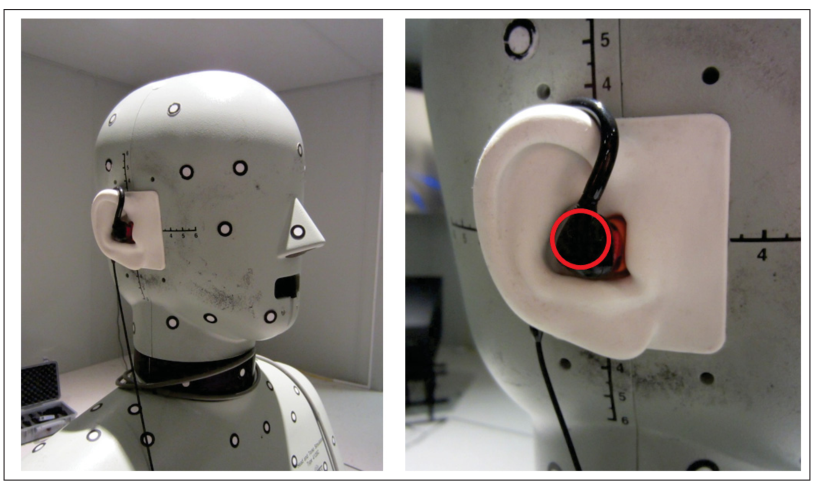

Figure 2.13 Sonomax® earpiece on the ATF's built-in ear simulator with the location of microphone encircled in red

## 2.3 Measurement procedures

This section presents the two types of measurements conducted during the study: the frequency response and noise levels measurements. For each type of measurements, the microphone placement towards the loudspeakers and with regards to the ATF are described for both chambers, together with the acquisition and analysis of the measurements.

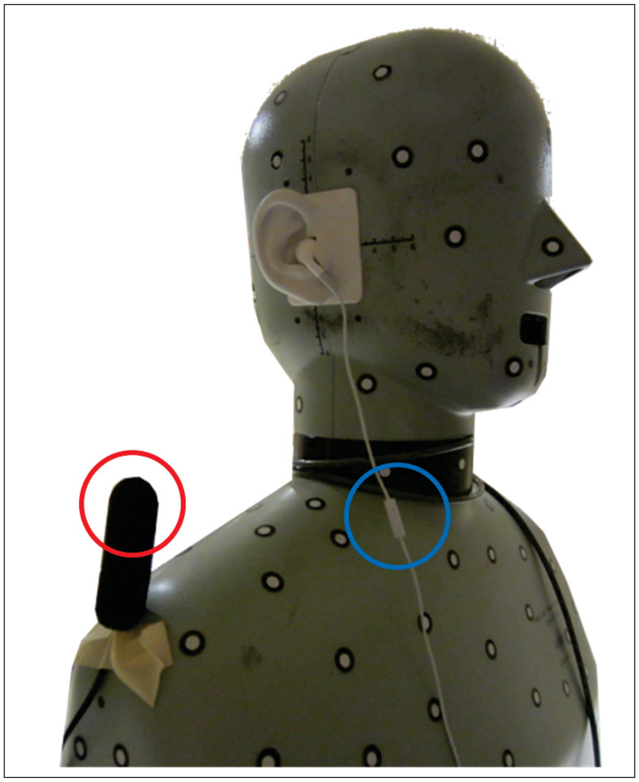

Figure 2.14 Placement of the Apple iPhone® headset microphone (encircled in blue), and the standardized noise dosimeter (encircled in red) on the ATF

### 2.3.1 Frequency response measurements

Frequency response measurements were conducted as a part of the investigation of the mobile phone limitations and as part of the calibration measurements for the design of the frequency-dependent algorithms. The frequency response measurements consisted in the simultaneous measurements of a 30-second noise signal (Source 1, Figure 2.3) with a reference measurement system and a mobile phones-based solution. The noise source was emitted at a reference noise level of 90 dB(A) and the signal was recorded by the phone as a PCM audio signal. From these measurements, a transfer function was calculated, intended for the design of the frequency-dependent algorithm.

#### 2.3.1.1 Measurements set-up

Measurements took place in the semi-anechoic chamber; as illustrated in Figure 2.15, the loudspeaker was positioned on the floor in one corner and directed towards the ceiling with an approximate $45°$ angle with the floor. For the measurements with the built-in microphones, the reference microphone and the phone were positioned at 1.66 m above the floor, 1.65 m away from the loudspeaker and 1 m away from the closed pyramid shaped ceiling absorbent piece. The location of the reference microphone corresponds to the center plane of the ATF's head, on a line with the eyes without the ATF present. The microphones' diaphragms pointed towards the loudspeaker so that normal incident sound on the microphone membrane was considered. For measurements with the external microphones, two procedures were used depending on the purpose of the measurements:

- the external microphones attached on a stand at 1.65 m away from the loudspeaker with the microphone diaphragm pointing towards the speaker;
- the external microphones located on the ATF, as illustrated in Figures 2.13 and 2.14 with the built-in ear simulator at 1.66 m above the floor.

Earpiece measurements for the calculation of the transfer functions were investigated for two ATF positions relative to the source: the ATF facing the source and the ATF oriented so the earpiece was facing the source, as referred to as "Exposed Ear" in Figure 2.16. The measurements from the "Exposed Ear" position were later used for the design of the frequency-dependent calibration algorithms.

The reference microphone signals were recorded and processed, at a sampling rate of 22050 Hz, using an in-house MATLAB® script developed by the author. Mobile phone measurements were recorded as 16-bit PCM audio signals, sampled at 22050 Hz using the measuring noise app.

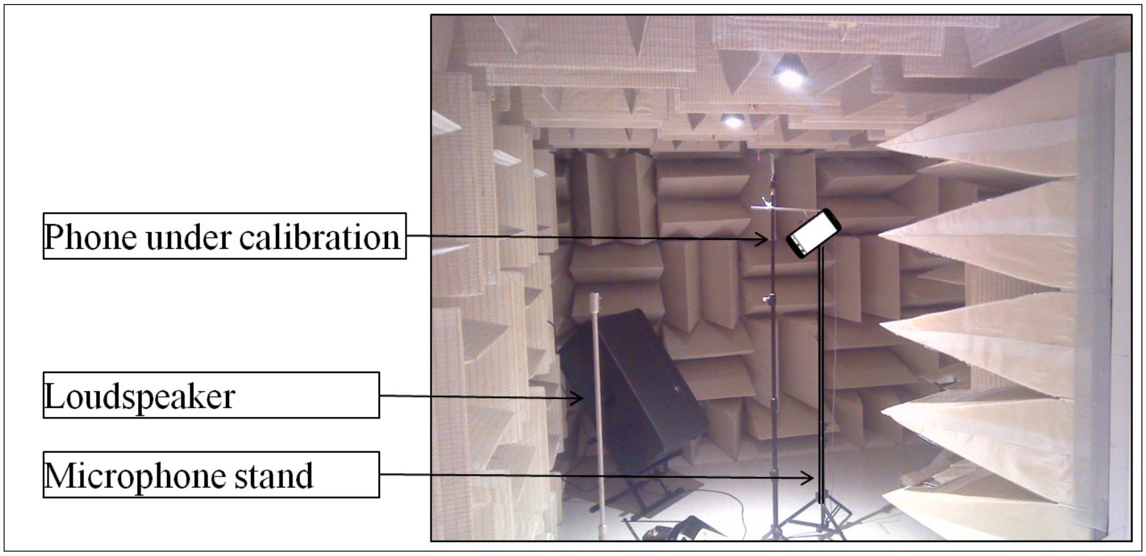


Figure 2.15 Setup of the calibration measurement in the semi-anechoic chamber showing a mobile phone under calibration and the loudspeaker

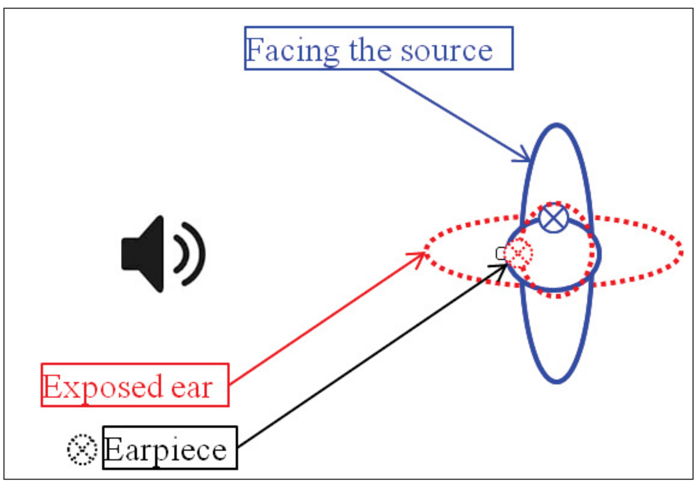


Figure 2.16 ATF position relative to the loudspeaker

#### 2.3.1.2 Factory default calibration measurements

Table 2.5 summarizes the factors that were investigated during the factory calibration. In order to quantify the effect of the earpiece placement in the vicinity of the ear on the magnitude of the frequency response, slight variations of the earpiece mounting in the ear were investigated with different placements and insertion depths, as illustrated in Figure 2.17.

Table 2.5 Factors and measurements parameters investigated with the frequency response measurements

| Factor | Device | Variable parameters |
|---|---|---|
| ATF Vs microphone stand | Headset and earpiece | Microphone located on a stand or on the ATF |
| Microphone placement relative to the ATF | Headset | Microphone located on the ATF (Figure 2.14), oriented towards the exterior (facing the loudspeaker) or the interior (facing the ATF) |
| | Earpiece | Slight variations of the earpiece placement within the built-in ear simulator |
| Inter-unit variability | Built-in microphone | Frequency responses measured with the four units of the same mobile phones model (ZTE N762) |
| Acoustical field | Earpiece | Frequency responses measured in the semi-anechoic and reverberant chambers |

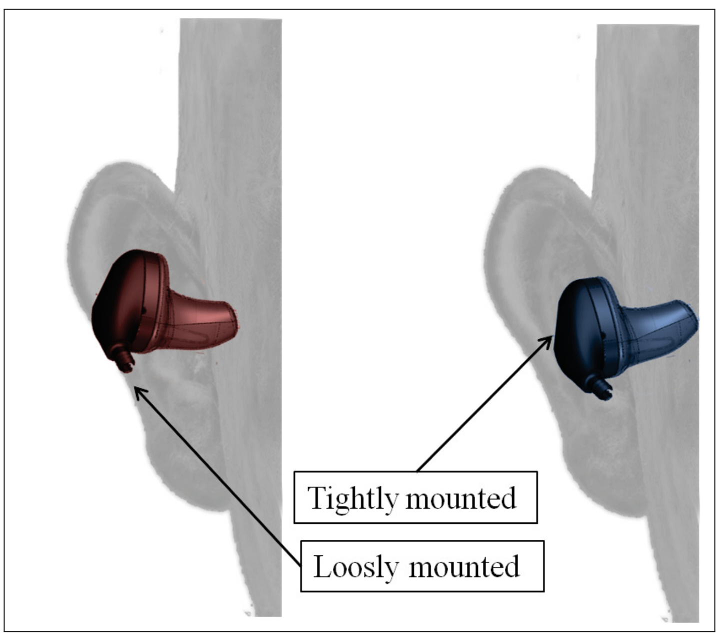


Figure 2.17 Variations of the earpiece mounting in the vicinity of the ear

### 2.3.2 Noise levels measurements

Noise level measurements consisted in comparing reference and mobile phones noise level measurements for different type of noise sources, at noise levels from 75 dB(A) to 105 dB(A). Table 2.6 resumes the use of noise levels measurements in the study with the noise sources and the acoustical environment.

Table 2.6 Characteristics of the noise levels measurements of the three phases of the study

| **Study phase** | **Noise sources** | **Acoustical environments** |
|---|---|---|
| Investigation of the mobile phones' limitations | Sources 1,2,3 | Semi-anechoic |
| Factory default calibration | Sources 1,2,3 | Semi-anechoic and reverberant |
| Laboratory validation | Sources 1,2,3 and validation noise sources | Semi-anechoic and reverberant |

#### 2.3.2.1 Measurement set-up

The procedure in the semi-anechoic chamber was identical as the one used for the frequency response measurements. Measurements with the headset were conducted with the ATF facing the source whereas measurements with the earpiece were conducted with "Exposed Ear" ATF position (Figure 2.16). In order to evaluate the microphone placement error for the headset and earpiece measurements, the ATF was oriented towards 4 directions, that were defined with the angles of the incident sound with regards to the loudspeaker, as illustrated in Figure 2.18.

In order to quantify the effect of the built-microphone orientation on the overall A-weighted noise levels, noise levels measurements were conducted with the mobile phone on a stand for the following the microphone placements:

- Four microphone orientations with respect to the loudspeaker in the horizontal axis, as illustrated in Figure 2.21;
- Two positions in the vertical axis: the phone placed flat and on the edge, as illustrated in Figure 2.22.

It is worth noting that except where mentioned otherwise, the measurements with the built-in microphones were carried out with the phone placed flat.

In the reverberant chamber, the measurement procedure varied depending on the type of microphone being tested:

- Measurements with the built-in microphones were conducted with the reference measurement microphone and the mobile phones on a microphone stand, placed at a location slightly offset from the center of the reverberant chamber;
- Measurements with the external microphones were conducted at the same location with the ATF, as illustrated in Figure 2.20.

Although the reverberant chamber meet the diffuse field requirements of the standard ISO 3741, the diffuse field was investigated in order to find the best position in the chamber. The measurements were repeated with the ATF oriented towards various directions in order to calculate spatially averaged noise levels, as illustrated in Figure 2.19.

In both chambers, reference measurements were recorded and processed using MATLAB® scripts described in the previous section. Mobile phone noise levels measurements were carried out using the measuring noise app and the phone XML measurement files were parsed and analyzed using a MATLAB®-based user interface together with automated scripts.

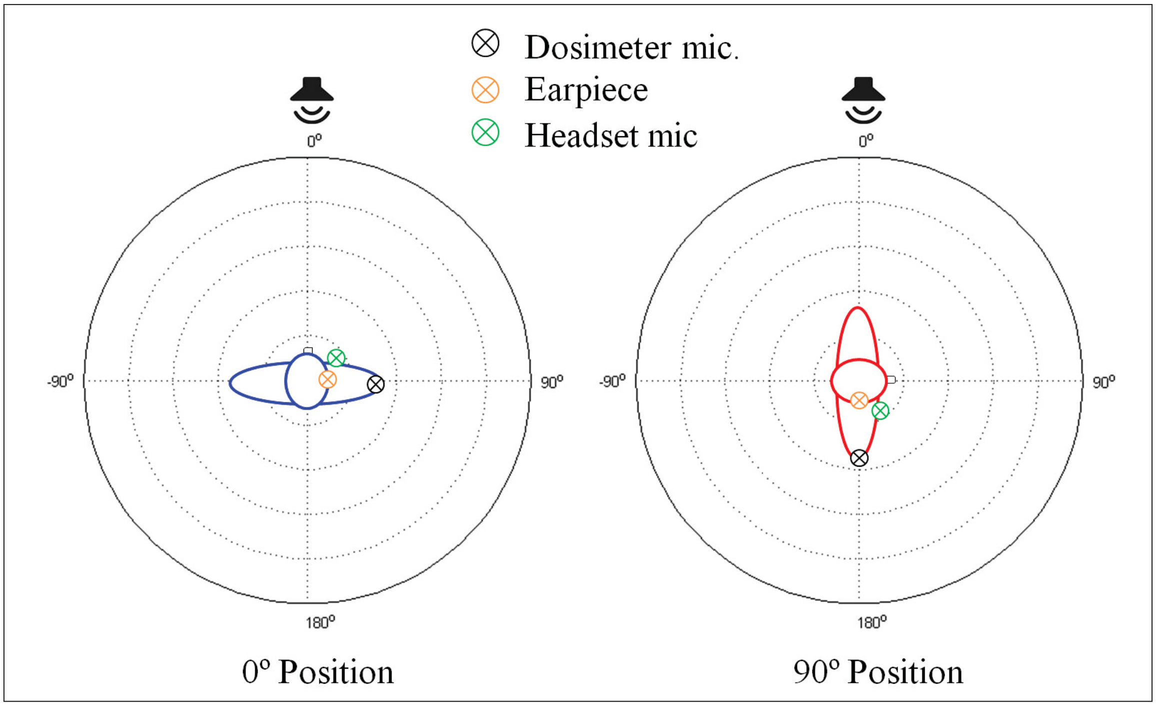


Figure 2.18    Top view of 2 of the 4 ATF positions relative to the source in the semi-anechoic chamber

#### 2.3.2.2    Factory default calibration measurements

Factory default calibration measurements consisted in comparing reference and mobile phones noise level measurements for Sources 1, 2 and 3 at various noise levels from 75 dB(A) to 105 dB(A) and in both reverberant and anechoic chambers. The objectives were:

- To measure noise level corrections, pairs of mobile phone noise levels and their corresponding reference noise level, required for the design of noise level-dependent calibration algorithm;
- To determine the main factors that affect the noise level corrections measurements and quantify their effect.

When reporting the calibration procedure of the *NoiseTube* application, Stevens (2012) highlighted the time to conduct the calibration measurements and to analyze the results as a major

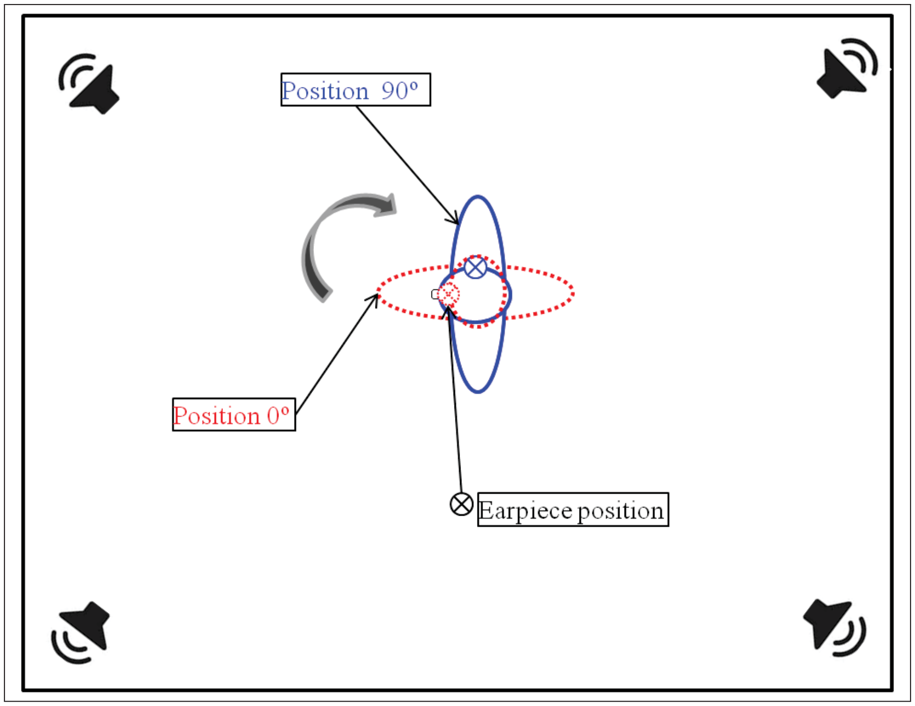


Figure 2.19 Top view of two ATF positions relative to the sources in the reverberant chamber

drawback: the measurements lasted at least 16 minutes by device (16 noise levels were evaluated with1 minute per level). In our study, efforts were made to minimize the time duration of the calibration measurements, seven noise levels were evaluated with 30 seconds per level. The total duration of the noise level calibration measurements were 245 seconds per device. The measuring app implemented a frequency-dependent algorithm that was designed based on the frequency response measurements (section 2.4.1) and adapted for each type of microphone. Measurements with the built-in microphone and the external microphones were conducted with one mobile phone unit, referred to as Phone #4. Table 2.7 summarizes the factors that were investigated for each device being tested and for the reverberant (diffuse field) and semi-anechoic chambers (free field), the "Results" column refers to the sections that present the results for each factor.

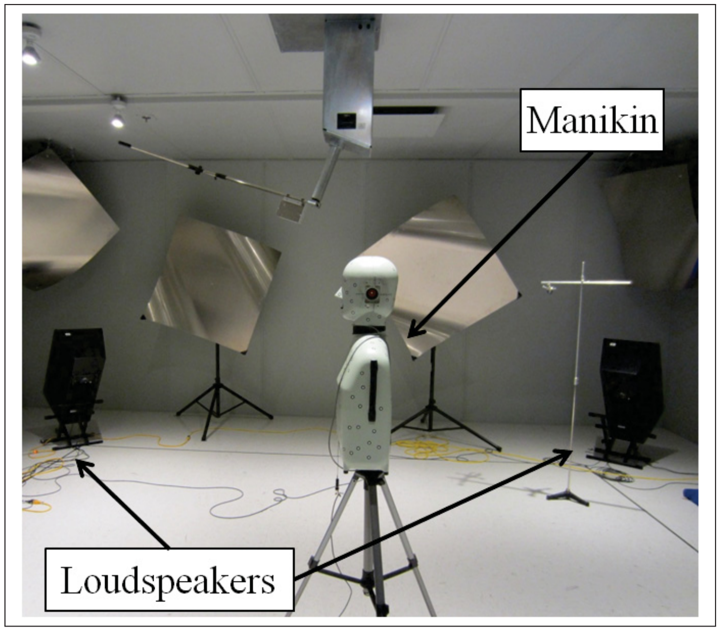


Figure 2.20 Measurement set-up in the reverberant chamber with the ATF located on the center of the reverberant chamber

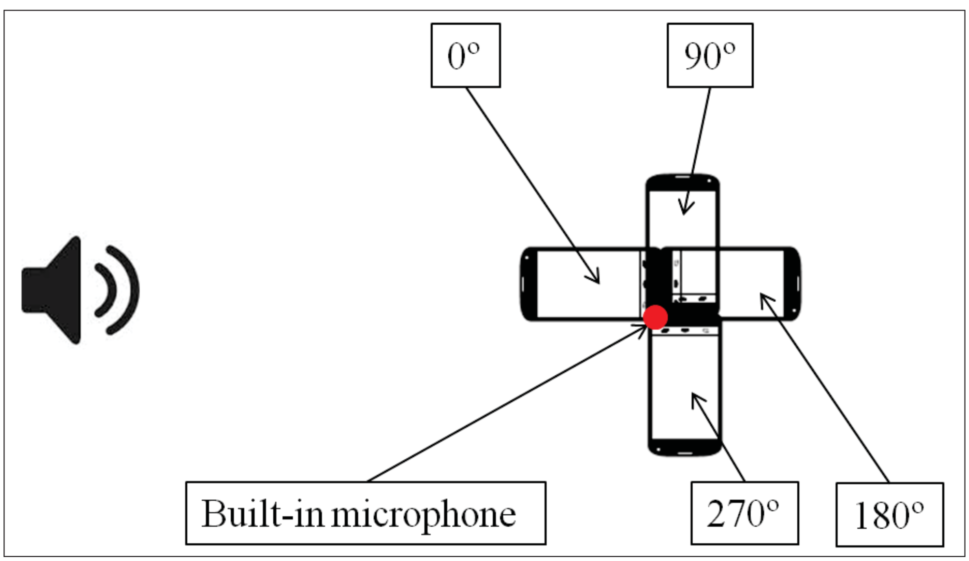


Figure 2.21 Top view of the built-in microphone orientation in the semi-anechoic chamber with the mobile phone placed flat

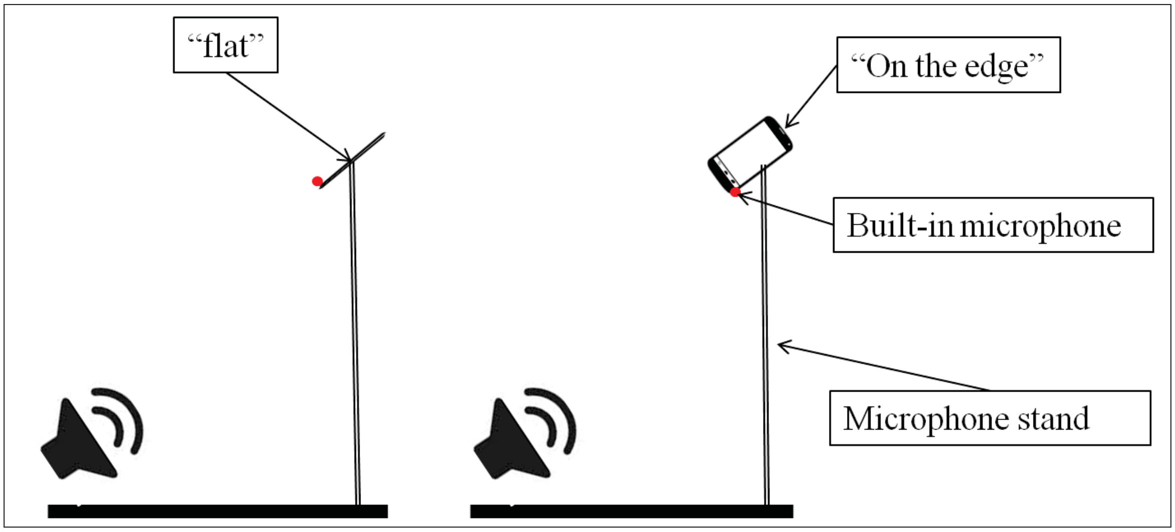


Figure 2.22 Side view of the built-in microphone orientation in the semi-anechoic chamber: mobile phone placed flat (on the left) and on the edge (on the right)

Table 2.7 Factors and measurements parameters investigated during the noise levels corrections measurements depending on the device being tested and the acoustical field

| Device | Acoustical field | Factor & Parameters | Results |
|---|---|---|---|
| Headset & Earpiece & Built-in microphone (Phone #4) | Diffuse | Microphone placement relative to the source, four orientations | §3.2.2.2 |
| | Free | Frequency linearisation, with and without the frequency-dependent algorithms implemented | §3.3.1.3 |
| Headset & Earpiece | Diffuse and Free | ATF dressed with a sweater | §3.2.2.5 |
| Headset | Diffuse | Microphone placement relative to the ATF, mic. facing the exterior or the interior | §3.2.2.4 |
| Earpiece | Free | Microphone placement relative to the ATF, slight variations of the earpiece placement within the built-in ear simulator | §3.2.2.3 |

#### 2.3.2.3 Laboratory validation measurements

Laboratory validation measurements were carried out in two parts:

- In the first part, referred to as Measurements #1, measurements were conducted just after the calibration measurements, under repeatability conditions except the noise-level dependent algorithm calculated from the noise level calibration measurements was implemented in the phone app;
- In the second part, referred to as Measurements #2, a measurement campaign was performed two weeks after calibration measurements under reproducibility conditions: the set up was reinstalled in both chambers, including the microphones and the sound system placement and the configuration of the equalizer and the amplifier.

While most of the measurements were conducted with one mobile phone unit, referred to as Phone #4 implementing both frequency and level-dependent calibration algorithms designed for Phone #4, the investigation of the inter-unit variability used the four mobile phones implementing the (unit-dependent) calibration algorithms designed for Phone #4. Table 2.8 summarizes the factors that were investigated during the validation measurements in both reverberant (diffuse field) and semi-anechoic chambers (free field), the "Results" column refers to the sections that present the measurements results for each factor investigation.

The objective of the "Microphone placement relative to the source" investigation was to evaluate the overall A-weighted errors due to four microphone orientations relative the source(s), the measurements were taken with the device under-test at four azimuthal angles: (0°, 90°, 180°, 270° (Figure 2.20). In the reverberant chamber, four loudspeakers were used whereas only one fixed loudspeaker was used (Figure 2.19) in the semi-anechoic chamber.

The "acoustical field cross-calibration" factor consisted in measurements with mobile phone implementing a "cross-calibration": for the semi-anechoic chamber measurements, the calibration algorithms implemented in the phone originated from measurements in the reverberant chamber, inversely, measurements in the reverberant chamber were conducted with the app implementing a free-field calibration. The objective was to evaluate the measurement error due the difference of acoustical field between the laboratory used for the calibration and the measurement location.

Repeatability measurements consisted in noise levels measurements of Sources 1, 2 and 3 sequences with noise levels from 80 to 105 dB(A). They were carried out following two procedures:

- Procedure #1: 5 measurements were repeated one after the other with the measuring app operating uninterrupted;
- Procedure #2: 5 measurements were repeated one after the other with the mobile phone turned on and off after each measurement.

The measurements with the two built-in microphone orientations "placed flat" and "on the edge" (Figure 2.22) aimed to quantify the effect of the built-in microphone orientation on the overall A-weighted noise levels.

## 2.4 Design and implementation of the calibration algorithms

The design and implementation of calibration algorithms are the last steps of the factory default calibration. The calibration algorithms, implemented in the measuring app, aim to improve the accuracy of the phone noise level measurements. The first section presents the design and implementation of the proposed frequency-dependent calibration algorithms and the second section details the design and implementation of the proposed noise level-dependent calibration algorithms.

Table 2.8 Factors and measurements parameters investigated during the validation measurements depending on the device being tested

| Device | Factor & Parameter | Resullts |
|---|---|---|
| Headset & Earpiece & Built-in mic. | Microphone placement relative to the source: four orientations | §3.4.3.3, §3.4.4.4, §3.4.5.4 |
| | Noise sources: Source 1,2,3 & "real-world" recordings | §3.4.3.1, §3.4.4.1, §3.4.5.1 |
| | Acoustical field cross-calibration: measurements with a "Diffuse calibration" in the free field, and vice versa | §3.4.3.5, §3.4.4.5, §3.4.5.5 |
| | Measurement repeatability: 3 to 5 measurements under repeatability conditions | §3.4.1 |
| Earpiece & Built-in mic. | Inter-unit variability of the phone as an signal acquisition system: 4 mobile phones of the same model one earpiece | §3.4.2.2 |
| Earpiece | Microphone placement relative to the ATF: various earpiece placements within the built-in ear simulator | §3.4.5.3 |
| Built-in mic. | Microphone orientation: phone placed flat and on the edge | §3.4.4.3 |
| | Inter-unit variability of the phone with the built-in mic.: 4 mobile phones of the same model | §3.4.2.1 |
| Headset | Microphone placement relative to the ATF, microphone orientation: mic. facing the exterior or the interior | §3.4.3.3 |

### 2.4.1 Frequency-dependent calibration algorithm

#### 2.4.1.1 Design of IIR and FIR filters

The frequency-dependent algorithm consists in applying a digital filter on the microphone signal in order to flatten the frequency response of the mobile phone and the microphone used. The design and implementation of frequency-dependent calibration algorithms involves the following steps :

- the calculation of the frequency response of the transfer function, calculated from the frequency response measurements;

- the design of a digital filter that fits the frequency response;
- the implementation of the filter in the noise measuring app software.

The transfer function between the phone recording (as the input) and the reference measurement (as the output) was calculated based on the frequency response measurements using the Dual channel FFT analysis, B&k (1984). The Dual channel FFT analysis was implemented by the author in MATLAB®. The transfer function (with a frequency resolution of 10 Hz) was calculated averaging the two estimates of the complex frequency response function with the first estimate that is the cross spectrum between the input and the output signals divided by the input autospectrum and the second estimate which is the output autospectrum divided by the cross spectrum between the input and the output signals.

The design of a filter that fits the transfer function was investigated for both FIR and IIR filters using the algorithms and design methods available in the MATLAB® signal processing™and DSP System™ toolboxes, version 6.9 and 8.2 respectively. Thereafter, the calculated filter coefficients were implemented in the noise measuring app software, as described in section 2.4.1.2. The design of IIR filters was investigated using the MATLAB®*invfreqz* function that converts a transfer function to filter coefficients. An script developed by the author using the MATLAB® *invfreqz*, allowed to investigate the fitting of the transfer function with the three following parameters:

- the filter order;
- the range of the transfer function, initially from 0 to 11025 Hertz, was truncated at the beginning and the end of the transfer function;
- the bandwidth of the frequency analysis of the transfer function: from the initial resolution of the transfer function to various octave bands analysis.

The code source of MATLAB® script used for the determination of the filter coefficients is given below, with the *order*, *cut_1* and *cut_2* parameters referred to as the filter order, the number of samples truncated at the beginning and at the end respectively. The design of FIR filters was investigated using the MATLAB® *firls* function that designs a discrete-time FIR filter based on the transfer function. The fitting of the transfer function was investigated with the same three parameters previously described for the design of IIR filters.

Since the processing time increases with the filter order, the objective was to design a filter that fits the transfer function with the lowest filter order.

```
order = 13 % order of the IIR filter
cut_2=350;   % number of samples truncated at the end, corresponds ...
    to transfer function truncated at 7250 Hz
cut_1=9;  %number of samples truncated at the beginning, corresponds ...
    to transfer function truncated at 86 Hz
ang = (2*pi().*fm1)./Fs;    % Frequency associated with the transfer ...
    function, specified in radians between 0 and pi
[b,a] = invfreqz(H3m1(cut_1:end-cut_2),...
        ang(cut_1:end-cut_2),order,[],'iter','tol');
%With  H3m1, the transfer function
% H3m1 contains 1024 values, defined from 0 to 11025 Hz.
```

#### 2.4.1.2 Implementation of IIR and FIR filters

The study regarding the measuring app implementation focused on the stability of the filter and the processing time, which is the time between the acquisition of the microphone signal and the storage of one noise level in the XML file (section 2.2.1). The processing time must remain under 1 second since a processing time above 1 second would cause a shift in time and for example, a one-minute measurement would contain less than 60 $L_{\text{eq,A,1sec}}$ values.

### 2.4.2 Noise level-dependent calibration algorithm

The proposed noise level-dependent calibration algorithm approach was based on two hypothesis. First, it was expected that the frequency-dependent calibration would not compensate for the non-flat devices' frequency response perfectly mostly because of filter design limitations. Second, changes of the magnitude of the frequency response (frequency distortion) were expected to occur for saturated signals. Based on the first hypothesis, it seemed relevant to have a noise level dependent calibration depending on the signal frequency content. However, the second hypothesis highlighted the need for a signal spectral content indicator that is robust enough to the frequency distortion. Comparing to fractional-octave analysis that remain sensitive to the frequency distortion, the C-weighted noise level minus A-weighted noise level

(C-A) seemed to be the most robust indicator of the spectral content. Therefore, the proposed noise level-dependent calibration algorithm was function of the C-A value.

The design and implementation of the noise level-dependent calibration algorithms implied the following steps :

- Interpolation of the noise level corrections based on the calibration measurements;
- Software implementation of the interpolated noise level corrections.

A-weighted noise level corrections are the difference between noise level measured by the reference system and by the mobile phone, as shown in following equation:

$$\Delta_{\text{A}} = L_{\text{eq,A,ref}} - L_{\text{eq,A,phone}} \tag{2.1}$$

The interpolation process aimed to generate correction values within the measured correction values, results of the calibration measurements. In the proposed noise level-dependent calibration algorithm, the correction values depend on the uncalibrated phone noise level measurements, $Lp_{\text{A,phone}}$ and the C-A values. Once calculated, the interpolated values, rounded to one decimal place, were implemented in the app as a lookup table. A Java™ method called *findInCalibrationTableA* was developed with $L_{\text{eq,A,phone}}$ and $C - A_{\text{phone}}$ as parameters. Every second, the *findInCalibrationTableA* method returns a correction value. If a $L_{\text{eq,A,phone}}$ or a $C - A_{\text{phone}}$ value is not in the range of values included in the lookup up table, the algorithm, whose the code source is in Annex VI, returns the correction value associated with the closest, either maximum or minimum, $L_{\text{eq,A,phone}}$ and/or $C - A_{\text{phone}}$ values. Finally, a $L_{\text{eq,A,calibrated phone}}$ is calculated using Equation 2.2:

$$L_{\text{eq,A,calibrated phone}} = L_{\text{eq,A,phone}} + \Delta_{\text{A}} \tag{2.2}$$

Data interpolation methods were investigated such as triangle-based linear interpolation, triangle-based cubic interpolation or nearest neighbor interpolation available through the MATLAB®

*griddata* function. The memory limitations and the processing time associated with the size of the lookup table algorithm were investigated.

# CHAPTER 3

# RESULTS

This chapter contains all the results of the study. The first section describes the study of the electro-acoustical limitations of mobile phones and external microphones with an emphasis on microphones' frequency responses and the signal saturation. In a second section, the results of the factory calibration measurements are presented, it includes the results obtained with the frequency response measurements (section 3.2.1) and with the noise levels measurements (section 3.2.2). In the third section, design and implementation of the frequency and noise level-dependent calibration algorithms are detailed:

- The design of IIR and FIR filters and the mobile phone implementation of the frequency-dependent algorithms;
- The effect of the frequency-dependent calibration on the phone noise levels;
- The results associated with the design and implementation of the noise level-dependent algorithm, including the evaluation of interpolation methods for the noise levels corrections to-be -implemented in the measuring app;

Finally, an analysis of the laboratory validation measurements is given in the fourth section. Results were obtained with mobile phones fully calibrated (implemented the frequency and the noise level-dependent calibration algorithms). First the results of the repeatability and inter-unit variability measurements are presented, second, the results are detailed by device including:

- The measurements with various noise sources;
- The measurements with various microphone placement relative to the source and the ATF;

- The measurements with acoustical field cross-calibration measurements (the "diffuse field" and "free field" calibrations used in the semi-anechoic and reverberant chambers respectively).

## 3.1 Electro-acoustical limitations of mobile phones and external microphones

Measurements presented in this section include frequency response measurements and noise level measurements, whose procedures were presented earlier in section 2.1. They focused on phone and external microphones' frequency responses and on the saturation that appears at high noise levels. All the mobile phone measurements were conducted using the noise measuring app with no frequency or level-dependent calibration algorithm implemented. The measurements with the built-in microphone and with the external microphones were conducted with the same mobile phone unit, referred to as Phone #4.

### 3.1.1 Mobile phone and external microphones' frequency responses

Frequency response were calculated from the measurements in the semi-anechoic chamber with the microphones (built-in and external microphones) attached on a stand and for the Sources 1 and 3. Figure 3.1 presents the relative magnitude of the frequency response of the phone measurement (with the measurement microphone plugged into the phone, the headset, the earpiece and the phone with the built-in microphone), as subtracted to the magnitude of the reference system measurement's frequency response. It can be seen from Figure 3.1 and particularly from the frequency response of the measurement conducted with the reference microphone plugged into the phone, that the microphone signal is processed by the phone with a high-pass filter-like audio processing that has a roll-off at around 380 Hz and a rate of -6 dB/octave. This processing also appeared on the built-in and headset measurements as similar shapes can be seen at the low-end of their frequency responses. Finally, non-linearities in the magnitude of the frequency response for frequencies above 1 kHz can also be seen in Figure 3.1: the built-in microphone and the earpiece frequency responses show both a peak centered around 6350 Hz that goes up to 10 dB.

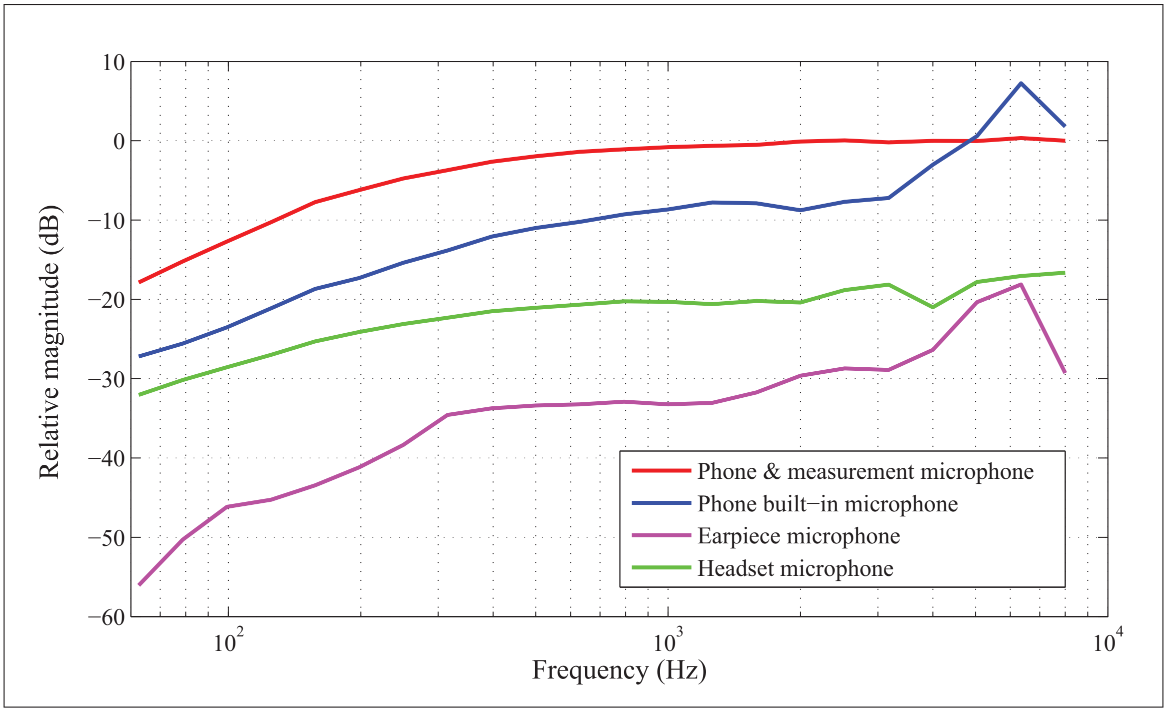


Figure 3.1 Relative magnitude of the frequency of response as subtracted to the magnitude of the reference system measurement frequency response, while measuring Source 3 at 90 dB(A)

### 3.1.2 Saturation of the phone's audio signal at high noise levels

Saturation of the phone's audio signal at high noise levels was investigated using both the spectral analysis and overall noise levels. Figure 3.2 shows A-weighted phone noise levels measured in the semi-anechoic chamber for Source 1. It highlights:

- Large variation of the device's sensitivity. At a reference noise level of 80 dB(A), the difference (offset) between the headset and the earpiece noise levels was 40 dB(A) and between the headset and the built-in noise levels 16 dB(A);
- The noise level-linearity of the earpiece and headset measurements for a range of noise levels from 75 to 105 dB(A). At a reference noise level of 105 dB(A), the devices measured 47 and 86 dB(A), respectively;

- Non-linearities in level for the built-in microphone measurement and for the measurements conducted with the reference microphone plugged into the mobile phone. The saturation appeared at a reference noise level of 86 dB(A) and at a phone noise level of 85 dB(A);
- A maximum saturation noise level for the built-in microphone measurements which was reached at a reference noise level of 104 dB(A) and phone noise level of 91 dB(A).

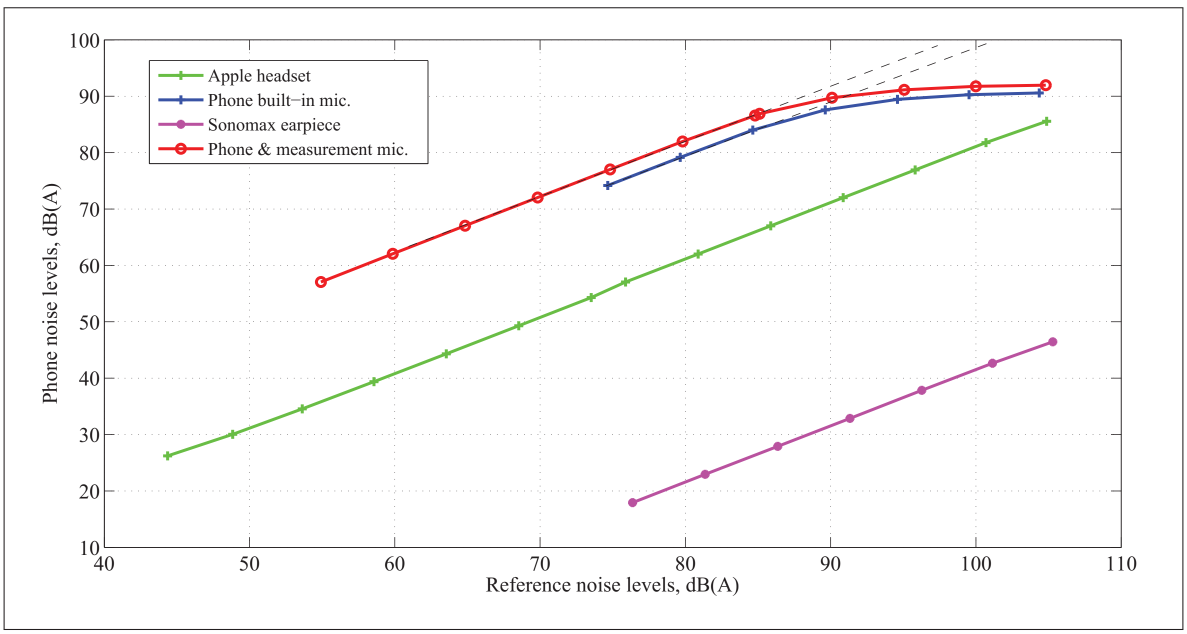


Figure 3.2 Mobile phone noise levels measured in the anechoic chamber while measuring Source 1

Figure 3.3 presents the built-in microphone noise levels and reference noise levels measured in the semi-anechoic chamber for the Sources 1, 2, 3 . While the difference between the reference noise levels measured for Sources 1, 2 and 3 was 0.9 dB(A), it can be seen that the offsets between the phone noise levels measured for the Source 1 and 3, at a reference noise level of 85 dB(A), was 4.4 dB(A). Figure 3.3 also highlights that, as the saturation increased, the offset between the measurement of each sources decreased, from 4.4 dB(A) to less than 0.4 dB(A). For the headset and the earpiece, the offset between the measurements of Source 1 and 3 were constant over the range of noise levels. Figures VIII-1 and VIII-3 in Annex VIII shows an a

1.3 dB(A)-offset for the headset measurements and a 3dB(A)-offset for earpiece measurement.

A frequency analysis of the saturation at high noise levels are presented for the built-in and

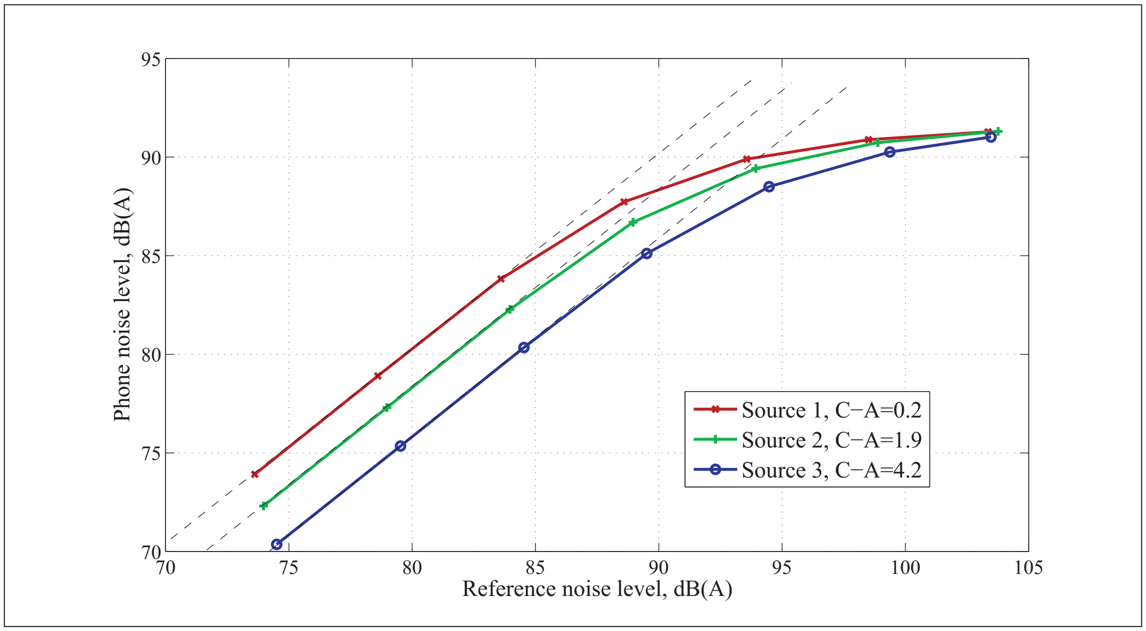


Figure 3.3  Built-in microphone noise levels while measuring Source 1, 2 and 3 in the semi-anechoic chamber

external microphones measurements in Figures 3.4, 3.5 and 3.6. The top graph of Figure 3.4 shows the frequency responses of the measurements conducted with built-in microphone for Source 1 and for noise levels from 75 to 105 dB(A). The bottom graph shows the frequency responses for the 7 noise levels, with their magnitude normalized at the 1 kHz third-octave band noise level. It can be seen from Figure 3.5 (measurements with the reference microphone plugged into the phone) and Figure 3.4 (built-in microphone measurements), 1-to-3-dB shifts of the frequency response's magnitude at multiple frequencies ranges and appearing only for noise level above 85 dB(A). However, the frequency response of devices whose noise levels did not saturate at high noise levels (the headset and the earpiece) do not not have similar magnitude shifts, as illustrated in Figure 3.6 with the frequency response of the headset measurement.

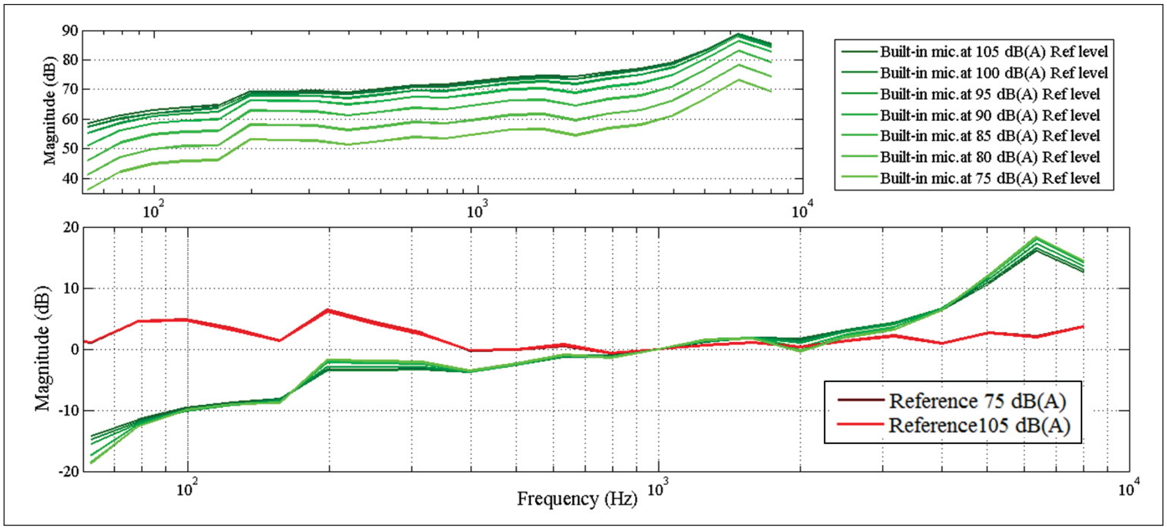


Figure 3.4 Frequency responses of the measurements conducted with the built-in microphone (top half), frequency responses with the magnitude normalized at the 1 kHz third-octave band noise level (top bottom)

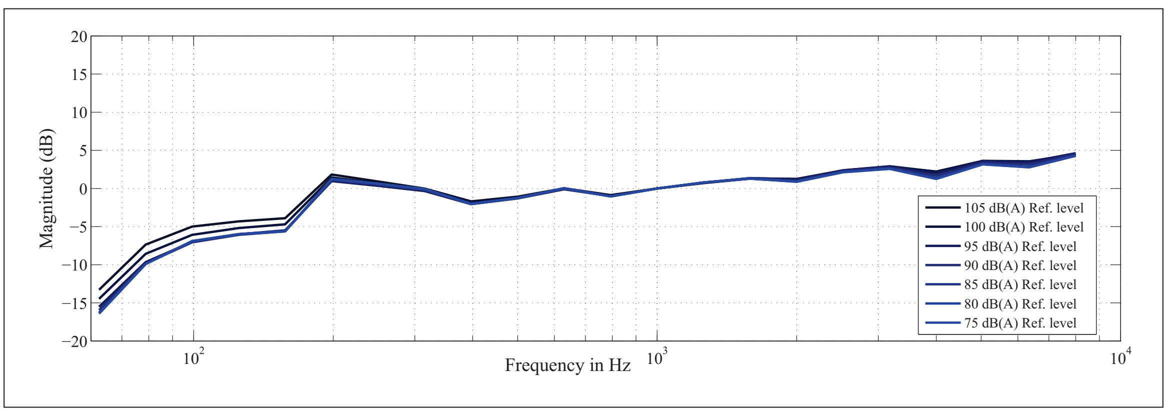


Figure 3.5 Frequency responses of the measurements conducted with reference microphone plugged into the mobile phone with the magnitude normalized at the 1 kHz third-octave band noise level

## 3.2 Factory default calibration measurements

The goal of the investigations presented in this section, was to define the factors that impact the factory default calibration measurements and subsequently to design a factory default calibration approach. This section includes the results obtained with the frequency response measurements (section 3.2.1) that were used to design IIR and FIR filters and the results obtained with

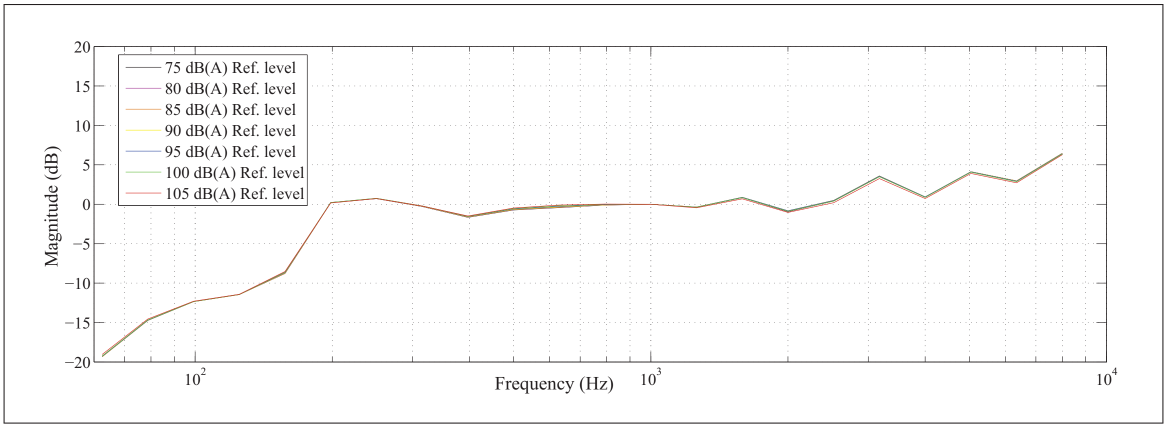


Figure 3.6 Frequency responses of the measurements conducted with the headset with the magnitude normalized at the 1 kHz third-octave band noise level

the noise levels measurements (section 3.2.2) used for the design of noise-level dependent algorithms. Measurements were carried out under repeatability conditions (same operator, same equipment and over a short time period) with one factor at a time that was modified.

### 3.2.1 Frequency response measurements

Mobile phone measurements were conducted with the same mobile phone unit, referred to as Phone #4, implementing no frequency or level-dependent calibration algorithm. The results of the frequency response measurements are presented using a transfer function and a coherence function. Both are calculated using the Dual channel FFT analysis with audio recordings of the device being tested (as the input) and of the reference system (as the output), as detailed in section 2.4.1.1. Considering that the reference measurement system has a flat frequency (frequency and level independent) response, the shape of the transfer function's magnitude corresponds to the inverse of the device under test's frequency response. Thereby, the "high pass" filter-like processing with roll-off at 380 Hz, observed on the phone's frequency response can be seen on the transfer function as a magnitude that attenuates from the very low-end frequencies to 380 Hz.

Figure 3.7 shows the transfer function and the coherence values calculated from the earpiece measurements for the microphone located on a microphone stand and for two ATF positions relative to the source (Figure 2.16). It can be seen from Figure 3.7 that the magnitude corresponding to the measurement on a stand is 5 to 20 dB lower than the "exposed ear side" position magnitude for frequencies between 150 Hz and 4 kHz.

Figure 3.8 shows the differences in magnitude between the transfer functions from the headset measurements conducted on a stand and on the ATF for two microphone placements with regards to the ATF (towards the exterior and towards the interior). The magnitude of the transfer function differs by 5 dB between 400 Hz and 2 kHz. The differences in magnitude of the frequency response for the microphone oriented towards the exterior and the interior varied between 2 and15 dB for frequencies between 2 and 5 kHz.

Figure 3.9 presents the transfer functions calculated from earpiece measurements for four variations of the earpiece placement within the built-in ear simulator. The placement variations went from tightly and deeply mounted, referred to as Insertion #1, to lightly inserted, referred to as Insertion #4. It can be seen from Figure 3.9 that for frequencies above 2500 Hz, the offset in magnitude is between 4 and 10 dB between Insertion #1 and #4. Moreover, a looser insertion corresponds to a higher magnitude in decibels.

The inter-unit variability of the built-in microphone phones' frequency responses is highlighted in Figure 3.10, as the figure presents the transfer functions calculated from built-in microphone measurements of 4 units of the same mobile phone model. Maximum offsets in magnitude of 10 and 7 dB occurs at 2 kHz and 7 kHz, respectively between the phone units #2 and #3.

The influence of the acoustical field on earpiece frequency responses measurements was investigated with measurements in both semi-anechoic and reverberant chambers with the earpiece on a stand and on the ATF. Figure 3.11 shows the transfer function and the coherence values calculated from measurements in both chambers. It can be seen that the magnitudes of the TFs based on the measurements conducted on stand in both chambers followed the same trend however their coherence values strongly differs with very low coherence values for the measurements in the reverberant chamber. Looking at the TFs based on the earpiece measurements located on the ATF, the magnitudes of the TFs differ greatly between the chambers with maximum variations from 10 to 20 dB in the frequency range between 200 Hz and 1 kHz.

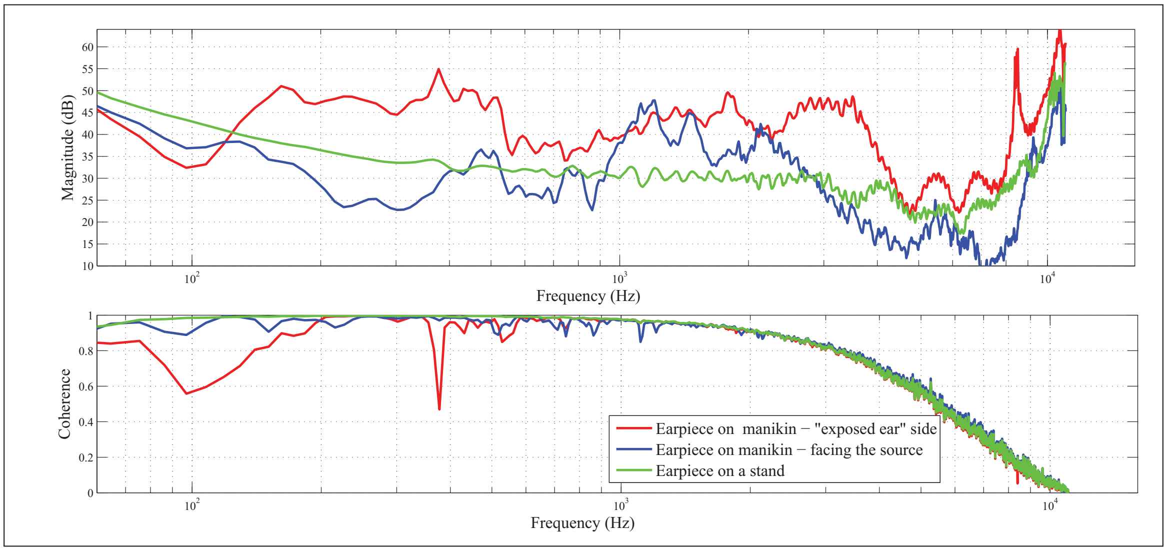


Figure 3.7 Transfer function and coherence values from the measurements conducted with the earpiece located on a microphone stand and for two positions on the ATF

### 3.2.2 Noise level corrections measurements

First, the effect of the acoustical field on the noise level correction values is presented with measurements in the reverberant and semi-anechoic chambers. Second, this section presents the results for each factor, as presented in Table 2.7 (section 2.3.2.3). Phone noise levels measurements were conducted with the noise measuring app implementing a frequency-dependent calibration algorithm adapted for each device and whose design and implementation are discussed later in section 3.3.1. External microphones were located on the ATF except where mentioned otherwise.

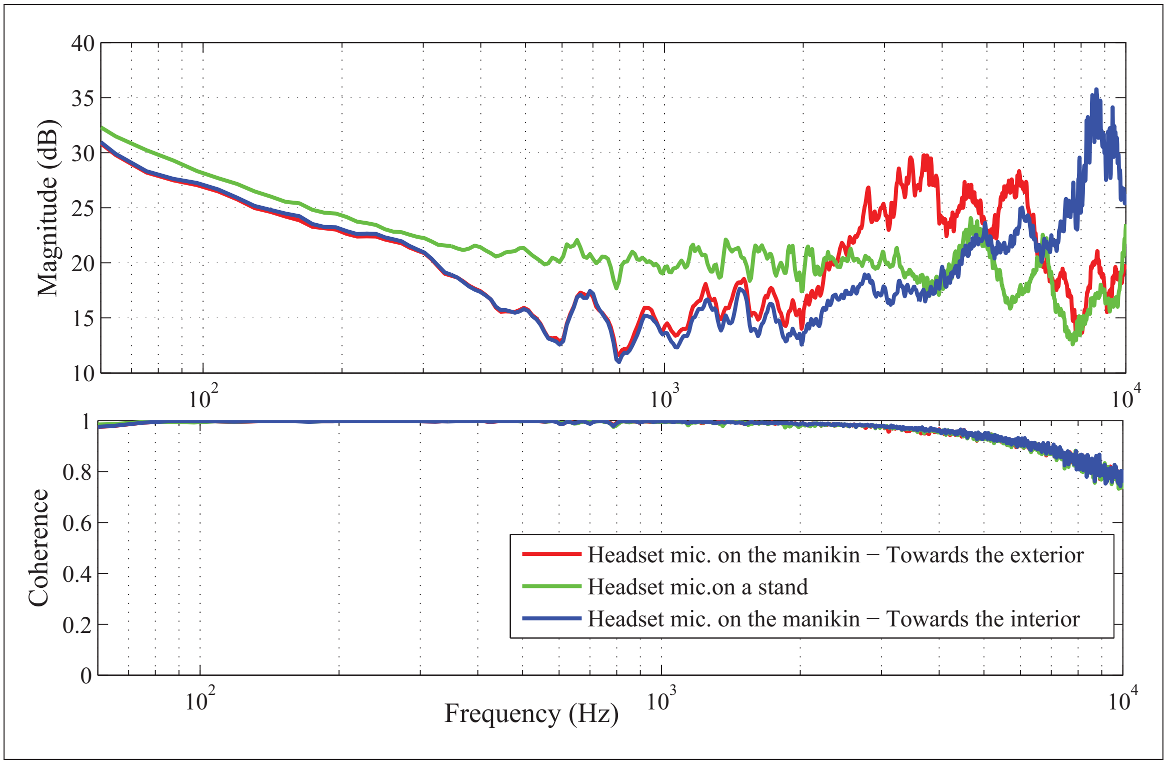


Figure 3.8 Transfer function and coherence values calculated from the measurements conducted with the headset microphone located on a microphone stand and on the ATF

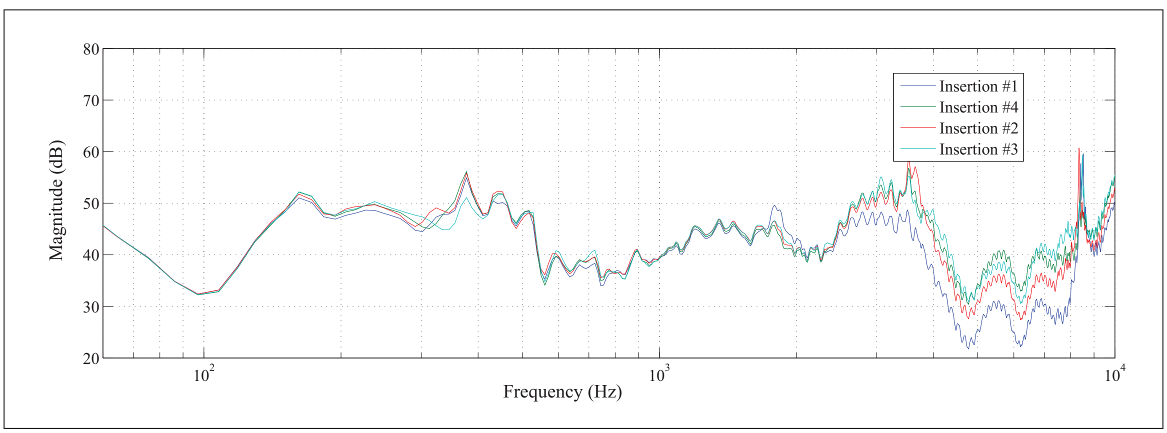


Figure 3.9 Transfer functions calculated from the earpiece measurements with slight variations of the earpiece placement within the built-in ear simulator

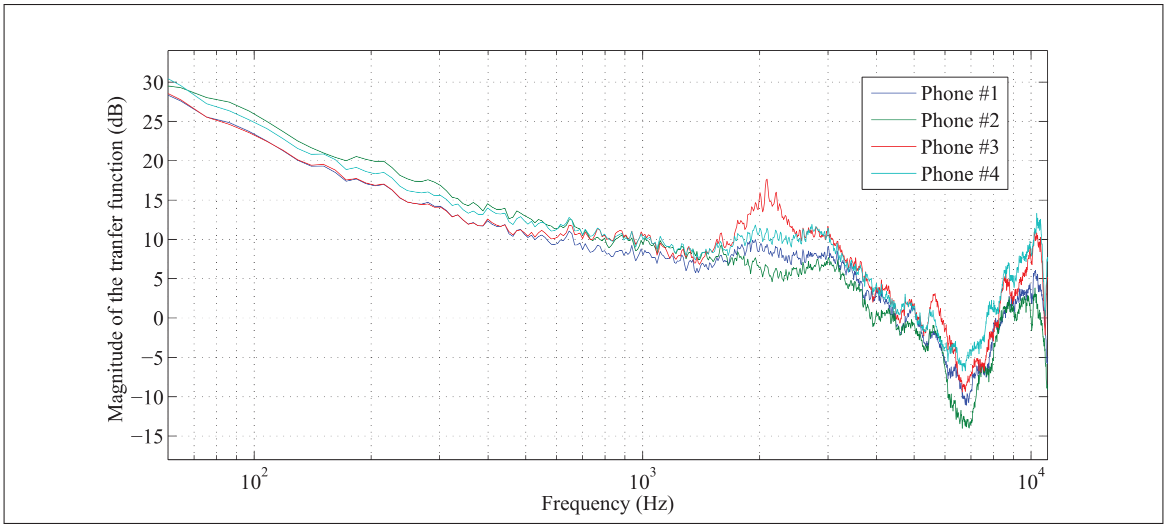


Figure 3.10 Transfer functions calculated from the built-in microphone measurements of the 4 ZTE N762 mobile phone units

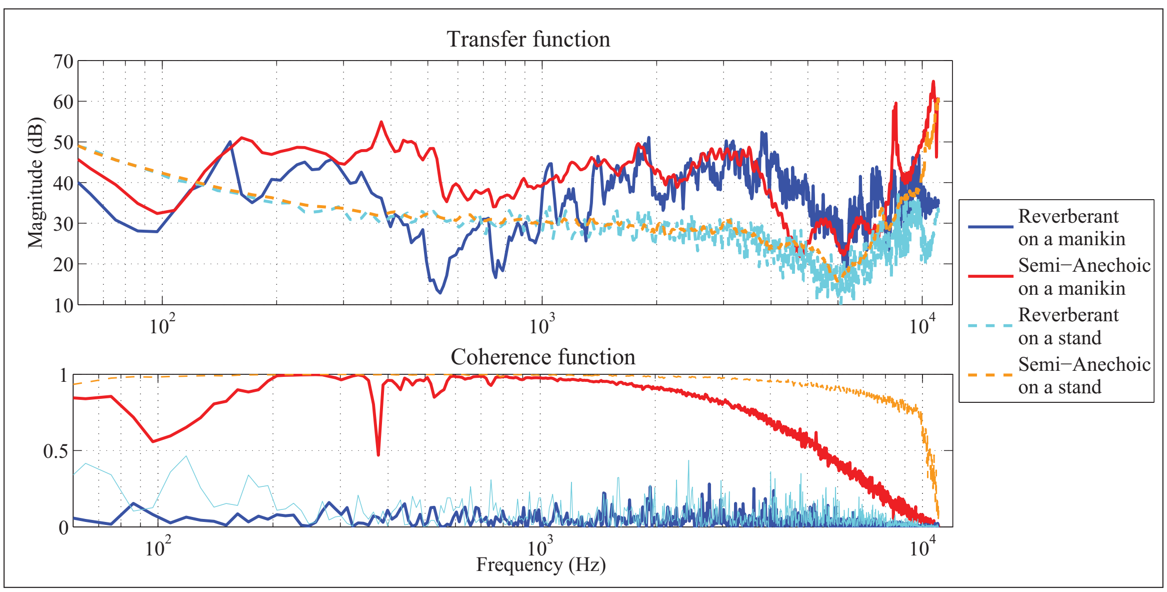


Figure 3.11 Transfer function and coherence values calculated from earpiece measurements in the semi-anechoic and reverberant chambers with the earpiece on a stand and on the ATF

#### 3.2.2.1 Differences due to the acoustical field

Table 3.1 contains the reference and phone C-A values for Sources 1, 2 and 3, measured in the reverberant and anechoic chambers for a reference noise level of 95 dB(A). It can be seen from

Table 3.1 that C-A values measured with the earpiece strongly differ from the reference values and depend on the acoustical field, unlike measurements with other microphones.

Table 3.1 Reference and phone C-A values measured for Sources 1, 2 and 3 in the reverberant (R) and semi-anechoic (S-A) chambers and at reference noise level of 95 dB(A)

| | **Reference** | | **Headset** | | **Built-in** | | **Earpiece** | |
|---|---|---|---|---|---|---|---|---|
| | R | S-A | R | S-A | R | S-A | R | S-A |
| Source 1 | -0.2 | 0.2 | -0.5 | 0.0 | -0.4 | 0.5 | 2.5 | 4.9 |
| Source 2 | 1.1 | 1.9 | 0.3 | 1.1 | 0.4 | 1.4 | 3.1 | 7.2 |
| Source 3 | 3.6 | 4.2 | 2.0 | 2.6 | 2.2 | 3.2 | 4.1 | 10.1 |

As discussed in section 2.4.2, the noise levels corrections values (reference noise levels minus phone noise levels) are interpolated from the noise level corrections measurements. In Figure 3.12, the interpolated values are represented as a 3D surface where the *x-axis* and the *y-axis* display the phone noise levels in dB(A) and the C-A values and the *z-axis* displays the noise level corrections in dB(A). Figure 3.12 shows the noise level corrections measured in the semi-anechoic (in red) and reverberant (in blue) chambers for the headset (top graphic), the built-in (middle graphic ) and the earpiece (bottom graphic). The flat part of the surface corresponds to constant correction values due to the level linearity of the devices at at low-end of the noise level range. At higher phone noise levels, the noise correction values increase due to the saturation that occurs. The difference, $\delta$, in dB(A) for a reference noise level of 80 dB(A), between noise level corrections from the reverberant and semi-anechoic measurements, also referred to as the free-field and diffuse field corrections are presented in Table 3.2. The $\delta$ values correspond in Figure 3.12, to the offsets in dB(A) between the blue "reverberant" and the red "semi-anechoic" surfaces. It can be seen from Table 3.2 that the noise level corrections for the earpiece in the free field greatly differ from the the diffuse field corrections, regardless of the noise source.

Figure 3.13 compares built-it microphone measurements for Sources 1, 2 and 3 in the reverberant and semi-anechoic chambers. It can be seen that the saturation level is 1.7 to 2.4 dB(A) higher for measurements in the reverberant chamber than for measurements in the semi-anechoic chamber, depending on the noise source.

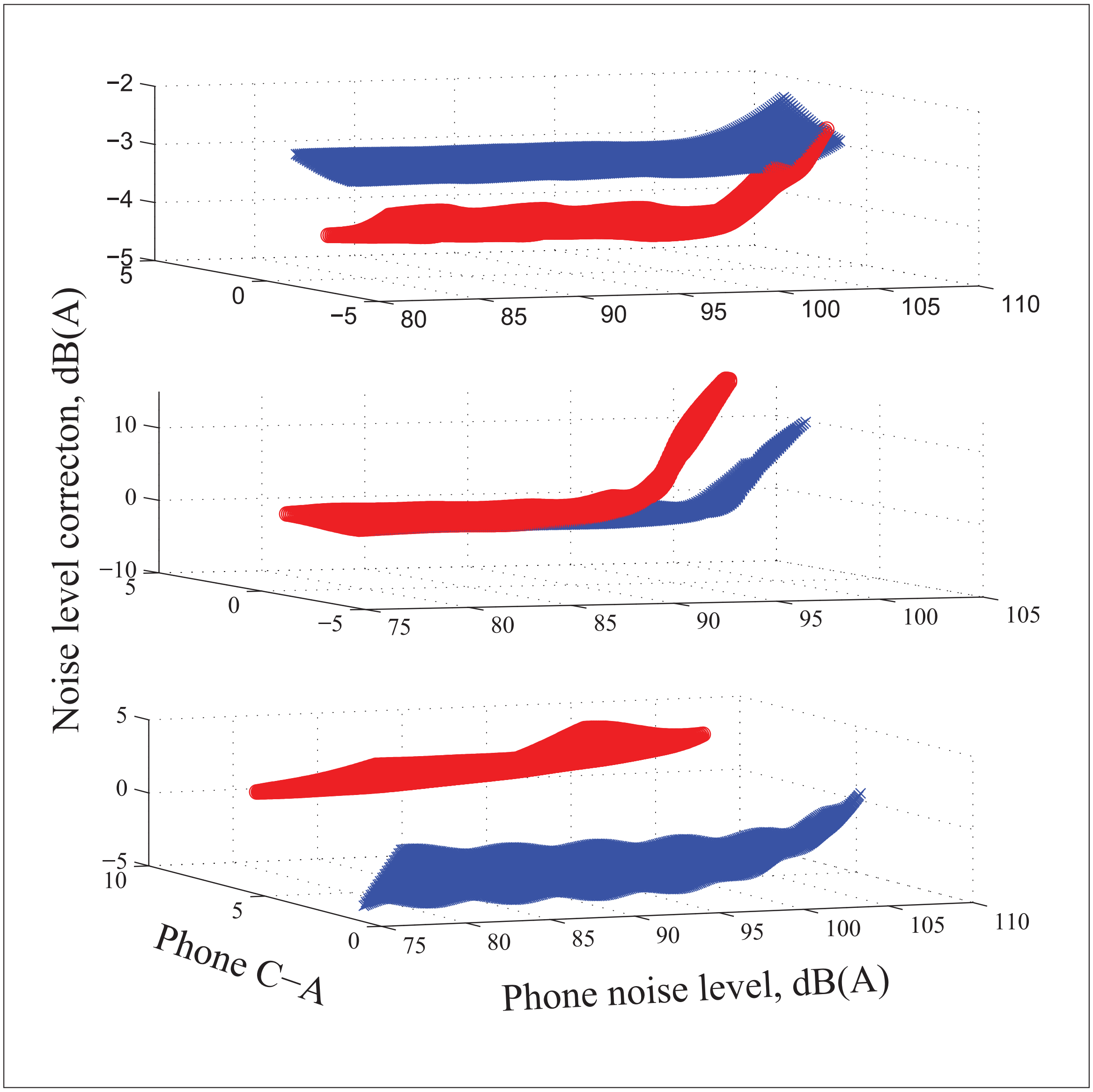


Figure 3.12 3D views of the interpolated noise level corrections measured in the semi-anechoic (in red) and reverberant (in blue) chambers for the headset (top), built-in (middle), and earpiece (bottom) microphones

Table 3.2 Noise level corrections for the Source 1,2 and 3, measured in the reverberant (R) and semi-anechoic (S-A) chambers for a reference noise level of 80 dB(A)

| | **Headset** | | | **Built-in** | | | **Earpiece** | | |
|---|---|---|---|---|---|---|---|---|---|
| | R | S-A | $\delta$ | R | S-A | $\delta$ | R | S-A | $\delta$ |
| Source 1 | -3.3 | -3.9 | 0.6 | -1.4 | -1.4 | 0.0 | -1.3 | 3.8 | -5.0 |
| Source 2 | -3.2 | -4.4 | 1.1 | -1.3 | -1.2 | -0.1 | -3.0 | 1.7 | -4.8 |
| Source 3 | -3.0 | -4.5 | 1.5 | -1.0 | -0.9 | -0.1 | -5.1 | -0.3 | -4.8 |

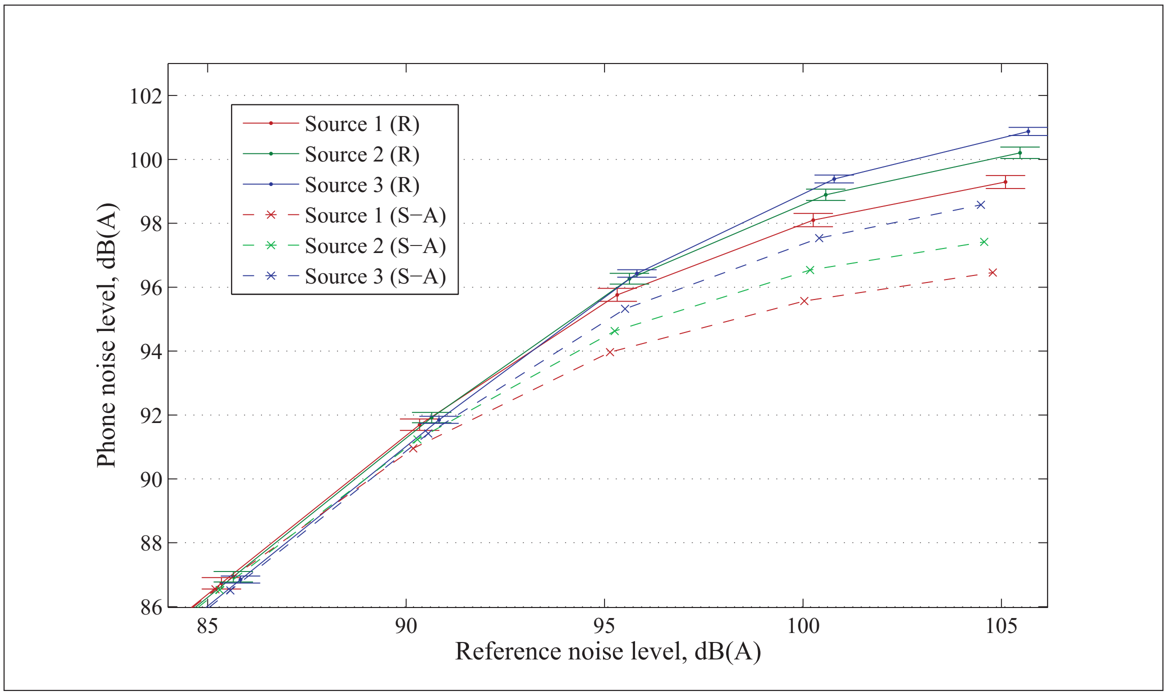


Figure 3.13 Built-in noise level measurements measured in the semi-anechoic (S-A, in dashed line) and reverberant (R) chambers

#### 3.2.2.2 Deviations due to the microphone placement relative to the source in the reverberant chamber

Measurements were conducted in the reverberant chamber for Sources 1, 2 and 3 and for four positions, two of which (positions $0°$ and $90°$) are illustrated in Figure 2.19. The standard deviation of the earpiece measurements over the 4 positions, decreased from 0.5 to 0.3 dB, as the noise levels increased and regardless of the noise source. The standard deviations for the headset and the built-in measurements were under 0.3 dB regardless of the noise level and the noise source. This results provides a good indication of the diffuseness of the reverberant chamber.

#### 3.2.2.3 Deviations due to the earpiece placement within the built-in ear simulator

Measurements were conducted with one ATF position relative to the source and Source 1. Figure 3.14 presents the noise level corrections measurements for five different variations of earpiece placement within the built-in ear simulator. The variations include the microphone placement and the insertion depth, Insertion #1 correspond to a tightly and deeply mounting and Insertion #4 to a light insertion. The range of noise levels (between Insertions #1 and #4) went from 9.3 dB(A) at a reference noise level of 80 dB(A) to 6.2 dB(A) at a reference noise level of 105 dB(A).

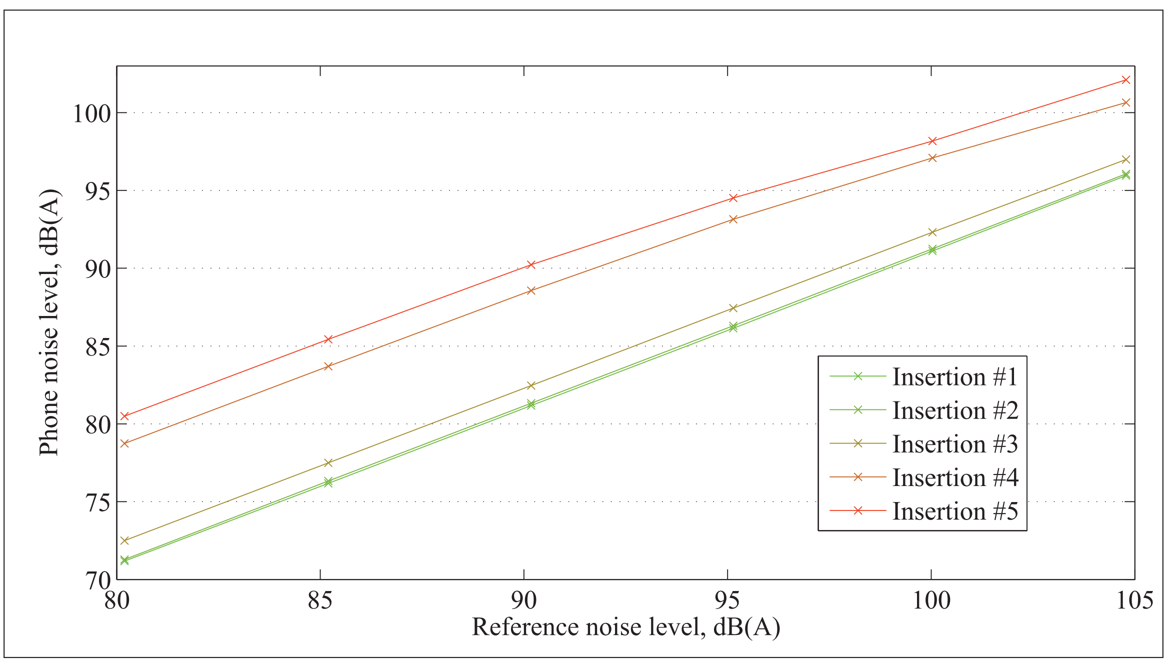


Figure 3.14 Noise level corrections measurements for five variations of earpiece placement within the built-in ear simulator measured in the semi-anechoic chamber

#### 3.2.2.4 Deviations due to the headset microphone placement relative to the ATF

Measurements were conducted in the reverberant chamber for one ATF orientation towards the source and with the Source 1. The headset microphone was located on the ATF as illustrated in Figure 2.14. Noise levels measured with the microphone towards the interior, facing the ATF, were 0.9 to 1 dB(A) higher than noise levels measured with the microphone towards the exterior, facing the loudspeakers.

#### 3.2.2.5 Deviations due to the ATF dressed with a sweater

Table 3.3 resumes the differences in dB(A) between the measurements without and with the ATF dressed with a sweater for the earpiece and headset measurements in both anechoic and reverberant chambers. From Table 3.3, it can be seen that:

- By dressing the ATF with a sweater, the A-weighted noise levels decrease from 0.6 to 1.1 dB(A), depending on the device and the noise source spectrum;
- The deviations are greater with the headset measurements;
- The deviations do not depend on the acoustical field.

Table 3.3 Deviations due to the ATF dressed with a sweater, measured in the reverberant (R) and anechoic (S-A) chambers while measure

| Noise Source | Location | Headset | Earpiece |
|---|---|---|---|
| Source 1 | R | -1.1 | -0.7 |
| Source 2 | | -0.8 | -0.6 |
| Source 3 | | -0.6 | -0.7 |
| Source 1 | S-A | -1.1 | -0.8 |

## 3.3 Design and implementation of the calibration algorithms

### 3.3.1 Design and implementation of frequency-dependent algorithms

#### 3.3.1.1 Design of IIR and FIR filters based on the device's frequency responses

The objective was to investigate the use of FIR and IIR filters to fit the transfer function (TF) calculated from phone measurements and reference system measurements. The investigation was conducted using MATLAB®functions and for the three following parameters:

- Filter order;
- Range of the TF, initially from 0 to 11025 Hz, was truncated at the beginning and the end of the transfer function;
- Bandwidth of the frequency analysis of the TF: from the initial resolution of the transfer function to various octave bands analysis.

Figure 3.16 shows the frequency responses calculated based on the built-in microphone TF, for sixth-order IIR filters with the low-end of the TF truncated at 80 Hz and with several truncated-end from 10485 Hz to 5635 Hz, as illustrated in Figure 3.15. It can be seen from Figure 3.16 that the truncation of the TF allowed to avoid the fitting of the very low and very high frequencies of the TF. Moreover, the truncation at the end of the TF improves, to a certain extent, the fitting of the transfer function's low frequencies.

Figure 3.17 shows the fitting of the built-in TF for IIR filters with an order from 2 to 14. It can be seen that for frequencies under 400 Hz, a good fitting was reached starting from a sixth-order filter. Regarding the headset, similar findings were observed for the IIR filters, moreover a good fitting was reached for the TFs based on measurements conducted on a stand and on the ATF, as illustrated in Figure 3.18.

The design of an IIR filter for the earpiece highlights an issue with regards to the fitting of irregular (in magnitude) TFs: as illustrated in Figure 3.7, the magnitude of the TF based on measurements with the earpiece located on the ATF was more irregular that the magnitude of the TF based on measurements on a stand. Figure 3.19 shows the "earpiece on the ATF" TF and the frequency responses of IIR filters with an order from 2 to 14. It can be seen from Figure 3.19 that none of the frequency responses fitted well the earpiece TF. However, for the "smoother" TF based on the measurements with the earpiece located on a stand, a better fitting of the TF was obtained, as shown in Figure 3.20.

The FIR filters design provided lower results than the IIR filters regarding the fitting of the transfer function's low frequencies, as it can be seen on Figure 3.21 with the frequency responses of IIR and FIR filters designed for the built-in TF. Moreover, the number of coefficients required for the FIR filters was considerably higher than for IIR filters: a $30^{th}$ order FIR filter has 31 coefficients whereas a $6^{th}$ order IIR filter has 14 coefficients.

The bandwidth of the TF frequency analysis was investigated as a factor of the IIR and FIR filter design with one-third, one-sixth and one-twelfth octave bands transfer functions. It did not show better results than when using the initial transfer function calculated with a frequency resolution of 10 Hz.

Figure 3.22 presents the transfer function and coherence values calculated from earpiece measurements in the semi-anechoic and reverberant chambers together with the frequency responses of IIR filter designed using the same parameters: a filter order of 12 and the same truncation of the initial TF. Figure 3.22 highlighted for the TF from measurements in the reverberant chamber, a very low coherence and a limitation of the IIR filter design method to fit properly the TF.

Finally, from the results presented in this section, four major conclusions can be drawn, three regarding the filter design methods and one specifically regarding the earpiece filter:

- The devices' transfer function was better fitted (and with less coefficients) with IIR filters than with FIR filters;
- High coherence values of the transfer function adversely affect the design of IIR filters;
- Frequency response measurements in a free-field may lead to a better design of IIR filters than those from a diffuse field;
- For the IIR filter associated with the earpiece, the filter design method used in this study require a transfer function from measurements conducted on a stand rather than a transfer function from measurements conducted on the ATF.

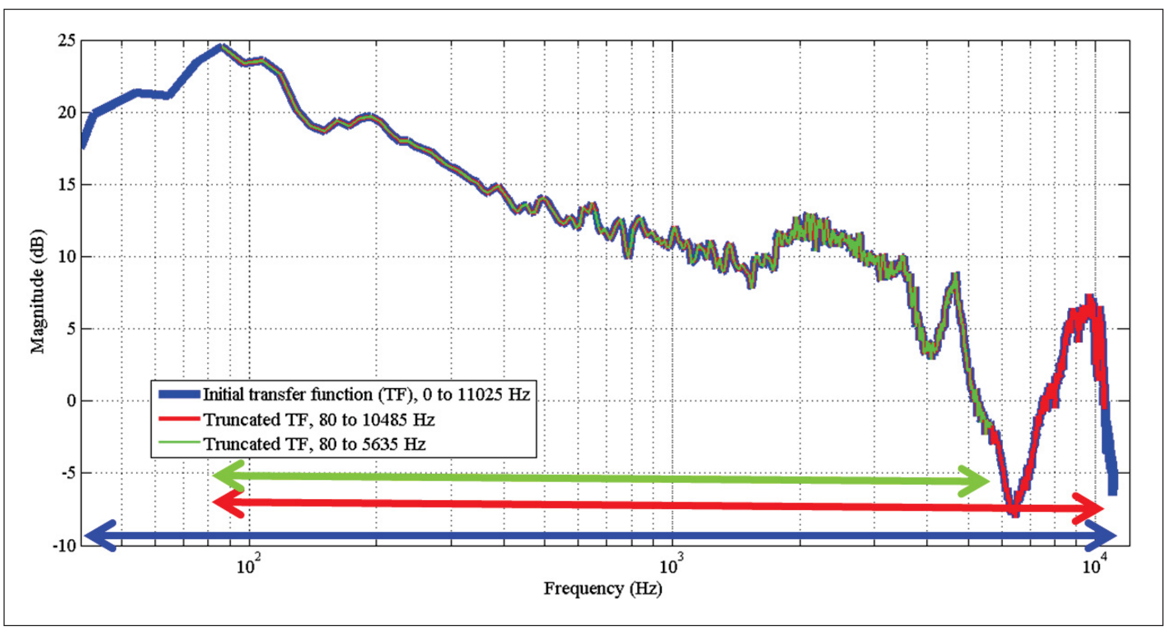


Figure 3.15 Initial transfer function (in blue) based on the built-in microphone measurement, truncated-transfer functions, defined from 80 Hz to 10485 Hz (in red) and to 5635 Hz (in green)

#### 3.3.1.2 Mobile phone implementation of the frequency-dependent algorithms

The implementation of IIR filters showed that there is a maximum order above which the number of operations needed per unit of time exceeds the phone's computing capabilities and

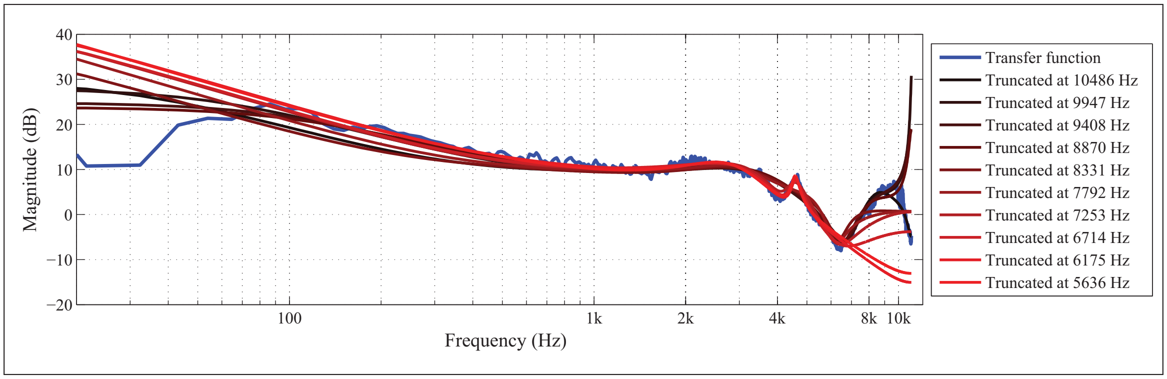


Figure 3.16 Initial transfer function based on the built-in microphone measurement and frequency responses of 6th-order IIR filters calculated from the truncated-transfer function, defined from 80 Hz to several truncated-end starting at 10485 Hz until 5635 Hz

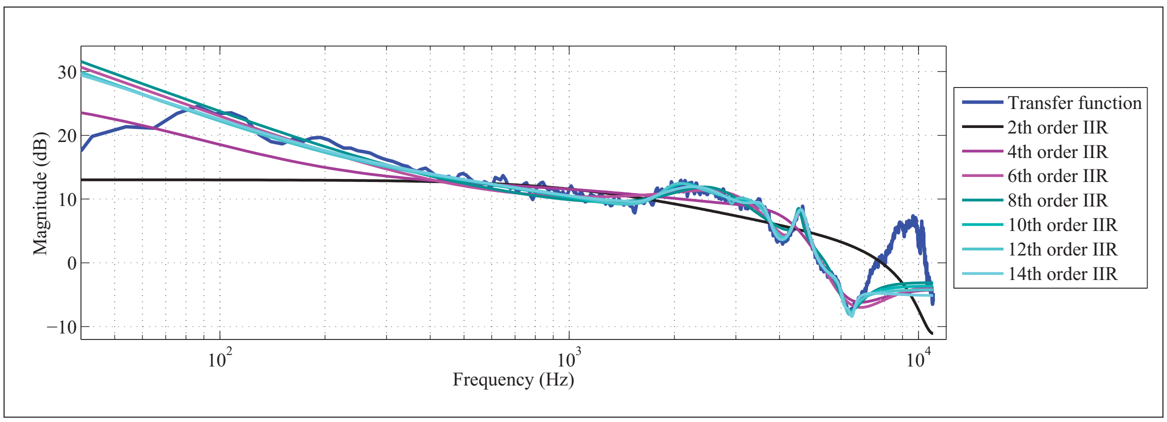


Figure 3.17 Built-in microphone initial transfer function, defined from 0 to 11025 Hz, and frequency responses of IIR filters for orders from 2 to 14, calculated from the truncated-transfer function (from 80 Hz to 6700 Hz)

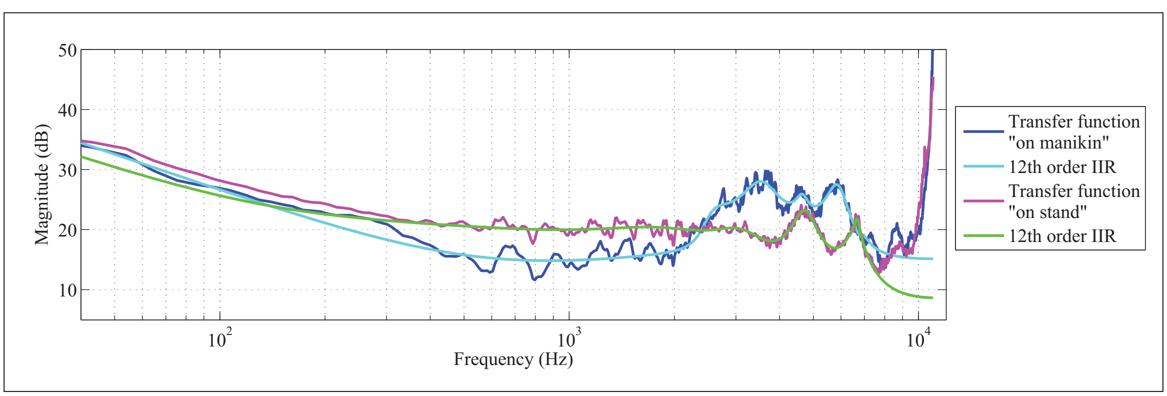


Figure 3.18 Headset transfer functions based on the measurement for different microphone placements and frequency responses of the 12th order IIR filters, calculated from the truncated-transfer functions (from 43 Hz to 7250 Hz)

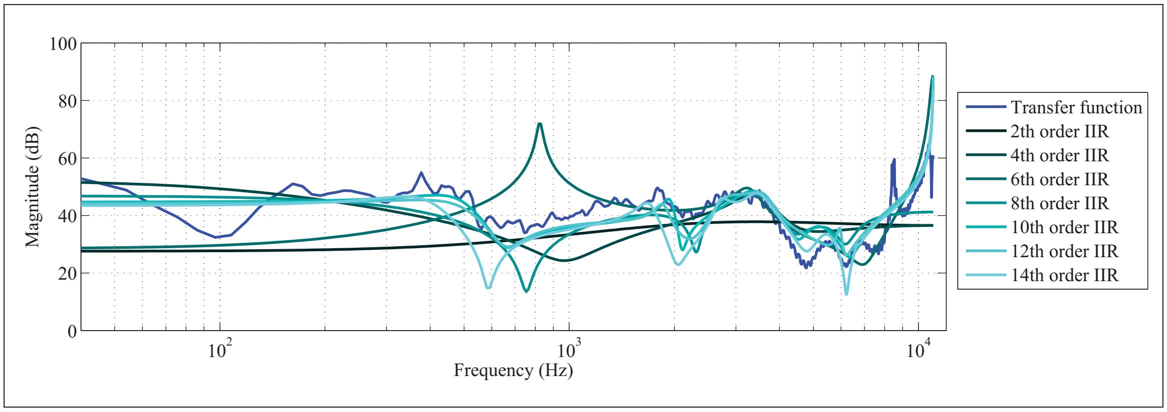


Figure 3.19 Earpiece initial transfer function for the earpiece located on the ATF and frequency responses of IIR filters for orders from 2 to 14

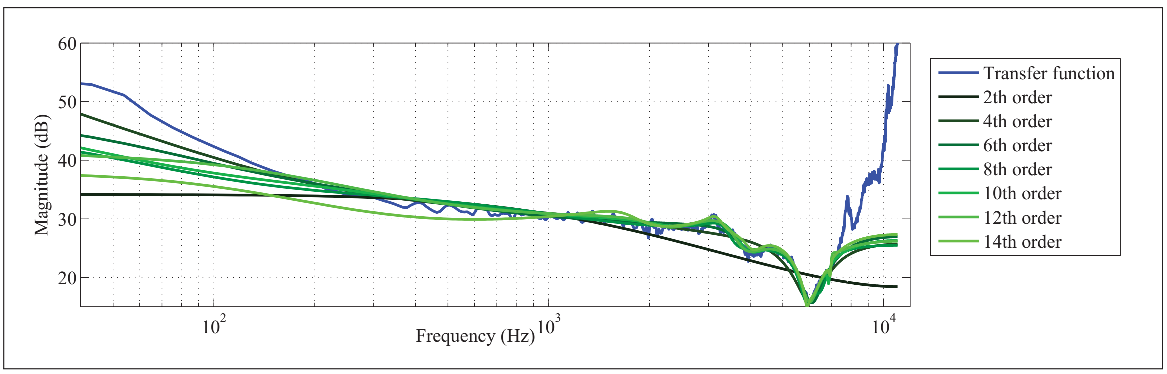


Figure 3.20 Earpiece initial transfer function for the earpiece located on a stand and frequency responses of IIR filters for orders from 2 to 14

causes the app to calculate unrealistic noise levels. The maximum order for the phones under-test (ZTE N72 mobile phones) was evaluated at 33 which corresponds to 68-coefficients.

For FIR filters, high-number-order filters did not cause the app to calculate unrealistic noise levels, however the processing time required to compute a $L_{\text{eq,A,1sec}}$ tended to exceed one second, as the number of order increased. As mentioned in section 2.4.1.2, the processing time needs to remain below 1 second. Above 1 second, a shift in time appears so a one-minute measurement would contain less than 60 $L_{\text{eq,A,1sec}}$ values, as illustrated in Figure 3.23 with the histogram of a one-minute measurements with 120$^{\text{th}}$ and 240$^{\text{th}}$order FIR filters. It can be

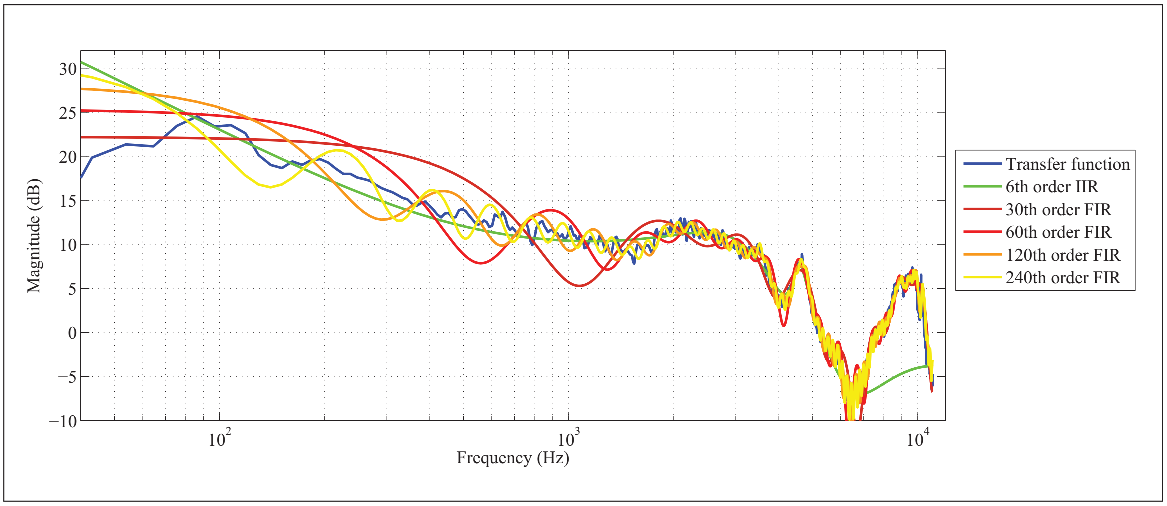


Figure 3.21 Frequency responses of IIR calculated from the truncated-transfer functions and frequency responses of FIR filters for orders from 30th to 240th order based on the initial built-in microphone transfer function

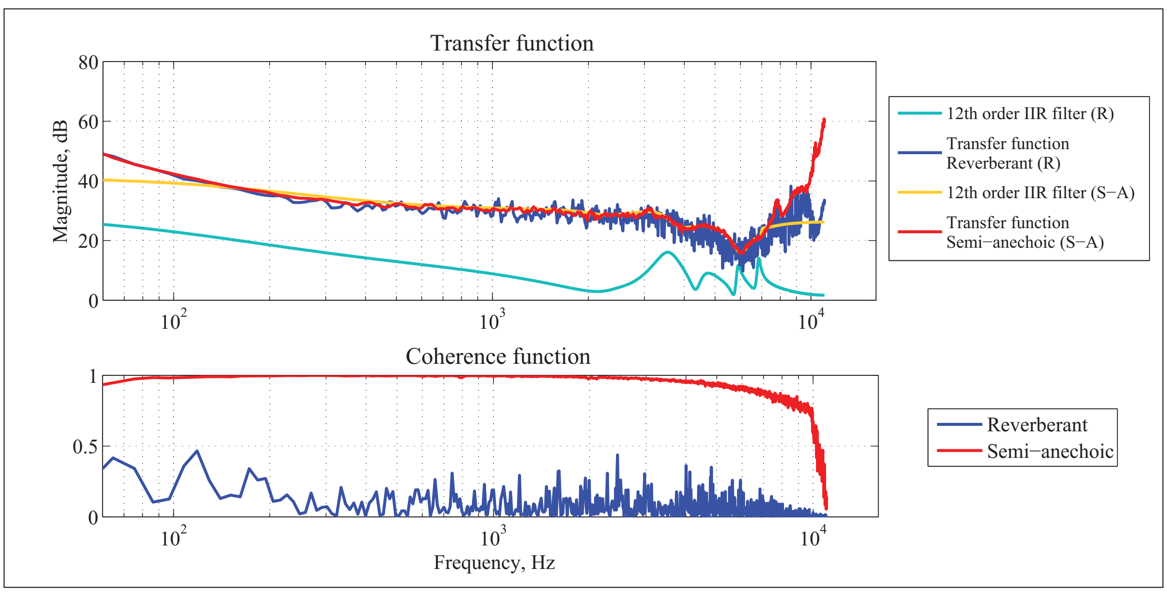


Figure 3.22 Earpiece transfer function and coherence values, frequency responses of 12th order IIR filters

seen from Figure 3.23 that for the the 240th order FIR filter, the number of occurrences strongly decreased, as the processing time increased.

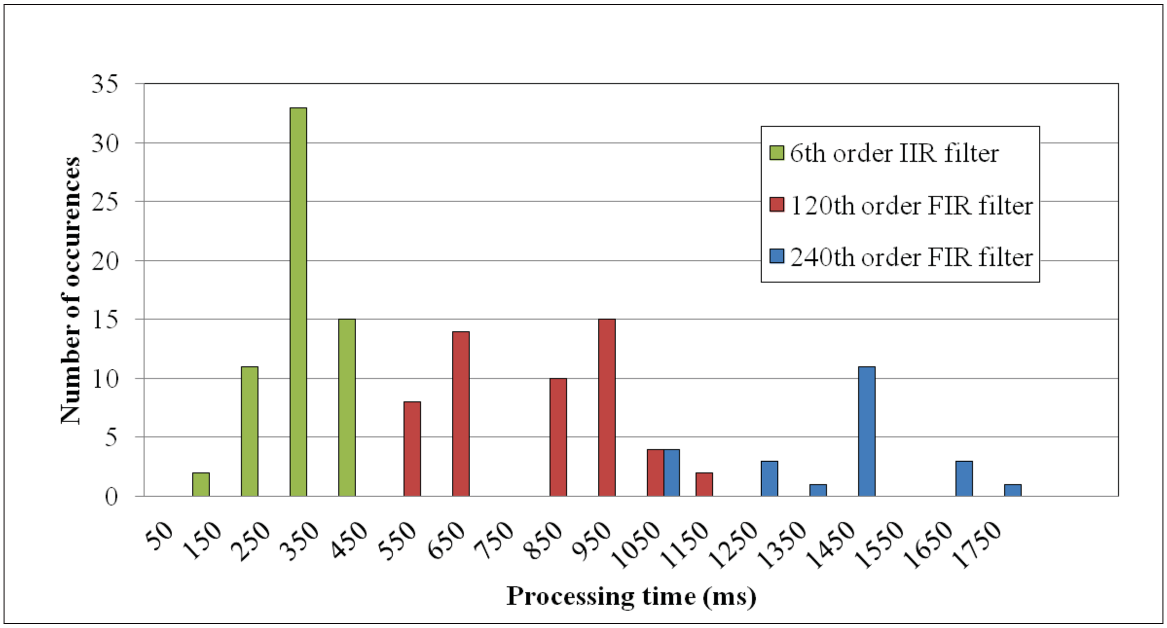


Figure 3.23 Histogram of the processing time required by the mobile phone app to compute a $L_{\text{eq,A,1sec}}$ over a one-minute-measurement and depending on the IIR and FIR filters order

### 3.3.1.3 Effect of the frequency-dependent calibration on the phone noise levels

This section compares the results of the noise levels measurements conducted with the measuring app with and without the implementation of the frequency-dependent algorithm. Difference between noise levels measured for Source 1 and Source 3 (offset) were used as indicator to evaluate the efficiency of the frequency-dependent calibration.

The offsets for built-in microphone measurements without frequency-dependent calibration were already shown in Figure 3.3 (section 3.1.2) which showed that as the saturation increased, the offset decreased, from 4.4 dB(A) to less than 0.4 dB(A). Table 3.4 contains the offsets in dB(A) between the built-in microphone noise level measurements, measured on a stand, with and without the IIR filter implemented. It can be seen from both Table 3.4 and Figure 3.24 that while the frequency-dependent calibration reduced the offset at noise levels below the saturation level, the offset re-increased at high noise levels due to saturation.

Table 3.4 Difference between noise level measured for Source 1 and Source 3 for the built-in microphone measurements using a mobile phone with and without a frequency-dependent calibration

| Measurement description | From 75 to 80 dB(A) | 105 dB(A) |
|---|---|---|
| without IIR filter | 4.4 | 0.3 |
| with IIR filter | -0.5 | -2 |

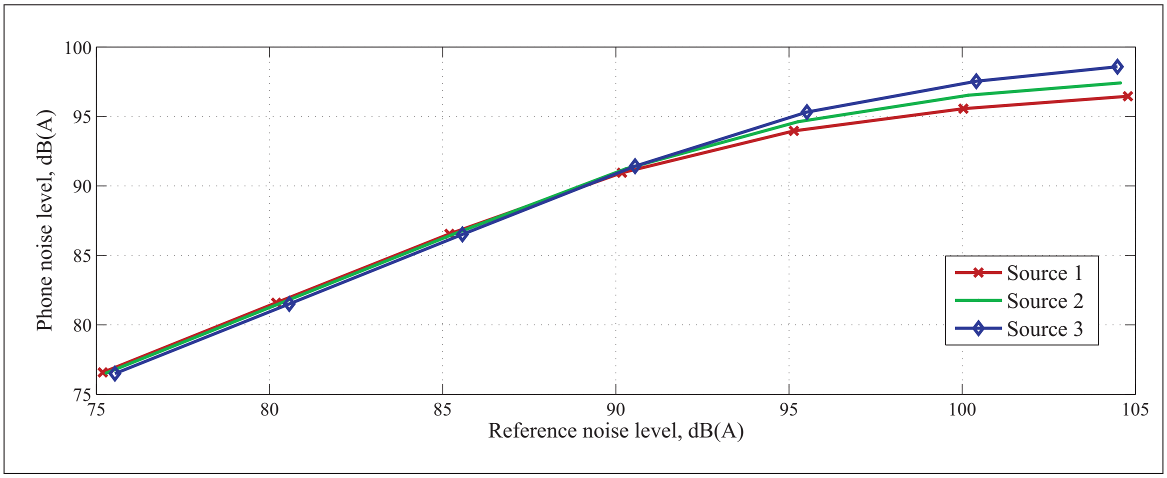


Figure 3.24 Built-in microphone noise level with a frequency-dependent calibration (6th order IIR filter), function of the reference noise level, while measuring Source 1, 2, 3

Table 3.5 contains the offsets in dB(A) for the earpiece and headset noise level measurements with and without their associated IIR filter implemented. From Table 3.5, it can be seen that:

- For the headset measurements, the frequency-dependent calibration was efficient as it decreased the offset;
- For the earpiece measurement, when located on the ATF, the frequency-dependent calibration was not efficient as it increased the absolute offset by 1 dB(A).

From this results for the three devices, it can be seen that the frequency-dependent calibration significantly reduced in overall A-weighted errors, as compared to the phone noise levels measured without any calibration, however, the phone noise levels with only the frequency-

Table 3.5 Difference between noise level measured for Source 1 and Source 3 for the headset and earpiece measurements using a mobile phone with and without a frequency-dependent calibration

| Measurement description | Headset | Earpiece |
|---|---|---|
| without IIR filter, measured on the ATF | -1.4 | 3 |
| with IIR filter based on measurements on a stand, measured on the ATF | -0.6 | -4 |
| with IIR filter based on measurements on a stand, measured on a stand | | -0.6 |
| with IIR filter based on measurements on the ATF, measured on the ATF | -0.3 | |

dependent calibration still did not match the reference noise levels, as illustrated in Figure VIII-2 for the earpiece, Figure VIII-4 for the headset and Figure 3.24 for the built-in microphone.

### 3.3.2 Design and implementation of the noise level-dependent algorithm

Four different methods from the MATLAB® *griddata* function were evaluated:

- *linear*, a triangle-based linear interpolation;
- *cubic*, a triangle-based cubic interpolation;
- *nearest*, a nearest neighbor interpolation;
- *v4*, a MATLAB® griddata method.

The evaluation of the interpolation methods was based on a visual evaluation with the measured and interpolated noise levels corrections represented in a 3D graphic, as illustrated in the Figure VII-1 with the measured (in the semi-anechoic chamber) and interpolated noise level corrections for the built-in microphone.

Based on the visual investigation, *Nearest* method was considered inappropriate for use because of the method's lack of resolution at high noise levels, as illustrated in Figure VII-2 which presents the measured built-in microphone noise level correction values (in red) and the values interpolated with the *nearest* method.

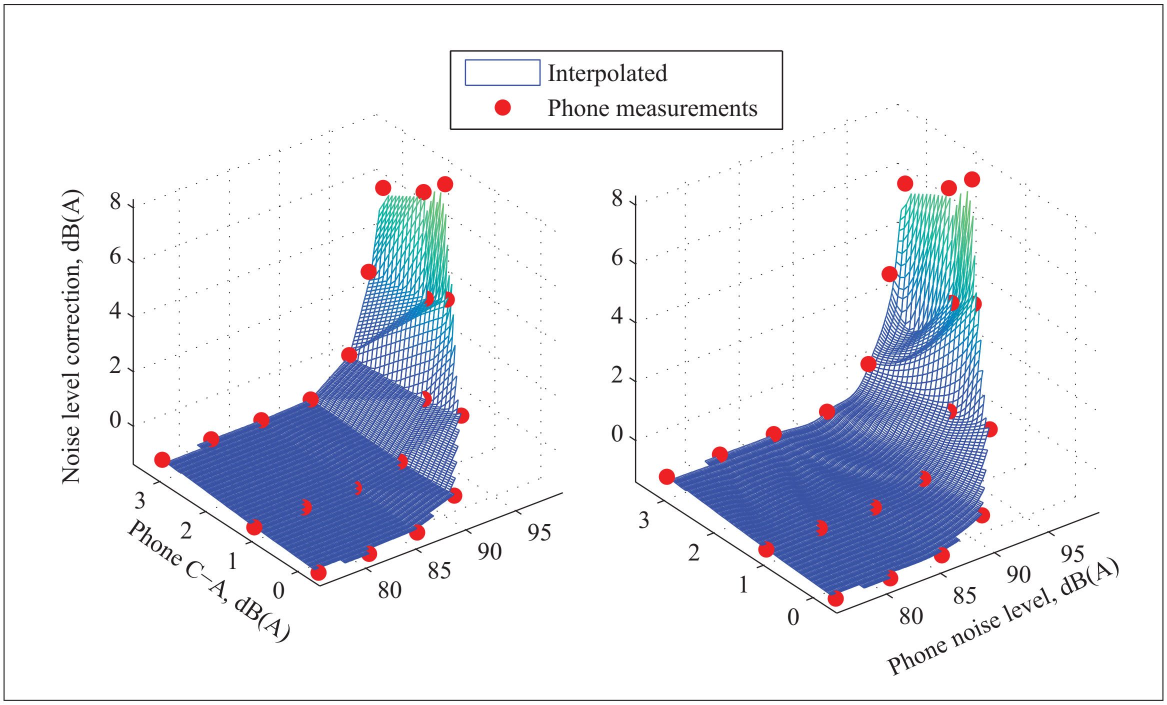


Figure 3.25 Built-in microphone measured noise level correction values (in red) and interpolated values with the *griddata* MATLAB function and the *linear* and *cubic* methods

The investigation allowed to identify one major design issue associated with the use the *cubic* and *linear* methods : the *Quickhull* algorithm, by Barber *et al.* (1996), used in the two methods, results in a array of interpolated corrections values which has at its ends undefined values, referred to as *NaN* values in MATLAB®, and standing for not a number. Thereby, the *cubic* and *linear* methods required an additional extrapolation for the "out of range" values. The extrapolation can be performed using *interp1*, a 1D linear interpolation MATLAB® function with the extrapolation method. However, this additional processing required a "manual" cleansing of the interpolated data due to extrapolation errors. Figure 3.27 highlights the lack of noise level corrections values at each end of the interpolated values array, associated with the *cubic* and *linear* methods. Unlike the 3 others methods, the *v4* method is based on a biharmonic Spline Interpolation, Sandwell (1987), that automatically extrapolates data over the range of the measured data and did not result in a matrix with *NaN* values.

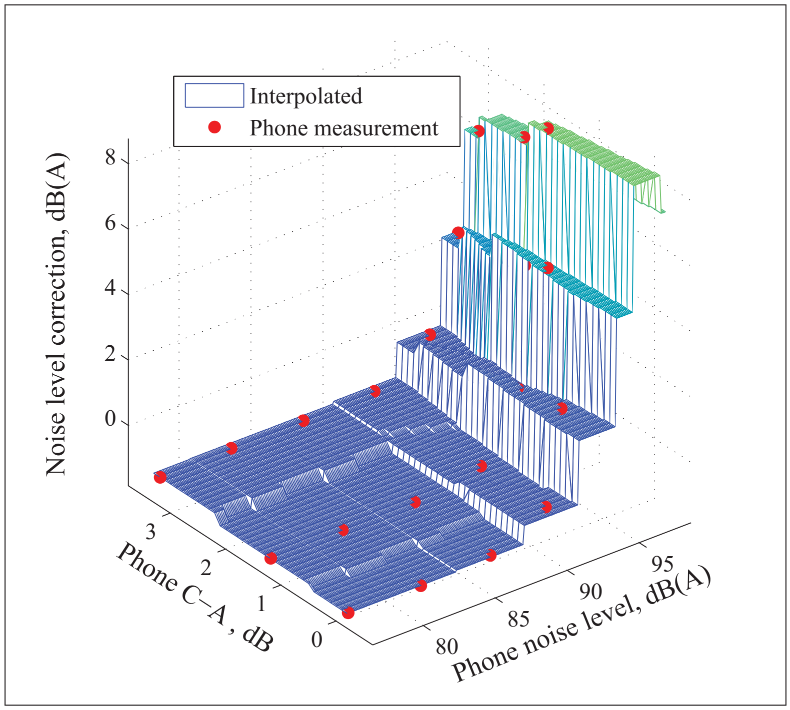


Figure 3.26 Measured built-in microphone noise level correction values (in red) and interpolated values with the *griddata* MATLAB function and its *nearest* method

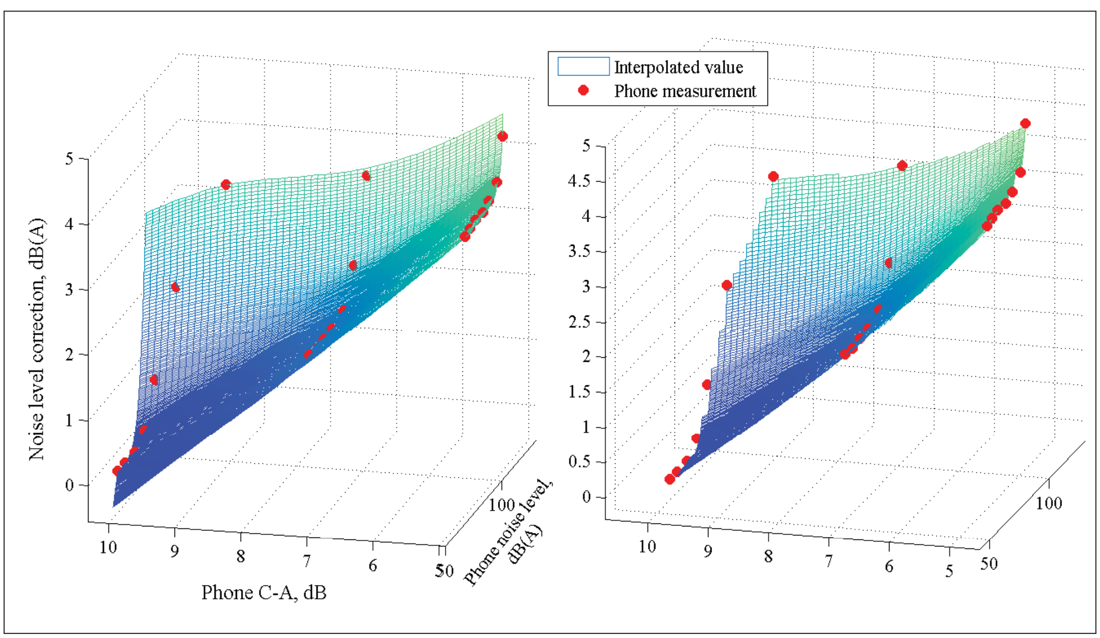


Figure 3.27 Measured earpiece noise level correction values (in red) and interpolated values with the *v4* method (on the left) and the *cubic* method (on the right)

The implementation of the noise level corrections highlighted one Java-oriented issue regarding the storage of the lookup table values. The lookup table was defined as a variable in a Java™ method, however methods have a size limitation of 65536 bytes. This size limitation corresponds to a lookup table containing 10500 corrections values rounded to one decimal place. For a lookup table with both phone noise level and phone C-A values and given with a 0.1 dB resolution, it corresponds, for example, to a phone noise levels range of 20 dB(A) values, and a C-A values range of 5.3 dB. In the case of the devices being tested in the study, the issue was overcome by suppressing a few dB(A) at the low-end of the noise level range where the noise corrections are always constant.

### 3.4 Laboratory validation measurements

The results of the measurement repeatability and inter-unit variability measurements are first presented. Then, the results are detailed by device and each subsection includes the results of the investigation with regards to:

- The measurements of noise sources Source 1, 2, 3 and "real-world" audio recordings;
- The microphone placement relative to the source and the ATF;
- The acoustical field cross-calibration measurements: the "diffuse field" and "free field" calibrations used in the semi-anechoic and reverberant chambers respectively.

The measurements were conducted during the second campaign of measurements, Measurements #2 (section 2.3.2.3) except where mentioned otherwise. Except for the investigation with regards to the acoustical field cross-calibration, the measurements were conducted using a phone implementing both frequency and level-depend calibration algorithms associated with the location of the measurement; for example, the "diffuse field" calibration were used for the measurements conducted in the reverberant chamber. Except where mentioned otherwise, the external devices were located on the ATF and the built-in microphone was located on a stand. Most of the noise level measurements results are expressed in:

- Overall A-weighted errors which are the phone A-weighted noise level measurements minus the reference system A-weighted noise level measurement conducted at the center-of-head without any ATF;
- Mean squared errors (MSE) calculated over a range of noise levels using Equation 3.1 where *n* is the number of noise levels measured (between 6 and 7) and *e* is the overall A-weighted error for one noise level.

$$MSE = \frac{\sum_1^n e^2}{n-1} \tag{3.1}$$

### 3.4.1 Measurement repeatability

Repeatability measurements consisted in three to five measurements of Sources 1, 2 and 3 sequences, conducted under repeatability conditions in the semi-anechoic (S-A) and reverberant (R) chambers. Measurements for each device including the earpiece and handset measurements were carried out with the Phone #4. Two repeatability measurements procedure, described in section 2.3.2.3, were investigated.

Standard deviations of both earpiece and headset repeatability measurements were less than 0.1 dB(A) regardless of the procedure, the noise level or the acoustical field, unlike the standard deviations of built-in microphone repeatability measurements which varied depending on the measurements procedure and on the noise level, as presented in Table 3.6.

Table 3.6 Standard deviation, in dB(A), of the repeatability noise level measurements carried out with a level-and frequency-calibrated phone following the measurements procedures procedure #1and #2

| **Device** | **Procedure** | **Noise level in dB(A) range** | **Standard deviation, dB(A) with n=5** |
|---|---|---|---|
| Headset | #1 | 80-105 | 0.0 |
| Earpiece | #1 & #2 | 80-105 | 0.0 |
| Built-in | #1 | 80-105 | 0.0 |
| | #2 | 80-100 | 0.1 |
| | | 100-105 | 0.4 |

Figure 3.28 shows $L_{eq,A,1sec}$ for the three devices with the phone implementing a frequency and level-dependent calibration, measured for Source 1 in the semi-anechoic chamber during the validation measurements. While the $L_{eq,A,1sec}$ noise level measured with the reference system are constant over the time, it can be seen in Figure 3.28 that a deviation appeared for the phone measurements, especially for the built-in microphone measurements between 100 and 105 dB(A). The standard deviation over a 20 second-sequence are given in Table 3.7. It can be seen that a large standard deviation, 1.3 dB(A), was obtained for built-in microphone at noise levels above 100 dB(A). The overall-weighted noise levels were calculated from the $L_{eq,A,1sec}$ sequences and it can be deduced that the high standard deviations of built-in microphone repeatability measurements at high noise levels are directly associated to the deviations illustrated in Figure 3.28.

Table 3.7 Standard deviation for the three devices of the $L_{eq,A,1sec}$ noise levels over a 20 seconds-sequence and for noise levels between 80 and 105dB(A), N=20 (seconds)

| **Device** | **Noise level range, dB(A)** | **Standard deviation, dB(A)** |
|---|---|---|
| Headset | 80-105 | 0.1 |
| Earpiece | 80-105 | 0.3 |
| Built-in | 80-90 | 0.1 |
| | 95 | 0.2 |
| | 100-105 | 1.3 |

### 3.4.2 Inter-unit variability in noise level measurements

#### 3.4.2.1 Inter-unit variability of built-in microphone measurements

The built-in microphone inter-unit variability was evaluated with four mobile phones of the same model implementing the Phone #4 (unit-dependent) calibration algorithms. At 105 dB(A), Phone #2 noise level differed greatly from Phones #1,3,4 noise levels. Table 3.8 contains the

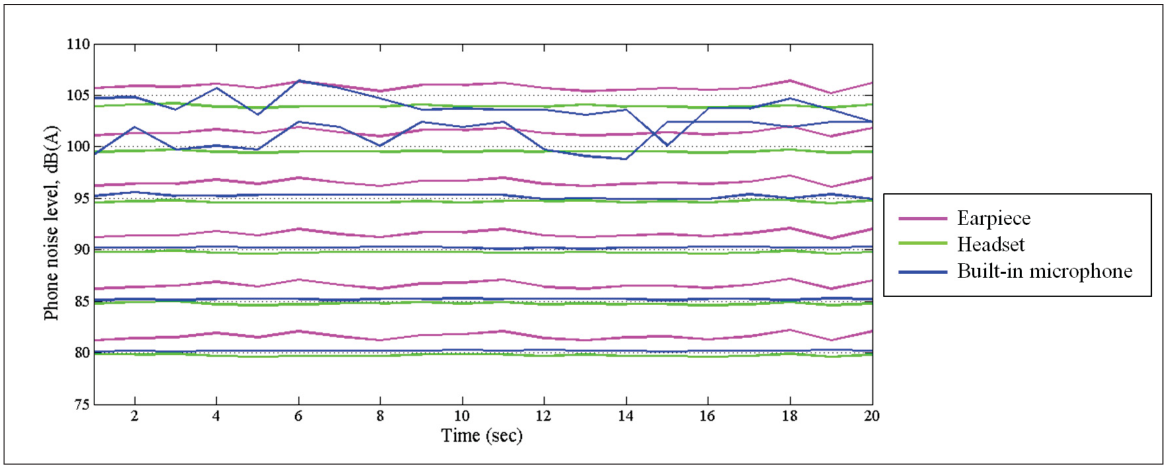


Figure 3.28 Built-in microphone, headset and earpiece $L_{eq,A,1sec}$, measured during the validation measurements for 6 noise levels

standards deviations calculated with and without Phone #2 measurements. It can be seen from Table 3.8 that:

- At 105 dB(A), Phone #2 measurements had a significant impact on the inter-unit variability standard deviation and can be seen as an outlier;
- At noise levels above 90 dB(A), standard deviations were observed to be smaller for measurements conducted in the reverberant chamber than for measurements conducted in the semi-anechoic chamber.

Table 3.8 Standard deviation, dB(A) of the built-in microphone inter-unit variability measurements in the reverberant (R) and semi-anechoic (S-A) chambers for Source 1, 2, 3 sequences (S1, S2, S3)

| | **Phones** | **#1,2,3,4** | **(S-A)** | **Phones** | **#1,3,4** | **(S-A)** | **Phones** | **#1,3,4** | **(R)** |
|---|---|---|---|---|---|---|---|---|---|
| **dB(A)** | (S1) | (S2) | (S3) | (S1) | (S2) | (S3) | (S1) | (S2) | (S3) |
| 80 | 2.4 | 2.0 | 1.8 | 2.0 | 1.9 | 1.8 | 1.9 | 1.8 | 1.7 |
| 85 | 2.3 | 2 | 1.8 | 2.1 | 1.9 | 1.8 | 1.8 | 1.7 | 1.6 |
| 90 | 2 | 1.6 | 1.5 | 2.1 | 1.8 | 1.8 | 1.5 | 1.5 | 1.6 |
| 95 | 2.2 | 2.1 | 1.8 | 2.6 | 2.6 | 2.1 | 1.1 | 0.9 | 0.9 |
| 100 | 2.7 | 2.2 | 2.3 | 2.3 | 2.3 | 1.6 | 0.6 | 0.8 | 1.3 |
| 105 | 3.7 | 3.9 | 2 | 2 | 1.9 | 0.7 | 0.8 | 0.6 | 0.4 |

#### 3.4.2.2 Inter-unit variability of the phone as an acquisition system

Investigation of the inter-unit variability of the phone as an acquisition system was carried out with the earpiece and the Phones #1, 2, 3, 4 implementing the frequency and level-dependent calibration algorithms calculated for the earpiece and the Phone #4. The inter-unit variability of the earpiece microphone was not investigated as only one earpiece was used. Table 3.9 contains the standards deviations calculated from Phones #1, ,2, 3, 4 measurements with the earpiece located on the ATF. It can be seen from Table 3.9 that the standard deviations of the earpiece inter-unit variability measurements did not vary with the acoustical field and remained below 0.4 dB(A) regardless of the noise level.

Table 3.9 Standard deviation (dB) of the earpiece inter-unit variability measurements with Phones #1, 2, 3, 4 in the semi-anechoic (S-A) and reverberant (R) chambers for Source 1

| **dB(A)** | **S-A** | **R** |
|---|---|---|
| 80 | 0.2 | 0.2 |
| 85 | 0.2 | 0.2 |
| 90 | 0.2 | 0.2 |
| 95 | 0.2 | 0.2 |
| 100 | 0.2 | 0.3 |
| 105 | 0.3 | 0.4 |

### 3.4.3 Headset validation measurements

#### 3.4.3.1 Measurements of Sources 1, 2 and 3

Measurements in the semi-anechoic chamber were conducted with the "facing the source" ATF position (Figure 2.16). Table 3.10 presents the results of the measurements conducted, right after the noise level corrections measurements (Measurements #1). They result in overall A-weighted errors (calibrated phone noise levels minus reference noise levels measured at the center-of-head position) below or equal to 0.1 dB(A) for a range of noise levels between 75 and 100 dB(A) and an 0.7 dB(A) overall A-weighted error at 105 dB(A).

Table 3.10 Headset overall A-weighted errors while measuring Source 1, 2, 3 (S1, S2, S3) in the **semi-anechoic chamber** during the **measurements #1**

| **Reference noise level, dB(A)** | **S1** | **S2** | **S3** |
|---|---|---|---|
| 75 | -0.1 | 0.1 | 0 |
| 80 | -0.1 | 0.1 | 0.0 |
| 85 | -0.1 | 0.0 | 0.0 |
| 90 | -0.1 | 0.0 | 0.0 |
| 95 | -0.1 | 0.0 | 0.0 |
| 100 | -0.1 | 0.0 | 0.0 |
| 105 | -0.7 | 0.0 | 0.0 |
| **MSE, dB(A)** | 0.1 | 0.0 | 0.0 |

Comparing results in Table 3.10 and Table 3.11 for the measurements in the semi-anechoic chamber, the overall A-weighted errors from Measurements #2 (section 2.3.2.3) were 0.1 to 1 dB(A) higher than errors from Measurements #1. It can be seen from Table 3.11 that:

- Errors from measurements in the reverberant chamber were lower than those from measurements in the semi-anechoic chamber;
- For measurements in the semi-anechoic chamber, errors varied depending on the source frequency content: greater measurement errors occurred for Source 1 which contains more high-frequency energy than for Source 2 and 3.

Figure 3.29 and Figure 3.30 regroup noise level measurements conducted in the semi-anechoic and reverberant chambers with the frequency-dependent calibration (FIR calibration) and with the frequency and noise level-dependent calibration (Full Calibration).

Table 3.11 Headset overall A-weighted errors while measuring Source 1, 2, 3 (S1, S2, S3) during the **measurements #2**, in the **semi-anechoic** (S-A) and **reverberant** (R) chambers

| **Reference noise level dB(A)** | **S-A** | | | **R** | | |
|---|---|---|---|---|---|---|
| | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** |
| 80 | -1.1 | -0.6 | -0.5 | -0.2 | -0.2 | -0.2 |
| 85 | -1 | -0.7 | -0.6 | -0.1 | -0.1 | -0.2 |
| 90 | -1.1 | -0.7 | -0.6 | -0.1 | -0.1 | -0.2 |
| 95 | -1.1 | -0.7 | -0.6 | -0.1 | -0.1 | -0.2 |
| 100 | -1.1 | -0.7 | -0.7 | -0.2 | -0.1 | -0.3 |
| 105 | -0.7 | -0.7 | -0.8 | -0.4 | -0.4 | -0.7 |
| **MSE, dB(A)** | 1 | 0.5 | 0.4 | 0 | 0 | 0.1 |

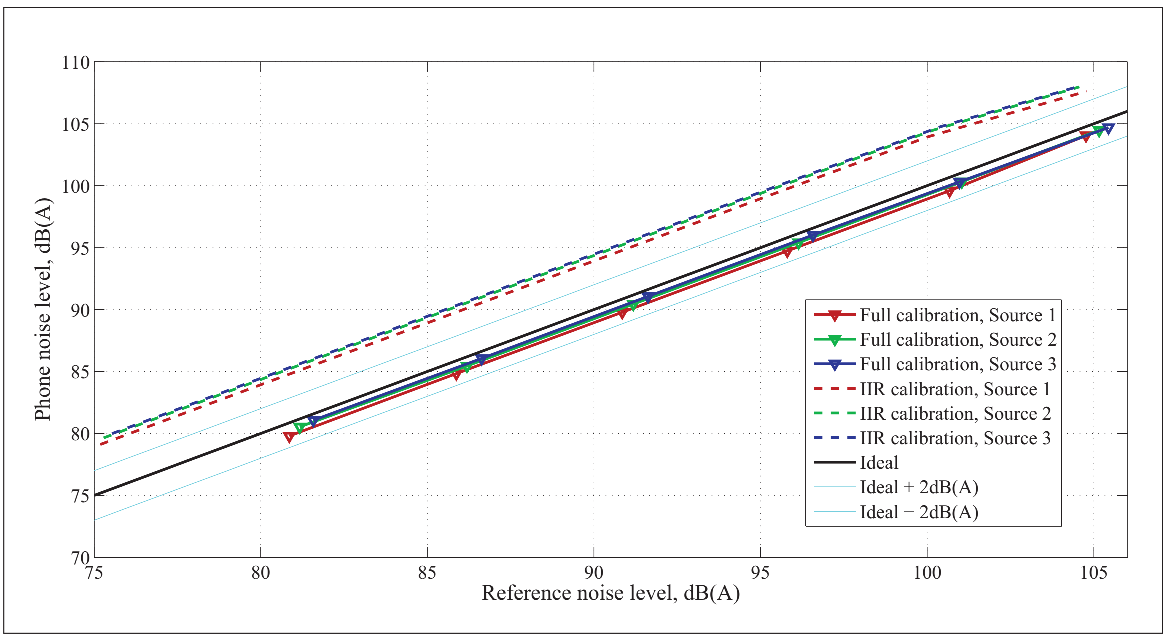


Figure 3.29 Headset noise level measurements carried out in the **semi-anechoic** chamber, with only a frequency-dependent calibration (IIR calibration) and with frequency and level-dependent calibration (Full Calibration)

### 3.4.3.2 Measurements of "real-world" audio recordings

Table 3.26 contains the overall A-weighted errors while measuring in both semi-anechoic (S-A) and reverberant (R) chambers the "real-world" recordings noise sources from the NOISEX-92 database and presented in section 2.1.3. Reference C-A and noise levels in dB(A) in Table 3.26

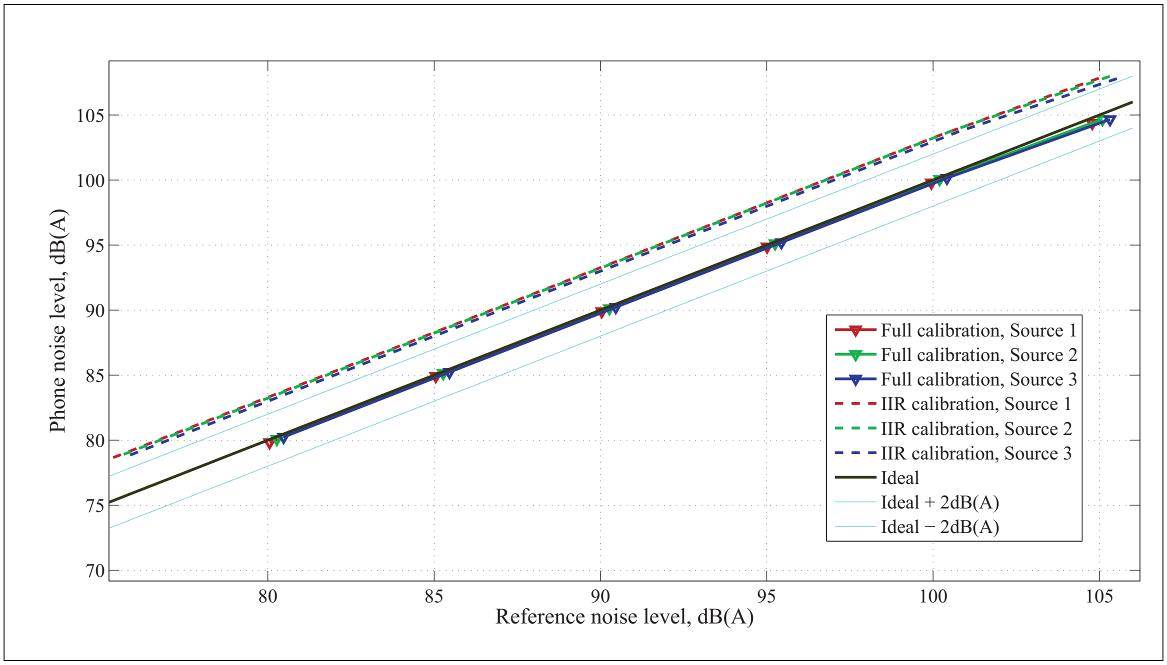


Figure 3.30 Headset noise level measurements carried out in the **reverberant** chamber, with only a frequency-dependent calibration (IIR calibration) and with frequency and level-dependent calibration (Full Calibration)

were measured with the reference measurement system. The ranges of errors were -0.7 to -1.8 dB(A) for the measurements in the semi-anechoic chamber and -0.1 to -1.3 dB(A) for the measurements in the reverberant chamber. Again, errors from measurements in the reverberant chamber were lower than those from measurements in the semi-anechoic chamber.

Table 3.12 Headset overall A-weighted errors while measuring "real-world" audio recordings noise sources, carried out with the headset located on the ATF in the semi-anechoic (S-A) and reverberant (R) chambers

| **Noise source** | **S-A** | | | **R** | | |
|---|---|---|---|---|---|---|
| | **Ref. C-A** | **Ref. dB(A)** | **Error dB(A)** | **Ref. C-A** | **Ref. dB(A)** | **Error, dB(A)** |
| Factory 1 | 3.2 | 99.4 | -1 | 2.2 | 98 | -0.5 |
| Factory 2 | 4.5 | 99.5 | -0.7 | 4.2 | 98.2 | -0.7 |
| Buccaneer | 1.3 | 99.2 | -0.7 | 0.9 | 97.9 | -0.1 |
| Tank | 5.7 | 103.1 | -1.8 | 7.5 | 102.2 | -1.3 |
| Music | 2.9 | 103.7 | -1.5 | 3.4 | 103.2 | -0.8 |

#### 3.4.3.3 Microphone placement relative to the ATF: microphone orientation

As presented in Table 3.13, the effect on the overall noise levels in dB(A) of the headset microphone orientation towards the ATF depended on the noise source frequency content: greater variations occurred for Source 1 which contains more high-frequency energy than for Sources 2 and 3. The range of variation was 0.3, for Source 3 at 105 dB(A), to -1.7 dB(A), for Source 1 for noise levels between 80 to 100 dB(A).

Table 3.13 Headset A-weighted noise levels with the microphone facing the exterior source minus the A-weighted noise levels measured with the microphone facing the interior in the semi-anechoic chamber

| Reference noise level dB(A) | S1 | S2 | S3 |
|---|---|---|---|
| 80 - 100 | -1.7 | -1.1 | -0.5 |
| 105 | -0.9 | -0.7 | -0.3 |

#### 3.4.3.4 ATF position relative to the source

The objective was to investigate the overall A-weighted errors due to the ATF position relative to the source in the reverberant chamber with four loudspeakers (Figure 2.20) and in the semi-anechoic chamber with one fixed loudspeaker (Figure 2.15). The ATF was oriented towards four directions, defined in the semi-anechoic chamber according to the angles of the incident sound with regards to the loudspeaker, as illustrated in Figure 2.18. Figure 3.31 presents the overall A-weighted errors, averaged over the range of noise levels for four ATF positions. The four different ATF positions were omitted from the figure for the sake of simplicity.

It can be seen that while the microphone placement had a very small impact on noise levels in the reverberant chamber (which highlights the diffuseness of the reverberant chamber), there were, as expected, significant differences in the overall A-weighted errors for the semi-anechoic measurements and depending on the angle of the incident sound. These differences were caused by the screening effects of the ATF and the microphone's directivity. The range of errors was -12.7 dB(A) for a 180°angle of incidence to -1dB(A) for a 0° angle of incidence corresponding to the ATF position used for the calibration measurements.

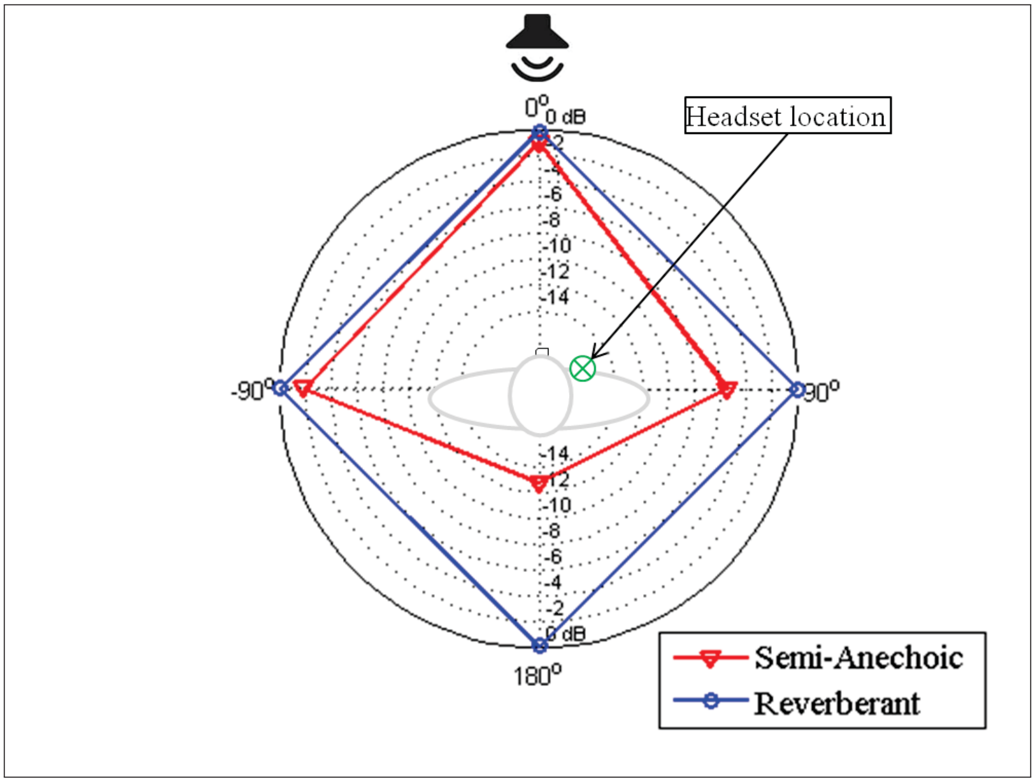


Figure 3.31 Headset overall A-weighted errors, averaged over the range of noise levels, in the semi-anechoic chamber (in red) and in the reverberant chamber (in blue)

#### 3.4.3.5 Acoustical field cross-calibration

Tables 3.14 and 3.15 contain the overall A-weighted errors for the headset measurements conducted in the semi-anechoic and reverberant chambers with the phone implementing a field cross-calibration which means, for example, that for the semi-anechoic chamber measurements, the calibration algorithms implemented originated from measurements in the reverberant chamber (section 2.3.2.3). It can be seen from Table 3.14 that the "diffuse field" (DF) calibration used in the semi-anechoic chamber minimized the overall errors compared to the measurements conducted with the "free-field" calibration. However, for the reverberant chamber measurements (Table 3.15) the "free field" calibration increased the overall errors. The same observations can be drawn concerning the overall A-weighted errors obtained with the "real-world" audio recordings measurements presented in Table 3.16.

Table 3.14 Headset overall A-weighted errors measured in **the semi-anechoic chamber** with the phone implementing the "free field" (FF) and the "diffuse field" (DF) calibration

| **Reference noise level dB(A)** | **FF calibration** | | | **DF calibration** | | |
|---|---|---|---|---|---|---|
| | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** |
| 80 | -1.1 | -0.6 | -0.5 | -0.5 | 0.3 | 0.7 |
| 85 | -1 | -0.7 | -0.6 | -0.5 | 0.3 | 0.7 |
| 90 | -1.1 | -0.7 | -0.6 | -0.4 | 0.3 | 0.7 |
| 95 | -1.1 | -0.7 | -0.6 | -0.4 | 0.3 | 0.7 |
| 100 | -1.1 | -0.7 | -0.7 | -0.4 | 0.3 | 0.5 |
| 105 | -0.7 | -0.7 | -0.8 | -0.7 | -0.3 | -0.2 |
| **MSE, dB(A)** | 1 | 0.5 | 0.4 | 0.3 | 0.1 | 0.4 |

Table 3.15 Headset overall A-weighted errors measured in **the reverberant chamber** with the phone implementing the "diffuse field" (DF) and the "free field" (FF) factory calibration

| **Reference noise level dB(A)** | **DF calibration** | | | **FF calibration** | | |
|---|---|---|---|---|---|---|
| | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** |
| 80 | -0.2 | -0.2 | -0.2 | -1 | -1.2 | -1.8 |
| 85 | -0.1 | -0.1 | -0.2 | -1 | -1.2 | -1.9 |
| 90 | -0.1 | -0.1 | -0.2 | -1 | -1.2 | -1.9 |
| 95 | -0.1 | -0.1 | -0.2 | -1 | -1.3 | -1.9 |
| 100 | -0.2 | -0.1 | -0.3 | -1.1 | -1.4 | -2.0 |
| 105 | -0.4 | -0.4 | -0.7 | -0.3 | -0.8 | -1.7 |
| **MSE, dB(A)** | 0 | 0 | 0.1 | 0.8 | 1.4 | 3.4 |

Table 3.16 Headset overall A-weighted errors while measuring "real-world" audio recordings noise sources in both semi-anechoic (S-A) and reverberant (R) chambers with the phone implementing the "diffuse field" (DF) and the "free field" (FF) calibration

| **Noise source** | **S-A** | | **R** | |
|---|---|---|---|---|
| | **FF** | **DF** | **DF** | **FF** |
| Factory 1 | -1 | 0.5 | -0.5 | -1.90 |
| Factory 2 | -0.7 | 0.8 | -0.7 | -2.20 |
| Buccaneer | -0.7 | 0.6 | -0.1 | -1.00 |
| Tank | -1.8 | -0.5 | -1.3 | -2.70 |
| Music | -1.5 | -0.4 | -0.8 | -1.80 |

### 3.4.4 Built-in microphone noise validation measurements

#### 3.4.4.1 Measurements of Sources 1, 2 and 3

Table 3.17 and Table 3.18 contain the overall A-weighted errors, measured in the semi-anechoic and reverberant chamber, right after the noise level corrections measurements (Measurements #1) and two weeks after the calibration measurements with the set up reinstalled (Measurements #2). Comparing results in Table 3.17 and Table 3.18, it can be seen that for the measurements in the semi-anechoic chamber, the overall A-weighted errors from Measurements #2 (section 2.3.2.3) were 0.5 to 1.1 dB(A) higher than overall A-weighted errors from Measurements #1. In the reverberant chamber, the differences between the two measurements campaigns were greater as overall A-weighted errors for noise levels above 100 dB(A) strongly increased during the second campaign.

Table 3.18 shows that:

- The maximum errors appeared for measurements in the reverberant chamber above 100 dB(A);
- For measurements in the reverberant chamber, errors varied depending on the source frequency content: greater measurement errors occurred for Source 1 which contains more high-frequency energy than for Sources 2 and 3.

It is worth noting that the overall A-weighted errors in the reverberant chamber, presented in Table 3.18, were averaged over measurements at four different ATF orientations. Figure 3.32 and Figure 3.33 regroup noise level measurements conducted in the semi-anechoic and reverberant chambers without any calibration, with the frequency-dependent calibration (*IIR calibration*) and with the frequency and level-dependent calibration (*Full Calibration*). Looking at Figure 3.32, it can be seen that the phone noise level saturation was corrected in measurements implementing the full calibration. Figure 3.32 shows that in the diffuse field, a saturation of the phone noise level remained starting at 95 dB(A) however for a level range between 80 and 95 dB(A), the calibration compensated for the measurement errors almost perfectly.

Table 3.17 Built-in microphone overall A-weighted errors measured during the **measurements #1**, in the semi-anechoic (S-A) and reverberant (R) chambers

| **Reference noise level** | **S-A** | | | **R** | | |
|---|---|---|---|---|---|---|
| **dB(A)** | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** |
| 75 | -0.2 | -0.3 | -0.3 | -0.2 | -0.2 | -0.2 |
| 80 | 0 | 0 | 0.1 | 0 | 0 | 0 |
| 85 | 0 | 0 | 0.1 | 0 | 0 | 0 |
| 90 | 0 | 0.1 | 0.0 | 0 | -0.1 | 0 |
| 95 | 0.3 | 0.2 | 0.0 | -0.3 | -0.2 | -0.1 |
| 100 | 0.7 | 1.1 | 0.4 | -1 | -1.3 | -0.4 |
| 105 | 0.4 | 0.7 | 0.4 | -2.5 | -1.1 | -0.7 |
| **MSE** | 0.1 | 0.3 | 0.1 | 1 | 0.4 | 0.1 |

Table 3.18 Built-in microphone overall A-weighted errors measured during the **measurements #2**, in the semi-anechoic (S-A) and reverberant (R) chambers

| **Reference** | **S-A** | | | **R** | | |
|---|---|---|---|---|---|---|
| **dB(A)** | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** |
| 80 | -0.9 | -0.8 | -0.8 | 0 | -0.1 | -0.1 |
| 85 | -0.9 | -0.8 | -0.8 | 0 | 0 | 0.0 |
| 90 | -0.8 | -0.8 | -0.8 | -0.1 | -0.1 | 0.0 |
| 95 | -0.7 | -0.6 | -0.8 | -0.9 | -0.6 | -0.1 |
| 100 | 0.7 | 0 | -0.1 | -2.7 | -3 | -1.5 |
| 105 | -0.3 | 0.1 | -0.4 | -6.3 | -4 | -1.9 |
| **MSE, dB(A)** | 0.6 | 0.4 | 0.5 | 7.9 | 4.2 | 1.0 |

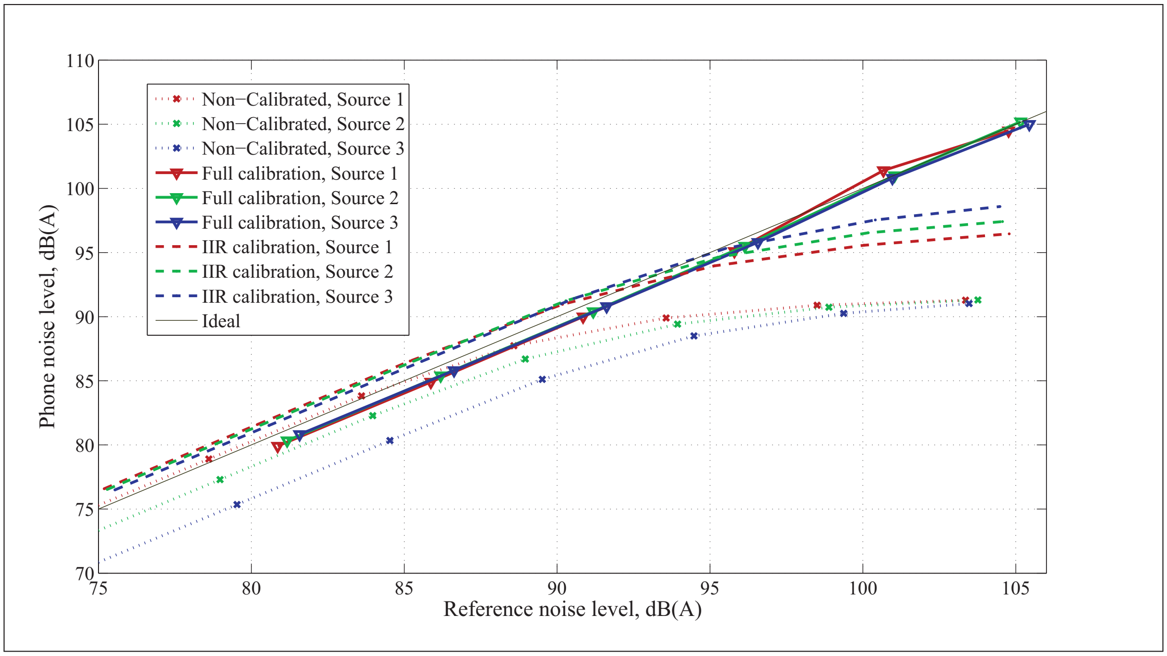


Figure 3.32  Built-in microphone noise level measurements in the **semi-anechoic** chamber without calibration, with only a frequency-dependent calibration (IIR calibration) and with frequency and level-dependent calibration (Full Calibration)

#### 3.4.4.2 Measurements of "real-world" audio recordings

Table 3.19 contains the overall A-weighted errors while measuring in both semi-anechoic (S-A) and reverberant (R) chambers the "real-world" recordings noise sources, from the NOISEX-92 database and presented in section 2.1.3. Reference C-A and noise levels in dB(A) in Table 3.19 were measured with the reference measurement system. It can be seen from Table 3.19 that:

- Errors from measurements in the reverberant chamber were lower than those from measurements in the semi-anechoic chamber;
- Very high errors occurred in the semi-anechoic chamber for the noise sources that have the lowest C-A values: the noise sources *Music* and *Bucaneer* with an error of 8.5 and 11.6 dB(A), respectively.

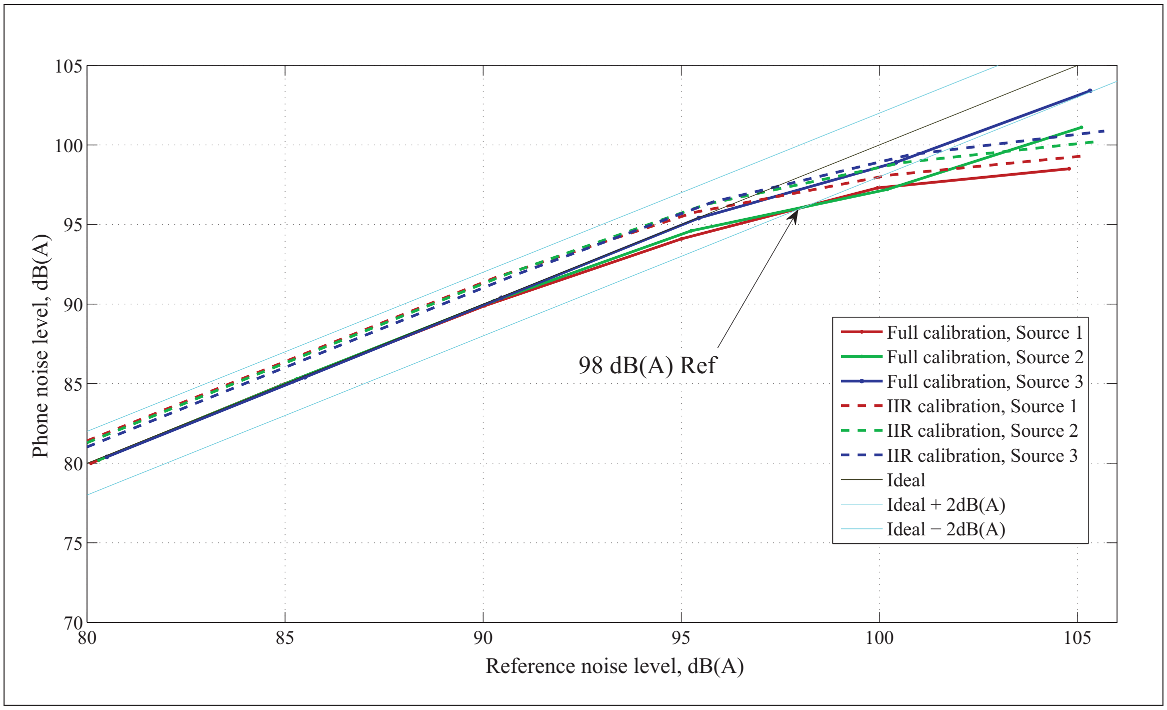


Figure 3.33 Built-in microphone noise level measurements in the **reverberant** chamber with only a frequency-dependent calibration (FIR calibration) and with frequency and level-dependent calibration (Full Calibration)

Table 3.19 Built-in microphone overall A-weighted errors while measuring "real-world" audio recordings noise sources in the semi-anechoic (S-A) and reverberant (R) chambers

| **Noise source** | **S-A** | | | **R** | | |
|---|---|---|---|---|---|---|
| | **Ref. C-A** | **Ref. dB(A)** | **Error dB(A)** | **Ref. C-A** | **Ref. dB(A)** | **Error, dB(A)** |
| Factory 1 | 3.2 | 99.4 | 2.5 | 2.2 | 98 | -1.3 |
| Factory 2 | 4.5 | 99.5 | 3.5 | 4.2 | 98.2 | -0.3 |
| Buccaneer | 1.3 | 99.2 | 11.6 | 0.9 | 97.9 | 1.6 |
| Tank | 5.7 | 103.1 | 0.5 | 7.5 | 102.2 | -2.3 |
| Music | 2.9 | 103.7 | 8.5 | 3.4 | 103.2 | 2.8 |

#### 3.4.4.3 Microphone orientation: phone placed flat and on the edge

The investigation aimed to evaluate the impact of the built-in microphone directivity by quantifying the effect of its orientations on the overall A-weighted noise levels. Both microphone orientations, "placed flat" and "on the edge" are illustrated in Figure 2.22. Table 3.20 contains the built-in microphone A-weighted noise levels with the microphone placed flat minus the A-weighted noise levels measured with the microphone placed on the edge. It can be seen that the effect of the variations of the phone's orientation was higher in the semi-anechoic chamber. Table 3.21 contains MSEs calculated from the overall noise levels in dB(A) for both microphone's orientations. While the calibration measurements were carried out with the phone placed flat, it can be seen from Table 3.21 that modifying the phone orientation with regards to the orientation used for the calibration measurements slightly increased the MSEs.

Table 3.20 Built-in microphone A-weighted noise levels with the microphone placed flat minus the A-weighted noise levels measured with the microphone placed on the edge in the semi-anechoic (S-A) and reverberant (R) chamber

| **Reference noise level** | **S-A** | | | **R** | | |
|---|---|---|---|---|---|---|
| **dB(A)** | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** |
| 80 | -0.5 | -0.3 | -0.2 | 0.2 | 0.2 | 0.2 |
| 85 | -0.4 | -0.3 | -0.2 | 0.2 | 0.2 | 0.2 |
| 90 | -0.5 | -0.3 | -0.2 | 0.2 | 0.2 | 0.2 |
| 95 | -0.4 | -0.5 | 0 | 0.1 | 0.2 | 0.1 |
| 100 | -0.6 | -0.5 | 0 | 0.2 | 0 | 0.1 |
| 105 | -0.3 | -0.5 | 0 | 0.1 | 0 | 0.0 |
| MSE, dB(A) | 0.2 | 0.2 | 0 | 0 | 0 | 0.0 |

Table 3.21 Mean Square Errors (MSE) of the built-in microphone A-weighted noise levels for two phone's orientations **"flat"** and **"on the edge"** measured in the semi-anechoic (S-A) and reverberant (R) chambers

| **Noise source** | **S-A** | | **R** | |
|---|---|---|---|---|
| | **Flat** | **Edge** | **Flat** | **Edge** |
| S1 | 1.4 | 1.3 | 7.2 | 7.7 |
| S2 | 0.8 | 0.9 | 3.8 | 3.8 |
| S 3 | 0.6 | 1.1 | 0.8 | 0.9 |

#### 3.4.4.4 Microphone placement relative to the source

Figure 3.34 and Figure 3.35 present the overall A-weighted errors for four microphone placement relative to the source, measured in the semi-anechoic and reverberant chambers. In the reverberant chamber, the overall A-weighted errors remained relatively constant regardless of the ATF position. In the semi-anechoic chamber, it can be seen from Figure 3.34 that, while the overall A-weighted errors remained constant regardless of the microphone placement at 90 dB(A), the overall A-weighted errors, greatly increased for angles of incident sound $90°$, $-90°$ and $180°$ at higher noise levels, as compared to the the error with position $0°$ which corresponds to the ATF position used for the calibration measurements. As a reminder, angles of the incident sound with regards to the loudspeaker were illustrated in Figure 2.18.

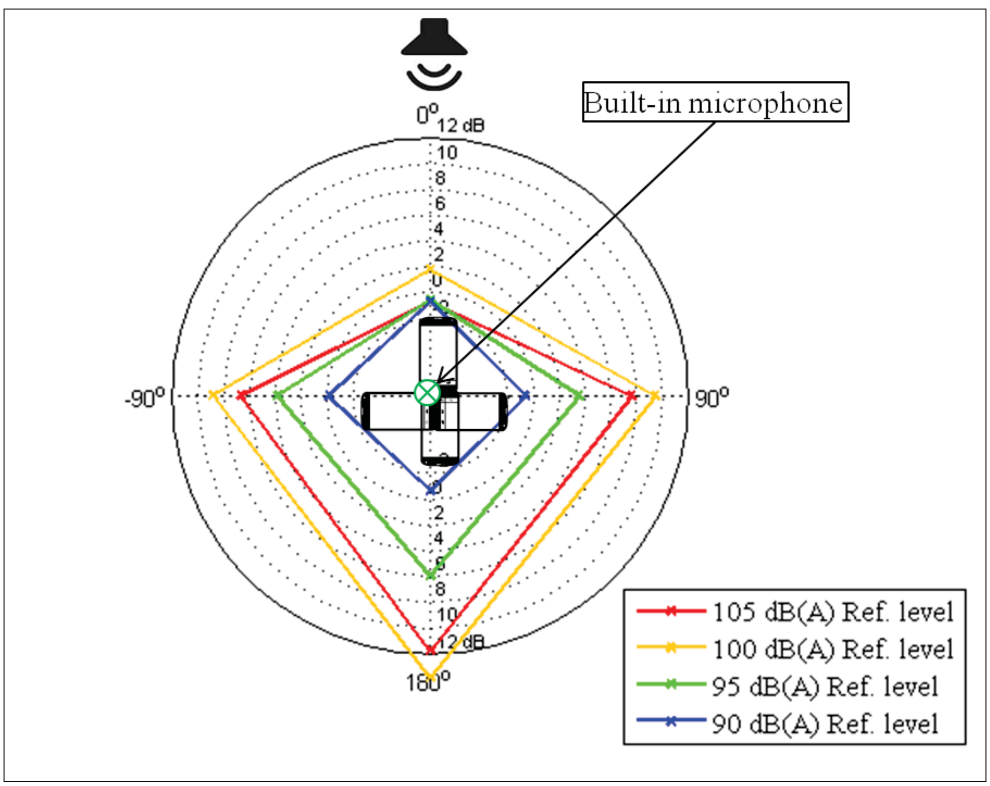


Figure 3.34 Built-in microphone overall A-weighted errors for various microphone placement and noise levels, while measuring Source 1 in the semi-anechoic chamber

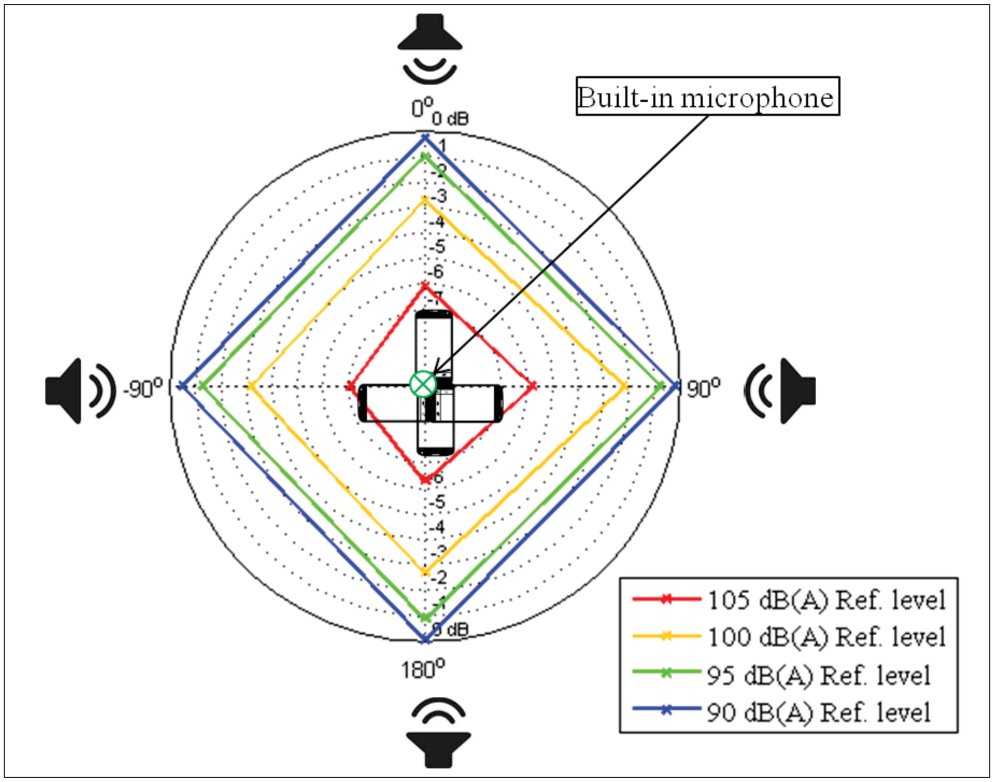


Figure 3.35 Built-in microphone overall A-weighted errors for various microphone placement and noise levels, while measuring Source 1 in the reverberant chamber

#### 3.4.4.5 Acoustical field cross-calibration

Tables 3.22 and 3.23 contain the overall A-weighted errors for built-in microphone measurements conducted in the semi-anechoic and reverberant chambers with the phone implementing a field cross-calibration (section 2.3.2.3). Looking at the two tables, it can be seen that between 80 and 90 dB(A) in both chambers, the cross-calibration did not increase the overall A-weighted errors. However, above 90 dB(A), the overall A-weighted errors greatly increased: the maximum absolute overall A-weighted error due to the cross-calibration in the semi-anechoic and reverberant chambers were respectively 8.9 dB(A), for Source 1 at 105 dB(A), and 13.9, for Source 1 at 100 dB(A). Two observations can also be drawn from the tables:

- The diffuse-field calibration measured in the semi-anechoic chamber led to lower overall A-weighted errors than a free-field calibration in the reverberant chamber;

- For both cross-calibrations, Source 1 measurements led to the highest overall A-weighted errors.

Table 3.22 Built-in microphone overall A-weighted errors in **the semi-anechoic chamber** with the phone implementing the "free field" (FF) and the "diffuse field" (DF) factory calibration

| **Reference noise level dB(A)** | **FF S1** | **calibration S2** | **S3** | **DF S1** | **calibration S2** | **S3** |
|---|---|---|---|---|---|---|
| 80 | -0.9 | -0.8 | -0.8 | -0.8 | -0.5 | -0.6 |
| 85 | -0.9 | -0.8 | -0.8 | -0.7 | -0.5 | -0.6 |
| 90 | -0.8 | -0.8 | -0.8 | -1.1 | -0.7 | -0.7 |
| 95 | -0.7 | -0.6 | -0.8 | -2.8 | -2 | -1.3 |
| 100 | 0.7 | 0 | -0.1 | -5.6 | -4.9 | -3.8 |
| 105 | -0.3 | 0.1 | -0.4 | -8.9 | -8.1 | -5.5 |
| **MSE, dB(A)** | 0.6 | 0.4 | 0.5 | 20 | 15.7 | 8.0 |

Table 3.23 Built-in microphone overall A-weighted errors in **the reverberant chamber** with the phone implementing the "diffuse field" (DF) and the "free field" (FF) factory calibration

| **Reference noise level dB(A)** | **DF S1** | **calibration S2** | **S3** | **FF S1** | **calibration S2** | **S3** |
|---|---|---|---|---|---|---|
| 80 | 0 | -0.1 | -0.1 | -0.2 | -0.3 | -0.1 |
| 85 | 0 | 0 | 0 | -0.1 | -0.2 | -0.1 |
| 90 | -0.1 | -0.1 | 0 | 0.5 | 0.1 | 0.0 |
| 95 | -0.9 | -0.6 | -0.1 | 6.8 | 6.1 | 0.6 |
| 100 | -2.7 | -3 | -1.5 | 13.9 | 12.9 | 5.5 |
| 105 | -6.3 | -4 | -1.9 | 11.4 | 9.2 | 1.5 |
| **MSE, dB(A)** | 7.9 | 4.2 | 1 | 61.3 | 48.1 | 5.6 |

### 3.4.5 Earpiece validation measurements

#### 3.4.5.1 Measurements of Sources 1, 2 and 3

Table 3.24 shows the validation measurements conducted in the semi-anechoic and reverberant chambers, right after the noise level corrections measurements (Measurements #1). It is worth noting that, in the semi-anechoic chamber, unlike the headset measurements, the earpiece measurements were conducted with the "Exposed Ear" ATF position (Figure 2.16). The ranges of error were -0.3 to 0.2 dB(A) for measurements in the semi-anechoic chamber and 0.3 to 1.3 dB(A) for measurements in the reverberant chamber. It can be seen that the free-field calibration in the semi-anechoic chamber resulted in lower overall A-weighted errors than the diffuse calibration in the reverberant chamber.

Table 3.24 Earpiece overall A-weighted errors measured during the **measurements #1** in the semi-anechoic (S-A) and reverberant (R) chambers

| **Reference noise level** | **S-A** | | | **R** | | |
|---|---|---|---|---|---|---|
| **dB(A)** | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** |
| 75 | -0.2 | 0.1 | 0.2 | 0.8 | 1.3 | 0.9 |
| 80 | -0.2 | 0.1 | 0.2 | 0.5 | 1.1 | 0.9 |
| 85 | -0.2 | 0.1 | 0.1 | 0.5 | 1.1 | 0.9 |
| 90 | -0.2 | 0.1 | 0.1 | 0.5 | 1.1 | 0.9 |
| 95 | -0.1 | 0.1 | 0 | 0.5 | 1 | 1.0 |
| 100 | -0.2 | 0 | 0 | 0.6 | 1.2 | 0.9 |
| 105 | -0.1 | 0 | -0.2 | 0.4 | 1.2 | 0.6 |
| **MSE, dB(A)** | 0 | 0 | 0 | 0.3 | 1.3 | 0.8 |

Comparing results in Table 3.24 and Table 3.25, the deviation between overall A-weighted errors from Measurements #1 and #2 were 0.1 to 0.9 dB(A) for the measurements in the semi-anechoic chamber and 0.3 to 2.8 dB(A) for the measurements in the reverberant chamber.

Table 3.25 Earpiece overall A-weighted errors measured during the **measurements #2** in the semi-anechoic (S-A) and reverberant (R) chambers

| Reference noise level dB(A) | S-A S1 | S-A S2 | S-A S3 | R S1 | R S2 | R S3 |
|---|---|---|---|---|---|---|
| 80 | 0.2 | 0.8 | 0.5 | -0.7 | -0.9 | -1.1 |
| 85 | 0.2 | 0.9 | 0.6 | -1 | -0.9 | -1.1 |
| 90 | 0.1 | 0.9 | 0.6 | -1 | -0.8 | -1.2 |
| 95 | 0.2 | 0.9 | 0.7 | -1 | -0.8 | -1.3 |
| 100 | 0.2 | 0.9 | 0.7 | -0.9 | -0.8 | -1.5 |
| 105 | 0.5 | 0.6 | 0 | -0.5 | -0.8 | -1.8 |
| **MSE, dB(A)** | -0.1 | -0.7 | -0.3 | 0.8 | 0.7 | 1.9 |

Figure 3.36 and Figure 3.37 regroup noise level measurements conducted in the semi-anechoic and reverberant chambers with only the frequency-dependent calibration (*FIR calibration*) and with the frequency and noise level-dependent calibration (*Full Calibration*).

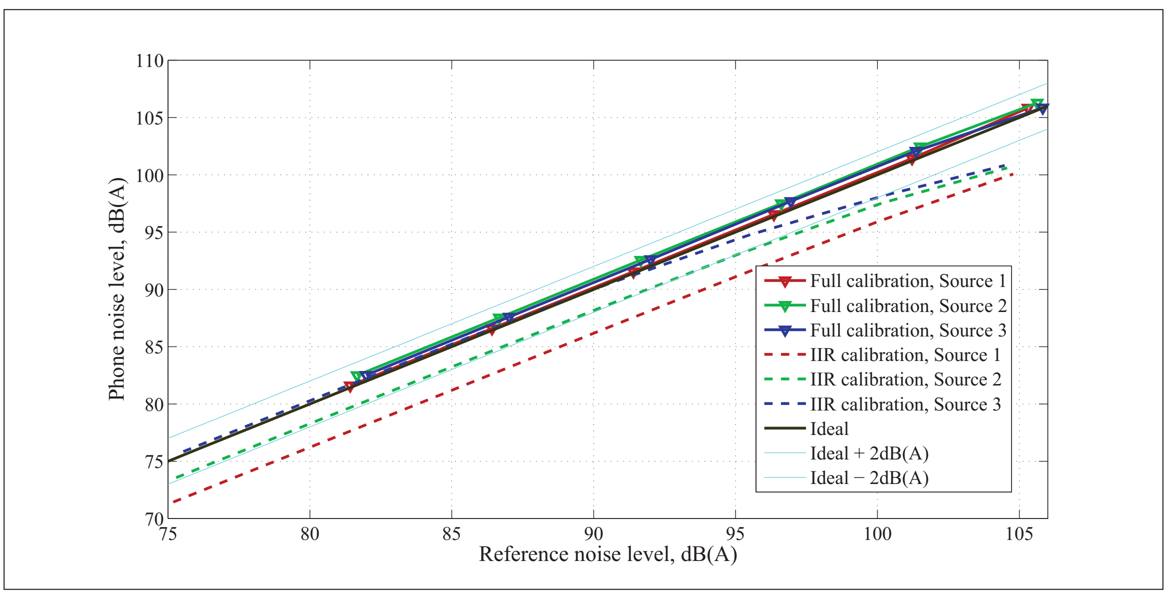


Figure 3.36 Earpiece overall A-weighted errors measured in the **semi-anechoic chamber** with only a frequency-dependent calibration (*FIR calibration*) and with frequency and level-dependent calibration (*Full Calibration*)

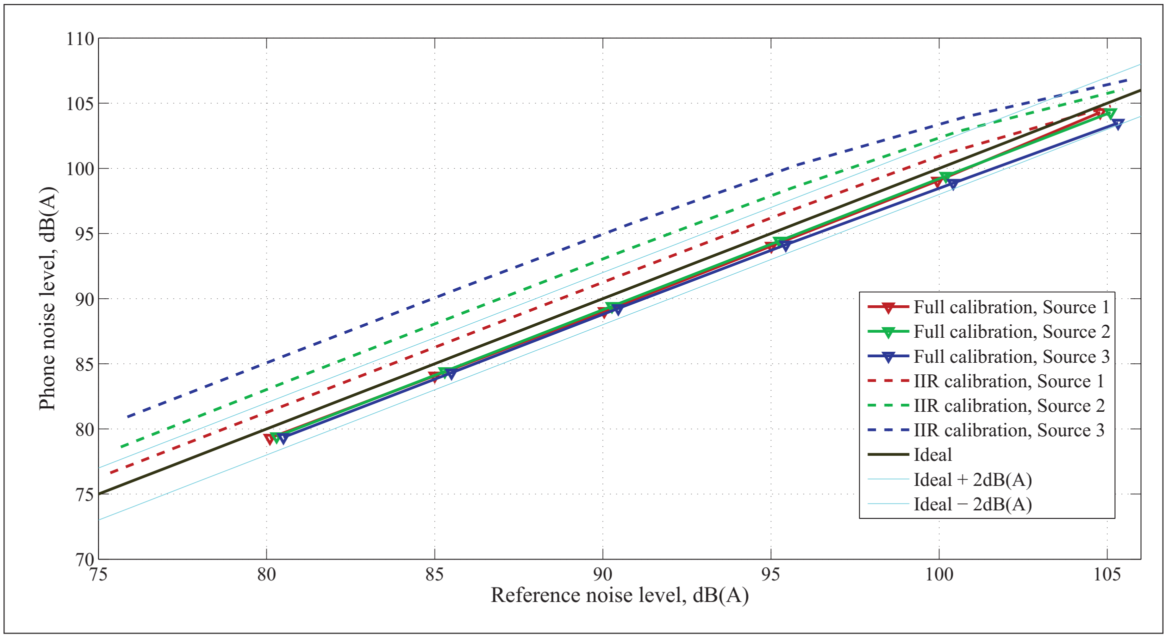


Figure 3.37 Earpiece noise level measurements, while measuring Sources 1,2, 3 in the **reverberant** chamber, with only a frequency-dependent calibration (*FIR calibration*) and with frequency and level-dependent calibration (*Full Calibration*)

#### 3.4.5.2 Measurements of "real-world" audio recordings

Table 3.26 contains the overall A-weighted errors while measuring in both semi-anechoic (S-A) and reverberant (R) chambers the "real-world" recordings noise sources from the NOISEX 92 database."Ref. C-A" and "Ref. dB(A)" in Table 3.26 were the C-A and the noise level measured with the reference measurement system. The ranges of errors were -0.7 to -1.8 dB(A) for the measurements in the semi-anechoic chamber. Errors from measurements in the reverberant chamber were lower than those from measurements in the semi-anechoic chamber. The measurements of the first three noise sources in the reverberant chamber were not available as a technical issue regarding the measurement files occurred after the measurement campaign.

#### 3.4.5.3 Microphone placement relative to the ATF: earpiece placement

The objective was to investigate the effect of the earpiece placement within the built-in ear simulator on the overall noise levels in dB(A). Figure 3.38 presents the noise level measurements

Table 3.26 Earpiece overall A-weighted errors while measuring "real-world" audio recordings noise sources in the semi-anechoic (S-A) and reverberant (R) chambers and with the phone implementing the factory calibration associated to each acoustical field

| **Noise source** | **S-A** | | | **R** | | |
|---|---|---|---|---|---|---|
| | **Ref. C-A** | **Ref. dB(A)** | **Error dB(A)** | **Ref. C-A** | **Ref. dB(A)** | **Error, dB(A)** |
| Factory 1 | 3.2 | 99.4 | 3 | 2.2 | 98 | ∅ |
| Factory 2 | 4.5 | 99.5 | 2.2 | 4.2 | 98.2 | ∅ |
| Buccaneer | 1.3 | 99.2 | -2.3 | 0.9 | 97.9 | ∅ |
| Tank | 5.7 | 103.1 | -1.1 | 7.5 | 102.2 | -2.3 |
| Music | 2.9 | 103.7 | 2.6 | 3.4 | 103.2 | -0.2 |

in the semi-anechoic chamber for five earpiece placements within the built-in ear simulator. Insertions #1, #2 and #3 correspond to tightly and deeply mounted earpieces, whereas Insertion #4 and #5 correspond to lightly mounted earpiece. Figure 2.17 illustrates two examples of earpiece placement. It is worth noting that for the earpiece measurements presented previously, a tight mounting in the vicinity of the ear was used. The range of noise levels (between Insertions #1 and #5) went from 12.3 dB(A) at a reference noise level of 80 dB(A) to 5.2 dB(A) at a reference noise level of 105 dB(A). It can be seen from Figure 3.38 that for the noise level measurement with Insertion #5, which had the highest noise levels, a saturation occurred between 95 and 100 dB(A).

Figure 3.39 presents the noise level measurements in the reverberant chamber for four earpiece placements. Again, Insertion #4 corresponds to a very lightly inserted earpiece. Comparing Figure 3.38 and Figure 3.39, it can be seen that in the reverberant chamber, the range of noise levels due to the placement variations was lower than in the semi-anechoic chamber. From this finding, it can be concluded that the diffuse field may reduce the effect of the earpiece placement on the overall noise levels in dB(A).

#### 3.4.5.4 ATF position relative to the source

Figure 3.40 presents the overall A-weighted errors for four ATF positions relative to the source measured in the semi-anechoic (S-A) and reverberant (R) chambers while measuring Source 1

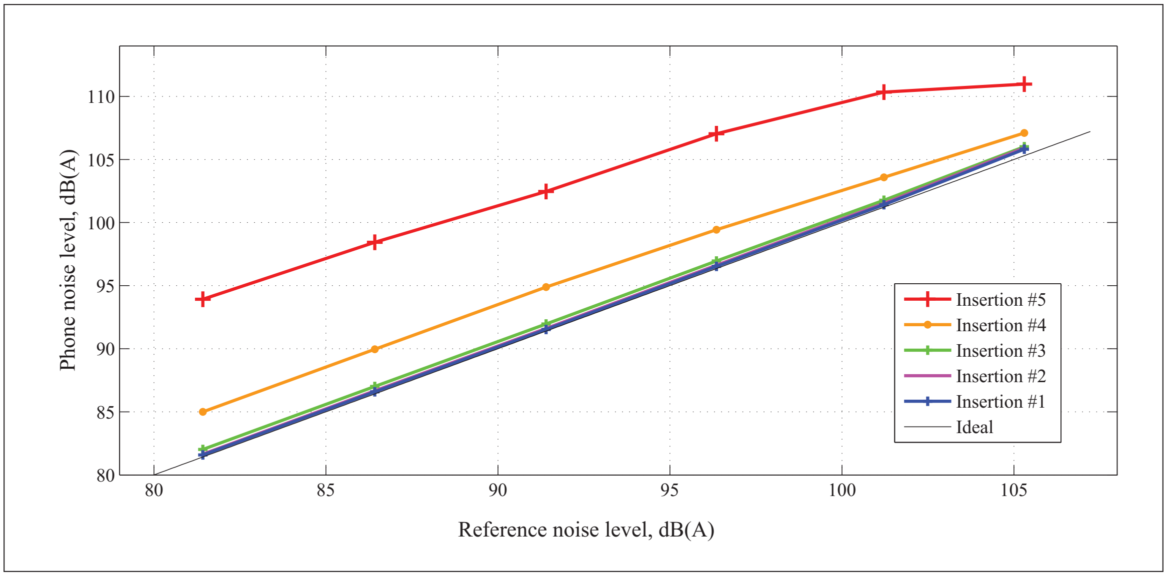


Figure 3.38 Noise level measurements for five variations of earpiece placement within the built-in ear simulator measured in the **semi-anechoic chamber**

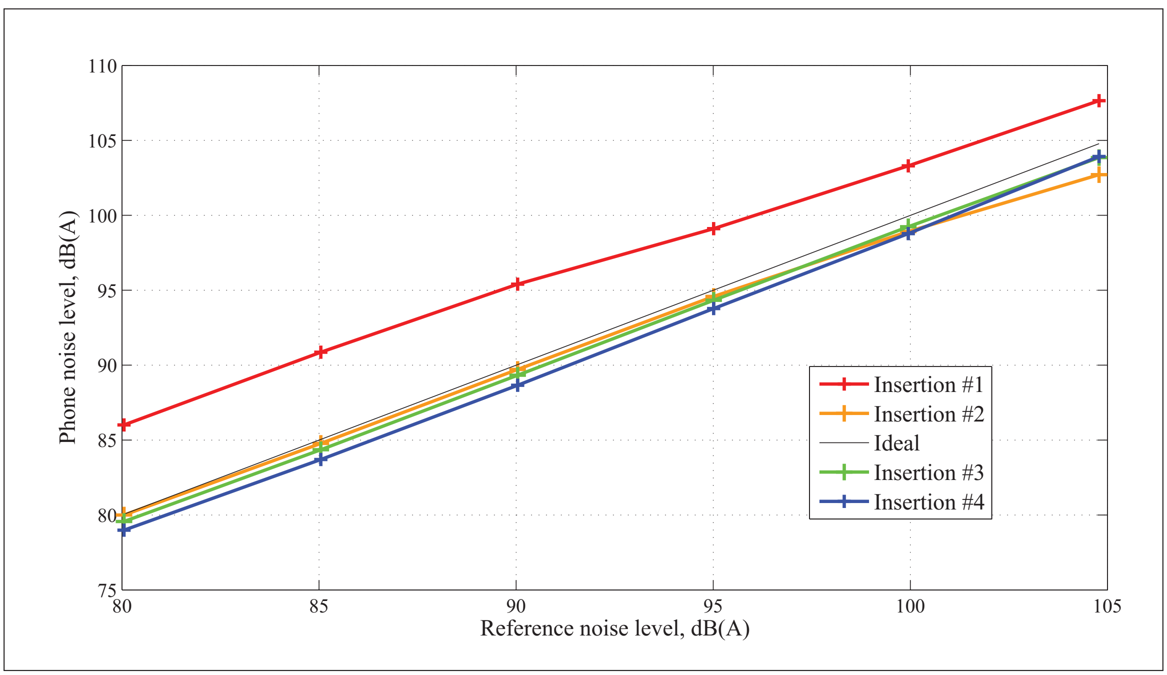


Figure 3.39 Noise level measurements for five variations of earpiece placement within the built-in ear simulator measured in the **reverberant chamber**

for a range of noise levels from 80 to 105 dB(A). The ATF was oriented towards four directions, defined in the semi-anechoic chamber by angles of the incident sound with regards to the loudspeaker, as illustrated in Figure 2.18. In Figure 3.40, the ATF position 0° corresponds to the placement used for the calibration measurements. The four different ATF positions were omitted from the figure for the sake of simplicity. In the reverberant chamber, the range of errors were -0.4 to -1.3 dB(A) with the overall A-weighted errors slightly decreasing at 105 dB(A), whereas in the semi-anechoic chamber, the range of errors was between 0.2 to 2.3 dB(A) and overall A-weighted errors slightly increased at 105 dB(A).

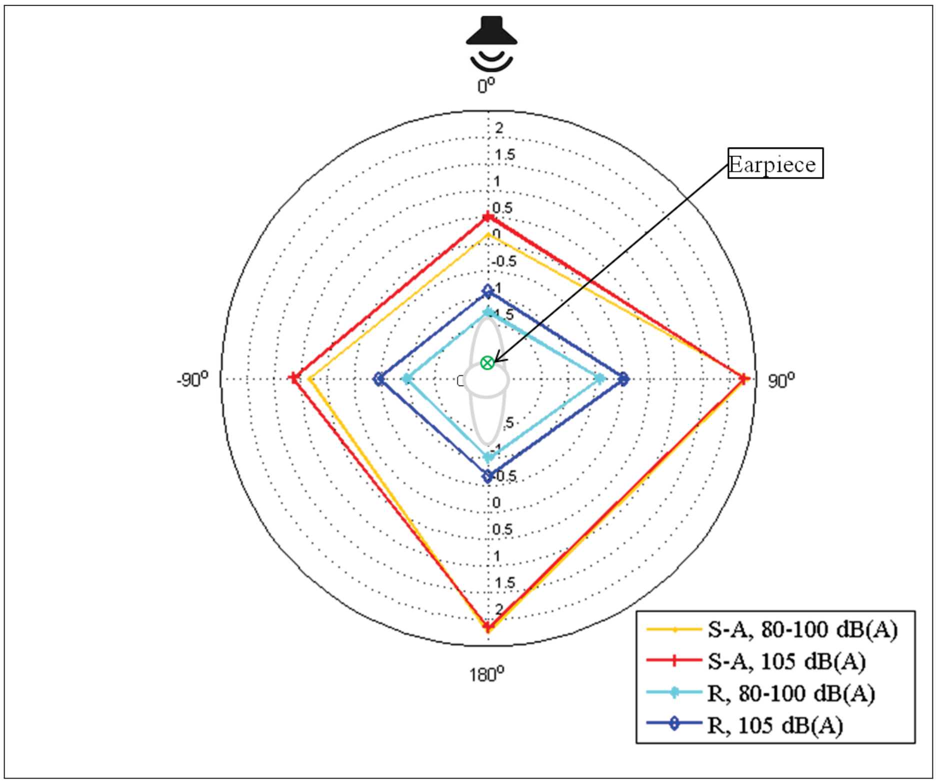


Figure 3.40 Earpiece overall A-weighted errors in the semi-anechoic chamber (in red an orange) and in the reverberant chamber (in blue)

#### 3.4.5.5 Acoustical field cross-calibration

Tables 3.27 and 3.28 contain the overall A-weighted errors for the earpiece measurements conducted in the semi-anechoic and reverberant chambers with the phone implementing a field cross-calibration (section 2.3.2.3). Looking at the two tables, it can be seen that in both chambers, the cross-calibration increased greatly the overall A-weighted errors. It can be seen that the errors for both cross-calibration measurement were very high: the range of errors was 3.7 to 7.6 dB(A) for the free-field calibration in the reverberant chamber and -5.1 to -9.1 dB(A) for the diffuse-field calibration in the semi-anechoic chamber.

Table 3.27 Earpiece overall A-weighted errors measured in **the semi-anechoic chamber** with the phone implementing the "free field" (FF) and the "diffuse field" (DF) factory calibration

| **Reference noise level** | **FF calibration** | | | **DF calibration** | | |
|---|---|---|---|---|---|---|
| **dB(A)** | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** |
| 80 | 0.2 | 0.8 | 0.5 | -9.1 | -6.9 | -5.1 |
| 85 | 0.2 | 0.9 | 0.6 | -9 | -6.8 | -5.1 |
| 90 | 0.1 | 0.9 | 0.6 | -9 | -6.9 | -5.3 |
| 95 | 0.2 | 0.9 | 0.7 | -9 | -7.1 | -5.8 |
| 100 | 0.2 | 0.9 | 0.7 | -8.9 | -7.6 | -7.1 |
| 105 | 0.5 | 0.6 | 0 | -8.8 | -8.1 | -8.2 |
| **MSE, dB(A)** | 0.1 | 0.7 | 0.3 | 80.2 | 52.5 | 38.3 |

Table 3.28 Earpiece overall A-weighted errors measured in **the reverberant chamber** with the phone implementing the "diffuse field" (DF) and the "free field" (FF) factory calibration

| **Reference noise level** | **DF calibration** | | | **FF calibration** | | |
|---|---|---|---|---|---|---|
| **dB(A)** | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** |
| 80 | -0.7 | -0.9 | -1.1 | 3.7 | 5.8 | 7.6 |
| 85 | -1 | -0.9 | -1.1 | 3.7 | 5.8 | 7.6 |
| 90 | -1 | -0.8 | -1.2 | 3.7 | 5.8 | 7.6 |
| 95 | -1 | -0.8 | -1.3 | 3.8 | 5.9 | 7.6 |
| 100 | -0.9 | -0.8 | -1.5 | 4.3 | 6.3 | 7.2 |
| 105 | -0.5 | -0.8 | -1.8 | 4.1 | 4.9 | 5.3 |
| **MSE, dB(A)** | 0.8 | 0.7 | 1.9 | 15.2 | 33.2 | 52.1 |

### 3.4.6 Noise dosimeter measurements

Table 3.29 contains the overall A-weighted errors, measured in the semi-anechoic and reverberant chamber with the noise dosimeter microphone located on the ATF as illustrated in Figure 2.14. In the semi-anechoic chamber, the measurements were conducted for the "Exposed Ear" ATF position (Figure 2.16). The ranges of error were 0.3 to 0.5 dB(A) for measurements in the semi-anechoic chamber and 0.7 to 1 dB(A) for measurements in the reverberant chamber.

Table 3.29 Noise dosimeter overall A-weighted errors measured in the semi-anechoic chamber (S-A) with the "Exposed Ear" ATF position and in the reverberant (R) chamber

| **Reference noise level** | **S-A** | | | **R** | | |
|---|---|---|---|---|---|---|
| **dB(A)** | **S1** | **S2** | **S3** | **S1** | **S2** | **S3** |
| 80 | 0.3 | 0.3 | 0.5 | 0.9 | 0.9 | 0.7 |
| 85 | 0.3 | 0.3 | 0.5 | 0.9 | 0.9 | 0.7 |
| 90 | 0.3 | 0.3 | 0.5 | 1 | 0.9 | 0.7 |
| 95 | 0.3 | 0.3 | 0.4 | 0.9 | 0.8 | 0.7 |
| 100 | 0.3 | 0.3 | 0.3 | 0.9 | 0.8 | 0.7 |
| 105 | 0.3 | 0.3 | 0.4 | 0.9 | 0.8 | 0.7 |
| **MSE, dB(A)** | 0.1 | 0.1 | 0.2 | 0.9 | 0.7 | 0.5 |

Table 3.30 contains the overall A-weighted errors while measuring the "real-world" recordings noise sources (section 2.1.3) in both semi-anechoic (S-A) and reverberant (R) chambers. In the semi-anechoic chamber, the measurements were conducted for the "facing the source" and "Exposed Ear" ATF positions (Figure 2.16). The difference in dB(A) between the two ATF positions, highlighted in Table 3.29, can be explained by the variation of the microphone's placement with regard to the source between the "facing the source" position and the "Exposed Ear" position. Differences due to the microphone placement relative to the source are illustrated in Figure 3.41, it shows the overall A-weighted errors, as compared with the reference center-of-head for four ATF position. The ATF was oriented towards four orientations as illustrated in Figure 2.18. The four ATF positions were omitted from Figure 3.41 for the sake of simplicity.

Table 3.30 Noise dosimeter overall A-weighted errors while measuring "real-world" audio recordings noise sources in the semi-anechoic chamber (S-A) and in the reverberant chamber (R)

| **Noise source** | **S-A** | | | | **R** | | |
|---|---|---|---|---|---|---|---|
| | **Ref. C-A** | **Ref. dB(A)** | **"Facing the source"** | **"Exposed Ear"** | **Ref. C-A** | **Ref. dB(A)** | |
| Factory 1 | 3.2 | 99.4 | -1.3 | 0.5 | 2.2 | 98 | 0.7 |
| Factory 2 | 4.5 | 99.5 | -1.2 | 0.6 | 4.2 | 98.2 | 0.7 |
| Buccaneer | 1.3 | 99.2 | -1.7 | 0.2 | 0.9 | 97.9 | 0.6 |
| Tank | 5.7 | 103.1 | -1.3 | 0.6 | 7.5 | 102.2 | 0.9 |
| Music | 2.9 | 103.7 | -1.4 | 0 | 3.4 | 103.2 | 0.5 |

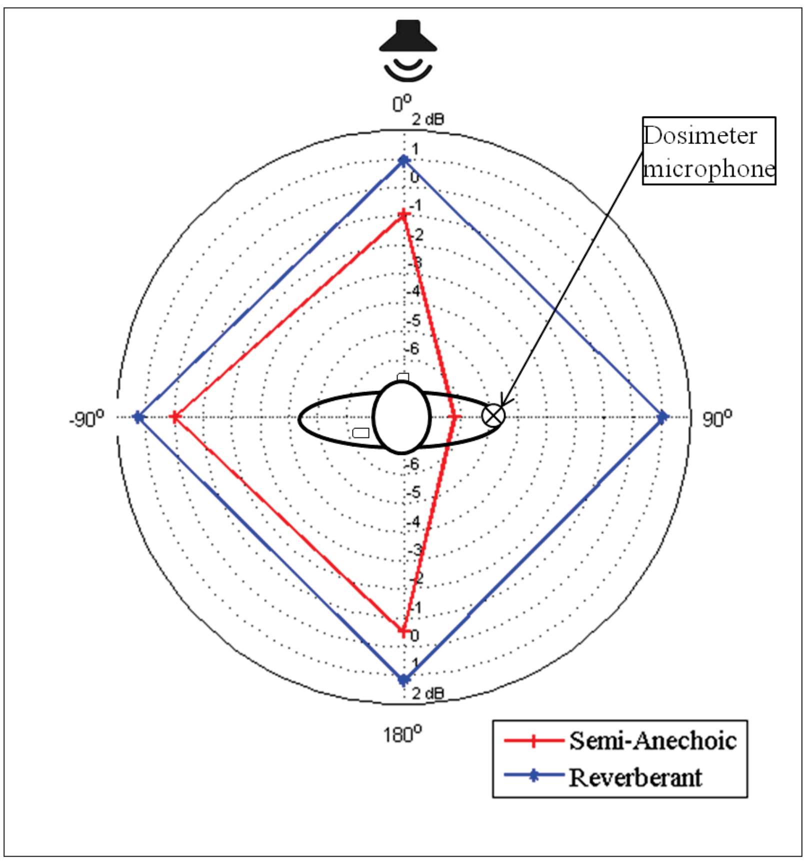


Figure 3.41 Noise dosimeter overall A-weighted errors averaged over the range of noise levels in the semi-anechoic chamber (in red) and in the reverberant chamber (in blue)

# CHAPTER 4

# DISCUSSION

While NIHL remains the number one occupational disease in developed countries, the cost and the usability of standardized noise exposure instruments limit their widespread use. With advanced technical capabilities, mobile phones can act as a noise exposure instrument. Moreover, the omnipresence of mobile phones around the world and as a part of everyday life represents an opportunity to make noise exposure measurements accessible. However, the use of mobile phones for measuring noise exposure is limited due to the lack of formal procedures for their calibration and challenges regarding the measurement procedure. The approach of a single, frequency and level-independent, calibration used for standardized noise exposure instruments is not suitable for mobile phone-based solution since the noise measuring app must be run on different mobile phones that have different microphones, hardware and software components, with variable range of quality. Microphone positions and the field calibration method recommended in the standards are not adapted for a mobile phone's (built-in and external) microphones. And finally, standardized values for noise exposure instrument uncertainties, used in standards to determine the noise exposure assessment uncertainty are not suitable for phone measurements. Studies have sought to improve the accuracy of phone measurements with calibration algorithms that are only based on noise level corrections. Studies have also aimed to evaluate the accuracy of mobile phone measurements. However, such factors as the phone microphone placement error or the effect of the acoustical field on the phone measurement have not yet been investigated. Our research investigated the calibration of mobile phone-based solutions for measuring noise exposure using mobile phone's built-in microphones and wearable external microphones. The mobile phone's electro-acoustical limitations and the procedure for calibration measurements were investigated. The study also sought to quantify the effect of noise exposure characteristics on the accuracy of calibrated mobile phone measurements.

This section includes: a summary, from section 4.1 to 4.4 of the major findings of each *Results* subsection is followed. Section 4.5 presents the results with regards to the following research questions. The basis of a mobile phone calibration methodology is discussed in section 4.6 and finally recommendations for future works and longer-term projects are presented in section 4.7.

## 4.1 Electro-acoustical limitations of mobile phones and external microphones

**Magnitude-dependent nonlinearities of frequency responses**

Frequency response measurements conducted with the built-in and the external microphones showed that the phone components that process the built-in microphone signal integrate a high-pass filter-like audio processing with a -3 dB roll-off at around 380 Hz with a rate of -6 dB/octave (Figure3.1). This high-pass-shape frequency response seems to be common to mobile phones as Faberacoustical (2012a) and Stevens (2012) highlight similar signal processing for iPhones models (Figure 1.8) and Nokia 5230 mobile phones, respectively.

Magnitude-dependent nonlinearities of the devices' frequency response for frequencies above 1 kHz were observed. The built-in microphone and earpiece frequency responses showed peaks up to 10 dB centered around 6350 Hz certainly due to the microphones' frequency response and their mounting in the devices. Manufacturers of such microphones typically used in the mobile phone industry highlights similar microphone response peaks due to the effects of sound inlet variations on microphone response, Knowles (2013). Investigation of the variability between mobile phone units of the same model of the built-in microphone's frequency response (Figure 3.10) showed up to 10 and 7 dB offsets occurring at 2 kHz and 7 kHz, respectively. From these findings, it can be concluded that for all three devices being tested, the implementation of a frequency-dependent calibration is likely to correct the devices' non-flat frequency response.

**Noise level saturation: devices' sensitivity and effect on the frequency response**

External devices plugged into the phone revealed a lower sensitivity than that of the mobile phones used with the built-in microphone. For a reference noise level of 105 dB(A), uncalibrated noise levels measured with the earpiece and the headset were 47 and 86 dB(A), respectively, whereas the built-in microphone noise level was capped at 91 dB(A) due to saturation. For both the earpiece and the headset measurements, no significant saturation occurred for noise levels up to 105 dB(A) (Figure 3.2) whereas saturation of the A-weighted noise levels started to occur at a reference noise level of 85 dB(A) for the built-in phone measurements and for the measurements conducted with the reference microphone plugged into the mobile phone.

The saturation of the noise levels measured with the reference microphone plugged into the mobile phone shows that the signal saturation was mainly due to high sensitivity of the built-in microphone and the saturation of the phone hardware components that process the microphone signal. Therefore, decreasing the sensitivity of the devices' microphone could prevent a saturation of the signal. On one hand, built-in microphone sensitivity is difficult to modify: it would require changing the phone's microphone or tweaking the phone hardware components. On the other hand, the sensitivity of the device's external devices would be easy to attenuate by using, for example, a voltage divider integrated in the phone adapter cable, as used in the study for the earpiece (Figure 2.11). Although decreasing the microphone sensitivity is always at the expense of the devices' internal electrical floor noise, the goal range of noise levels expected to be measured during noise exposure measurements, 70 dB(A) to 105 dB(A), should normally remain above the devices' internal floor noise.

The frequency response of the built-in microphone measurements (Figure 3.4) showed 1 to 3 dB magnitude shifts over the frequency range due to noise levels greater than 85 dB(A). For the headset and the earpiece, which did not get saturated high noise levels, the frequency response magnitude was not modified due to high noise levels (Figure 3.6). These findings validated the assumption of the phone's signal frequency distortion at high noise levels (section 2.4.2) and confirmed the relevance of a level-dependent calibration algorithm based on C-A values.

### 4.2 Factory default calibration measurements

Factory default calibration measurements investigated the effect of several measurement factors on the frequency responses and the A-weighted noise levels. Factors directly associated with the use of the ATF were the following:

- The external microphone located on a stand or on the ATF;
- The earpiece placement in the ATF's built-in ear simulator;
- The headset microphone placement relative to the ATF;
- The ATF dressed with a sweater.

Below are the main findings for the factors directly associated with the use of the ATF:

- Comparing frequency responses of semi-anechoic measurements conducted on a microphone stand and on the ATF showed that the mounting of the external devices on the ATF led to important variations up to 15 dB(A) in magnitude (Figures 3.7 for the earpiece and Figure 3.8 for the headset) mainly caused by acoustical reflections and ATF shadowing effects.
- The earpiece placement within the built-in ear simulator is an important factor to consider during the factory calibration measurements as its effect on both the frequency response and the overall A-weighted noise level was very significant: depending on the microphone placement and how deep or loose was the earpiece, 4 to 10 dB variations in magnitude between transfer functions and 6 to 9 dB(A) variations between A-weighted noise level measurements were observed.
- The effect of the headset microphone orientation on the noise level corrections was significant as it modified the A-weighted noise levels by approximatively 1 dB(A).
- Dressing the ATF with a sweater led to a decrease of the A-weighted noise levels of 0.6 to 1.1 dB(A), depending on the device and the noise source spectrum; as expected, deviations are greater with the headset measurements due to the close location of the headset microphone to the ATF (Figure 2.14).

Measurements for four ATF positions with regards to the loudspeakers in the reverberant chamber (Figure 2.19) resulted in standard deviations below 0.5 dB(A) for the earpiece and below 0.3 dB(A) for the headset and the built-in microphone, highlighting the diffuseness of the reverberant chamber.

Looking at the difference in C-A values and the noise level corrections between measurements in the reverberant and anechoic chambers (Tables 3.2 and 3.1), important variations were observed for the earpiece measurements. Three results may explain these variations:

- Since the earpiece was removed and refit into the ATF's ear simulator, a slight variation of the earpiece's position may have caused a slight variation in the noise levels in dB(A) and dB(C);
- The filter design method used for the frequency-dependent calibration showed its limitations to fit the transfer function magnitude based on measurements conducted on the ATF (section 3.3.1.1). Therefore, the filter used for the earpiece calibration was based on measurements conducted with the earpiece on a microphone stand and as mentioned previously, high variations in magnitude were observed between the transfer function from measurements conducted on a stand and on the ATF;
- Frequency responses measured in the reverberant and the semi-anechoic chambers with the earpiece on the ATF, highlighted variations in magnitude from 10 to 20 dB in a frequency range between 200 Hz and 1 kHz (Figure 3.11).

## 4.3 Design and implementation of the calibration algorithms

The design of a filter expected to fit the devices' transfer function was investigated using algorithms and design methods available in MATLAB® toolboxes and with the following parameters: filter order, range and bandwidth of the TF. FIR filters design provided lower results than the IIR filters regarding the fitting of the transfer function's low frequencies (Figure 3.21 for the built-in microphone). While the built-in microphone and headset TFs allowed the design of IIR filters that fitted well the devices' TFs, the main difficulties encountered concerned the design of an "Earpiece IIR filter" specifically with the TF measurements when the earpiece was on the ATF. As illustrated in Figure 3.7, the magnitude of the TF based on measurements with the earpiece on the ATF was more irregular that the magnitude of the TF based on measurements on a stand. The non-linearities in magnitude were a limitation of the current filter design method, as the "smoother" TF based on the measurements with the earpiece located on a stand led to an IIR filter with a good fitting (Figure 3.20).

The transfer function calculated from measurements in the reverberant chamber (Figure 3.22) highlighted a limitation of the IIR filter design method to fit properly a TF that has low coherence values.

From the results of the IIR and FIR filter design, four major conclusions can be drawn, three regarding the filter design method and one specifically regarding the earpiece filter:

- The fitting of the devices' transfer function was better achieved (and with less coefficients) with IIR filters than with FIR filters;
- High coherence values of the calculated transfer functions were necessary in order to improve the design of IIR filters;
- Frequency response measurements in a free-field may lead to a better design of IIR filters than those from a diffuse field;
- For the IIR filter associated with the earpiece, the filter design method used in this study require a transfer function from measurements conducted on a stand rather than a transfer function from measurements conducted on the ATF.

The implementation of IIR filters in the measuring app software highlighted a maximum filter order that exceeded the phone's capabilities and caused the app to calculate unrealistic noise levels. This value remains specific to the particular entry-level phone model used in this study (ZTE N72 mobile phones); phone models with higher processing performance may support higher order IIR filters. The processing time required to compute and store a $L_{\mathrm{eq,A,1sec}}$ remained inferior to one second with the $6^{\mathrm{th}}$ and $12^{\mathrm{th}}$ order IIR filters used for the headset, earpiece and built-in microphones.

The impact of the frequency-dependent calibration on the overall A-weighted noise level was evaluated with measurements with and without the implementation of the frequency-dependent algorithm for noise sources that have different frequency contents. Differences between noise levels measured for the noise sources (offsets) were used to evaluate the efficiency of the frequency-dependent calibration. The main findings were that:

- For the headset measurements, the frequency-dependent calibration was efficient as it reduced the offset;
- For the built-in microphone measurements, the frequency-dependent calibration reduced the offset at noise levels below the saturation level. However, the offset re-increased at high noise levels due to saturation (Figure 3.24);
- For the earpiece measurement when located on the ATF, the frequency-dependent calibration was not efficient as it increased the absolute offset by 1 dB(A). This increase may be explained by the fact that the IIR was designed based on measurements conducted on a stand and the magnitude of the transfer functions between measurements on a stand and on the ATF differed greatly(Figure 3.7);

From these findings, it can be concluded that the frequency-dependent calibration generally improved the noise level measurements, but that alone was not sufficient to compensate the overall A-weighted errors and the effect of saturation that occurred with the built-in microphone measurements.

Regarding the design of the noise level correction algorithm, the main issue was the interpolation of the measured noise level corrections in order to create a lookup table of noise level corrections easily implementable in the phone app. Four methods from the MATLAB® *griddata* function were evaluated based on a visual evaluation with the help of 3D graphics representing both interpolated and measured values (Figures VII-1 and VII-2). The *v4* method from the *griddata* function seemed the most appropriate. The *cubic* and *linear* methods showed a major limitation caused by their algorithm which resulted in:

- A lack of interpolated noise level corrections values at each end of the interpolated values array (Figure 3.27);

- A need for an additional extrapolation and a "manual" cleansing of the interpolated data.

In considering implementation of noise level corrections using a Java™method to contain the lookup table of noise level corrections, an issue of size limitation arose. This limitation would affect the noise level and C-A coverage when implementing the calibration algorithm. In the case of the calibration measurements presented in this study, the noise level ranges and the noise sources frequency contents led to a phone range of noise levels and a phone C-A range that were:

- Either just small enough, so the lookup table size associated could be contained in a Java™ method;
- Or slightly too large but the issue was overcome by suppressing the corrections values corresponding to the first dB(A) at the low-end of the noise level range where the noise corrections were constant.

Extending the calibration approach to a larger range of noise levels and more than three noise sources would require a different implementation method for the storage of the lookup table such as, for example, a method using the relational database management system embedded into Android devices (SQLite), Android (2013).

### 4.4 Laboratory validation measurements and accuracy of the calibrated devices

The standard deviations of the repeatability noise level measurements were less than 0.1 dB(A) for the earpiece and headset measurements. For the built-in microphone measurements, the standard deviation was 0.1 for noise levels between 80 and 100 dB(A) an 0.4 dB(A) for a noise level of 105 dB(A). The large standard deviation for the built-in microphone measurements may stem mainly from deviations associated with the noise level correction algorithms: the variation in level of the one-second noise levels measured by the built-in microphone for a very stable noise source (Figure 3.28) showed that at high noise levels, the noise levels varied greatly around the overall noise level value with a standard deviation greater than 1 dB(A), Table 3.7.

The inter-unit variability of the phone acting as an acquisition system was investigated with the earpiece and four mobile phone units of the same model. The standard deviations did not vary with the acoustical field and remained below 0.4 dB(A) regardless of the noise level. The inter-unit variability of the built-in microphone measurements highlighted one specific phone unit over the four units as an outlier, especially for a 105 dB(A) noise level. In the semi-anechoic chamber, the standard deviations over the units varied between 1.5 and 3.9 dB(A) when including the "outlier" phone and between 0.7 and 2.6 dB(A) without the "outlier" phone. At noise levels above 90 dB(A), the standard deviations for built-in microphones measurements were observed to be smaller for measurements conducted in the reverberant chamber than for measurements conducted in the semi-anechoic chamber, however the decrease of the standard deviation was certainly due to saturation of the phone signal more likely to occur in the reverberant chamber at noise levels above 90 dB(A), as discussed later in this section. The inter-unit variability of the phones' frequency responses measured with the built-in microphone (Figure 3.10) showed 10 and 7 dB differences in magnitude between phone units at 2 kHz and 7 kHz respectively. Based on the inter-unit variability of the frequency responses and considering the low standard deviations obtained with the earpiece inter-unit variability measurements, it can be deduced that the inter-unit variability was more likely due to the built-in microphone rather than to the phone's hardware and software components.

The previous findings provide an indication of the mobile phone calibration paradigm to use for the built-in microphone calibration. As a reminder, there are three mobile phone calibration paradigms: a single calibration for all devices, a calibration specific to a particular model and a calibration specific to a particular unit. In the context of our study and based on the mobile phones used for these tests, a calibration specific to each phone unit seemed best in order to obtain accurate noise exposure measurements.

Regarding the earpiece, based on the inter-unit variability of the microphone earpiece whose standard of deviation is around 3 dB, as specified in Sonion (2009), it was concluded that a calibration specific to each earpiece unit is the most suitable calibration paradigm. Considering the small inter-unit variability of the phone acting as an acquisition system, below 0.4 dB(A), a calibration specific to a particular model would be acceptable only if the device's microphone had a small inter-unit variability, which seems to be the case for the products from leading manufacturers of mobile phones and external audio devices.

Measurement of Sources 1, 2 and 3 (used for the calibration measurements) showed good results for the calibration of the earpiece and the headset as the overall A-weighted errors in both chambers were contained between -1.8 and 0 dB(A). Both devices were already linear over the range of noise levels before calibration. Calibration reduced greatly the offset with the center-of-head measurements as errors for the headset were between -1.1 and -0.1 dB(A) and the errors for the earpiece were between -1.8 and 0.9 dB(A). The built-in microphone calibration led to good results for noise levels between 80 and 95 dB(A) with errors between 0 and -0.9 dB(A). However, in the reverberant chamber, at 100 and 105 dB(A), the saturation of the phone noise level occurred with a strong increase of the errors, up to 6.3 dB(A), as illustrated in Figure 3.33. Nonetheless, at similar high noise levels, errors for the measurements in the semi-anechoic chamber remained below 0.7 dB(A). It can be deduced from the previous results that the built-in noise level-dependent correction was less efficient for handling the signal saturation in a diffuse field. As a comparison, noise levels measured by the noise dosimeter with the microphone mounted on the shoulder overestimated the center-of-head noise levels by 0.3 to 0.5 dB(A) in the free field and by 0.7 to 1 dB(A) in the diffuse field. With the exception of the built-in errors due to saturation, the noise dosimeters and the mobile phone-based devices errors have similar ranges.

Looking at the differences between the free-field and diffuse-field measurements for the headset and built-in microphone measurements (with the exception of the errors due to saturation), it can be seen that the smaller errors occurred in the diffuse field.

Validation measurements conducted just after the calibration measurements resulted in smaller overall A-weighted errors than the series of measurements performed two weeks after calibration measurements. Errors were 0.1 to 1 dB(A) higher for the headset and earpiece measurements. For the built-in microphone, errors went up to 1.1 dB(A) in the semi-anechoic and up to 3.9 in the reverberant chamber with maximum errors at the noise levels with saturation. The differences between measurement campaigns can be explained by the fact that the set up was reinstalled in both chambers between the two measurement campaigns. This caused slight variations in the positions of the microphone and sound system and slight changes in the setting of the equalizer that slightly modified the spectrum and the level of the signal. The results for the built-in microphone in the reverberant chamber and for noise levels above 100 dB(A) highlights that the built-in calibration is more sensitive to a set-up variation at noise levels for which the saturation occurs.

Overall, greater errors occurred for Source 1 which contains more high-frequency energy than for Sources 2 and 3. As expected, the measurements of "real-world" noise sources led to greater overall A-weighted errors than measurements with Sources 1, 2 and 3 (used for calibration). However for most of the "real-world" noise sources, errors remained contained in a relatively small range: between -1.8 and -0.1 dB(A) for the headset and between -2.3 and 3 dB(A) for the earpiece. As a comparison, the noise dosimeter measurements led to errors between -1.7 and 0 dB(A) (depending on the ATF positions) in the semi-anechoic chamber, and between 0.5 and 0.9 dB(A) in the reverberant chamber.

Two of the "real-world" noise sources measured with built-in microphone resulted in very high errors, 8.5 and 11.6 dB(A). These errors occurred while measuring the noise sources with the lowest C-A values *Music* and *Bucaneer*, in the semi-anechoic chamber. These deviations can be explained by examining Figure 4.1 which presents the noise level corrections measured in the semi-anechoic chamber and the interpolated and extrapolated noise level corrections implemented in the calibration of the built-in microphone. It can be seen that:

- For Source 1 (the noise source with the lowest C-A value) and for the highest noise level, the measured noise level correction (in red dots) is approximatively 8 dB(A);
- For low C-A values and high phone noise levels, the extrapolated noise level corrections are between 15 and 20 dB(A) whereas the noise level correction for low C-A values and low phone noise levels are around -1 dB(A).

Figure 4.1 highlights an overestimation of the extrapolated noise level corrections due to the inter/extrapolation method and a need to improve this method. A solution would be to add maximum thresholds defined from the measured noise level corrections in order to avoid over-extrapolated noise correction errors observed in Figure 4.1.

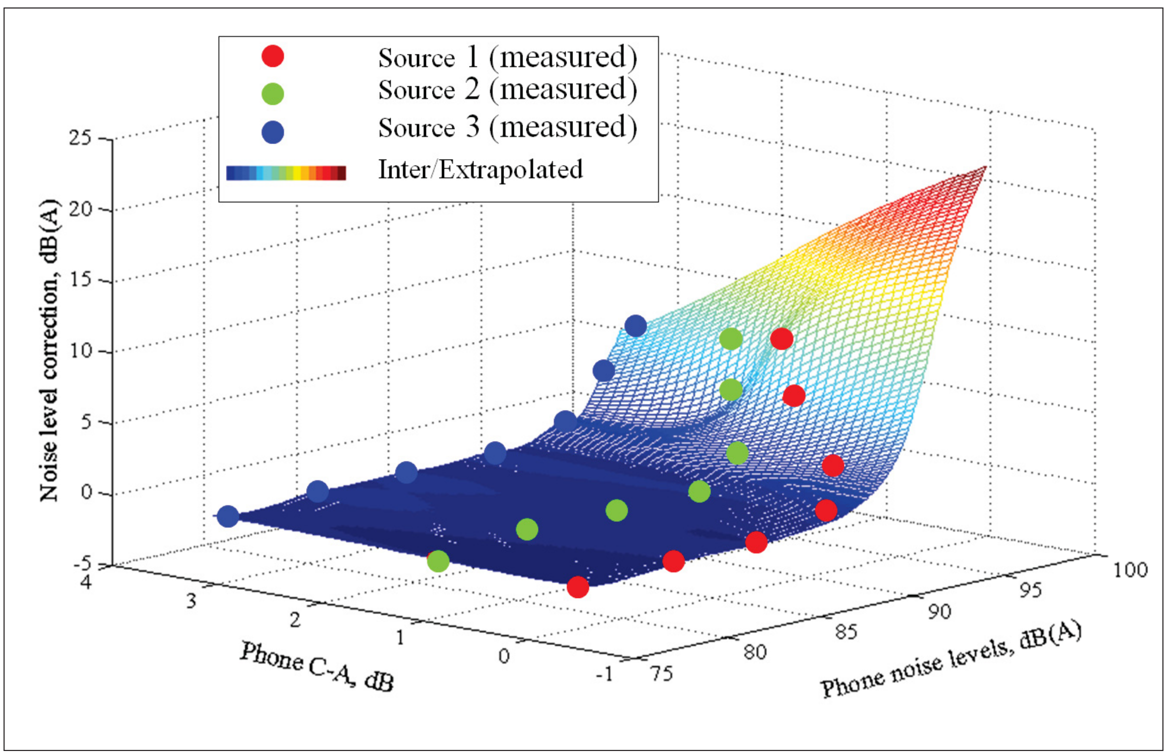


Figure 4.1 Built-in microphone noise level correction values measured in the semi-anechoic chamber (colored dots) and interpolated values calculated using the *v4* method

In the diffuse field, the errors due to the microphone placement relative to the source were relatively small as they varied, for all three devices, between -0.2 and -1 dB(A), with the exception of large errors for the built-in microphone of -2.7 dB(A) and -6.3 dB(A) associated with signal saturation at 100 and 105 dB(A) respectively. The errors for the three devices were compared with those published by Byrne and Reeves (2008) for the three following nonstandard noise dosimeter microphone positions: microphone mounted on the shoulder, resting on a subject's chest and hanging from a hard hat. The "resting" position corresponds to the headset microphone position and the "hanging" position is near the wearer's ears, close to the earpiece position. It is worth noting that in the study of Byrne and Reeves (2008), errors were measured with human subjects and for different noise sources than those used in our study. Moreover, unlike the calibration approach presented in this thesis, the calibration of the microphones did not depend on the microphone placement and a calibration check was performed on each microphone using a sound level calibrator. Considering the differences between the two studies, the comparisons of the results were limited to an overall comparison focused on the error patterns and error ranges.

With the exception of the large errors occurring for the built-in microphone at high noise levels, the range of errors in the diffuse field were very similar: the "shoulder mounted" and "hanging" positions led to errors between -0.2 to -1 dB(A) (depending on the type of noise source) and the "resting"position led to noise levels 1 dB(A) higher than measurements at the center-of-head position.

Table 4.1 summarizes the errors for the three devices in the free field with those published by Byrne and Reeves (2008) for the three nonstandard noise dosimeter microphone positions and measured with pink noise. The position $0°$ corresponds to the ATF facing the loudspeaker and the $90°$ position means that there is an azimuthal angle of $90°$ between the loudspeaker direction and the ATF orientation (Figure 2.18). It can be seen from Table 4.1, that:

- Lower errors occurred for the earpiece measurements, as compared to the measurements for the microphone hanging from a hard hat, from Byrne and Reeves (2008);

- For positions with little or no acoustical shadowing caused by the ATF (positions 0° and 270°) including the position used for the calibration measurements: lower errors occurred for the earpiece measurements, as compared to the measurements for the microphone resting on a subject's chest. For positions with acoustical shadowing caused by the ATF (the 90° and 180° positions), greater errors occurred with the earpiece measurements.

These results reflect the limitations of the mobile phone-based calibration when the angles of incident sound differ greatly from the position used during the calibration measurements and cause acoustical shadowing.

Table 4.1 Errors for the three devices measured in the free field and errors published by Byrne and Reeves (2008) for the three associated noise dosimeter microphone positions (marked with "*")

| **Mic. Position** | 0° | 90° | 180° | 270° |
|---|---|---|---|---|
| Headset | -1 | -5.5 | -12,7 | -2 |
| Right Chest* | 4 | -2.3 | 7.6 | 2.1 |
| Earpiece | 2.3 | 2.2 | (0.8 - 1.1) | (0.2 - 0.5) |
| Hanging-Right* | 2.9 | -4.2 | -0.1 | 4.2 |
| Dosimeter | -1 | -6.2 | -0.5 | 0 |
| Shoulder right* | 0.3 | -5.5 | 2.1 | 2.4 |

The results of the headset cross-calibration measurements show that the cross-calibration in the semi-anechoic chamber (with a diffuse-field calibration) slightly minimized the overall errors compared to the measurements conducted with a "normal" free-field calibration (Table 3.14). The "acoustical field" cross-calibration for the built-in microphone showed that for both chambers, and for noise levels between 80 and 90 dB(A), the cross-calibration did not increase the overall A-weighted errors. However, above 90 dB(A), the cross-calibration led to a large increase of the overall A-weighted errors, as compared to the errors with the measurements with a "normal" calibration with the maximum absolute overall A-weighted error of 8.9 and 13.9 dB(A) in the semi-anechoic and reverberant chambers respectively. Large errors due to the cross-calibration were also observed for the earpiece: the range of errors was 3.7

to 7.6 dB(A) for the free-field calibration in the reverberant chamber and -5.1 to -9.1 dB(A) for the diffuse-field calibration in the semi-anechoic chamber. Overall, the cross-calibration in the semi-anechoic chamber led to lower errors than the cross-calibration in the reverberant chamber. From these findings, it can be deduced that the type of calibration, diffuse or free-field, strongly affects the accuracy of mobile phone measurements depending on the acoustical characteristics of the measurement's location.

## 4.5 Sources of errors and improvement of the measurement accuracy

Certain sources of errors identified in this study are discussed, from the most important to the least important and, when applicable, user-defined adjustments intended to minimize the errors are presented along with methods to quantify the measurement accuracy.

The calibration approach compensates for the microphone placement error with calibration corrections depending on the microphone positions and the type of devices. Therefore, the most obvious prerequisite for an accurate measurement is using a calibration adapted to the device and positioning the microphone properly. Two sources of error corresponds to a microphone placement that does not correspond to the microphone placement used during the calibration measurements and a device model or device unit that does not correspond to the model or the unit used during the calibration measurements. In order to minimize these two sources of errors, the proposed method is to integrate into the mobile phone app, a graphical user-interface that would enable the selection of the appropriate device and microphone placement from a list of calibration data available in the app database. A method variant, inspired by the *NoiseTube* app by Stevens (2012), consists in adding an software feature that would automatically detect the mobile phone model without any user-involvement required. However, this variant is not suitable for the use of an external device since the automatic detection of the external device model by the app is very difficult, if not impossible.

The proposed mobile phone factory calibration approach is suitable for two calibration paradigms: a calibration specific to a phone's model (model-dependent calibration) and calibration specific to a phone's unit (unit-dependent calibration). If an external device is used, the calibration takes into account both the mobile phone as an acquisition system and the external device's characteristics. As discussed previously in the analysis of the validation measurements (section 4.4), the use of model-dependent calibration instead of unit-dependent calibration is a source of error. For measurements conducted with a phone implementing a model-dependent calibration, the device's inter-unit variability and particularly the standard deviation, calculated with measurements from several units, would quantify the range of the measurement errors.

The presence or the absence of noise level saturation over the range of noise levels under evaluation was shown to affect the quality of the calibration and thus, the accuracy of the mobile phone measurements. Indeed, the proposed calibration showed limitations for handling the saturation in a diffuse field. The magnitude of the errors mostly depends on the acoustical field, the noise level and the source spectrum. The only "method" that could decrease the errors associated with the noise level saturation is the use of external devices whose sensitivity is low enough to avoid saturation.

Cross-calibration measurements revealed that difference between the acoustical field of the calibration environments and the measurement location is a major source of error. The cross-calibration measurements correspond to the border line cases and led to maximum measurement errors. In real-world environments, the measurement location is likely to present acoustical characteristics between a free-field and a diffuse field. For environments more akin to a free-field than a diffuse field, the position of the microphone with regard to the source and the presence of acoustical shadowing become a source of error, as shown by the results of the validation measurement with different ATF positions in the semi-anechoic chamber. This finding is reflected in standards for noise exposure measurements, CSA (2013) and ISO (2008), that require the microphone to be located on the top of the shoulder at the side of the most exposed ear. The mobility of the wearer is another factor that needs to be considered in the evaluation of the sources of errors related to the acoustical field. Giardino and Seiler (1996) show that for noise dosimeters measurements in industrial environments, measurement errors when a user is mobile with respect to the noise source, are similar to measurement errors in a diffuse field. Comparing the findings from Giardino and Seiler (1996) and the results of the validation measurement with different ATF positions in the both chambers, the same conclusion about the mobility of the wearer can be drawn for mobile phone measurements calibrated with the proposed approach.

In short, the magnitude of the errors due to the acoustical field and the microphone placement relative to the source vary depending on the acoustical characteristics of the measurement location, the type of calibration used (diffuse or free field), the microphone placement relative to the source, and the mobility of the wearer. In order to minimize these sources of errors, a user-defined adjustment is proposed. It aims to determine the type of noise level correction (diffuse or free field) most adapted to the measurement conditions. The type of calibration can be selected directly by the user or determined through a graphical user interface that would collect a user's information about the measurements conducted. In addition to the calibrated noise levels, the measuring app also would record the non-calibrated A and C-weighted noise levels. Therefore, the noise-level corrections can be performed through post-treatment using the lookup table of noise levels corrections and the uncalibrated noise levels. The advantages of this approach are that the questions can be answered after measurements and if needed, a measurement can be split up in parts with different noise level corrections. For example, in a scenario where the phone-user moves from an outdoor space to a reverberant indoor space during the same measurement, free field noise level correction could be applied in the first part and a diffuse field noise level correction in the second part. Figure 4.2 presents a preliminary decision chart intended for the mobile phone user. The flow chart may require more research to optimize the questions, for example, the last question about the room's acoustics may be too complex for a non-specialist and a simpler formulation could be to ask the user to select a measurement location from a list of typical locations.

The validation measurements for the different noise sources highlighted that differences in spectrum with the noise sources used for the calibration affect the accuracy of the measurements. Temporal characteristics such as the presence of impulse noises were not extensively investigated as only one source contained impulse noises. However, impulse noises are ex-

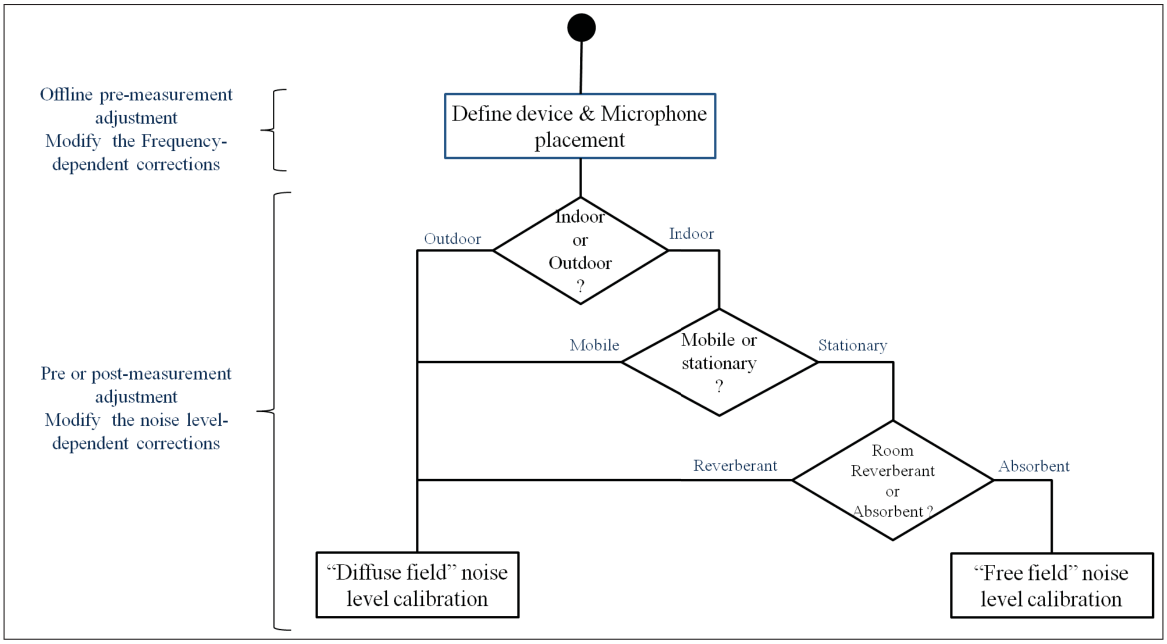


Figure 4.2 User-defined adjustment preliminary flow of questions, associated with the proposed calibration method

pected to be a source of error due to the limitations of the device's microphone and the phone hardware at properly sampling impulse noise, as highlighted by Kardous *et al.* (2005) for standardized noise dosimeters.

The earpiece placement within the ear, the headset microphone orientation or the built-in microphone orientation are all sources of errors associated with the measurement methodology. The sources of errors can be greatly reduced by following the same mounting and microphone placement characteristics as for the calibration measurements. For the wearable external devices, a source of uncertainties is inevitable due to differences between the ATF (or subject) used for the calibration measurements and the wearer of the device. Adding a sweater on the ATF decreased the overall A-weighted noise levels by 0.6 to 1.1 dB(A), depending on the external device and the noise source spectrum. Similar effects were observed by Johnson and Farina (1977) for the noise dosimeter microphone mounted on the shoulder. Since the ATF is made of plastic material, it is more likely to act as a reflector for mid and high frequencies than dressed human subjects. Slight differences in the results of the validation measurements could be expected if the calibration measurements were conducted with human subjects.

### 4.6 Basis of a mobile phone calibration methodology

In addition to the procedure detailed in the *Methodology* section, some additional basis for a standardized and unique mobile phone calibration methodology can be drawn from the results of the calibration and validation measurements:

- Close attention should be payed to the effects of the room acoustics on the calibration noise sources spectrum so that the C-A values measured for these sources should be as close as possible to the C-A values of the original signals;
- Close attention should be payed to microphone orientation and placement, especially for earpiece-type devices mounted in the vicinity of the ear;
- Frequency response measurements should be conducted in a free-field environment with the microphone on a stand;
- Noise-level calibration measurements should be conducted in both free-field and diffuse environments. If only a free field environment is available, a diffuse-field calibration method based on free-field measurements can be used, such as the method defined in the IEC-1183 standard, IEC (1994);
- For external microphones, noise-level calibration measurements should be conducted on a subject (or the ATF) with the microphone placement that corresponds to the intended usage of the microphone;
- IIR filters should be preferred to FIR filters for the design of the frequency-dependent calibration algorithm;
- For the design of the IIR filter, close attention should be payed to: the fitting of the transfer function at frequencies between 50 and 500 Hz and a filter order smaller than the maximum order supported by the mobile phone;

- The interpolation method used for the noise level corrections should integrate maximum thresholds based on the measured noise level corrections;
- Calibration data for any device under calibration should be stored in an optimized format that ensures a subsequent reuse for the calculation of mobile-dependent calibration algorithms;

### 4.7 Recommendations for future works and longer-term projects

Based on the results of the study, several recommendations for future works were determined. First, the evaluation of the electro-acoustical limitations of mobile phones and external devices were conducted with a very limited number of devices being tested (four units of the same phone model, one earpiece and one headset). A series of tests to establish a factory calibration with a larger set of mobile phone and external device models could provide a broader analysis of the phone limitations, taking into account the differences between mobile phone models and the importance of "outlier units". Results from this measurement series would allow us to evaluate the inter-unit variability of several mobile phones and external devices. One of the research questions to be answered would concern the relevance of using model-dependent calibration for external devices. In the study, the use of an ATF instead of human subjects limited the results interpretation of the validation measurements, the series of calibration measurement could also be an opportunity to investigate a calibration procedure with human subjects.

Second, the laboratory validation measurements in the study were conducted in controlled environments during a short period of time. Several uncertainties and sources of errors were not investigated such as the error due to the instrumental drift or the errors associated with measurements in a "real-world" environment (contributions from wind, the microphone rubbing on clothing,etc.). A field validation study should consist in noise exposure measurements in "real - world" environments with comparative measurements between standardized noise dosimeters, integrating sound level meters and mobile-phone based noise exposure monitoring devices. Several noise exposure scenarios could be studied depending on the acoustical characteristics of the measurement location, the microphone placement with regards to the source, the mobility of the wearer and the characteristics of the noise sources. The main objective of a field validation study could be to quantify the values of the uncertainties due to the instrumentation and the microphone location required in noise exposure standards such as ISO (2008). A field validation study could also be an opportunity to investigate the usability of mobile-phone based noise exposure monitoring device including the investigation of the measurement procedure and the user-defined adjustments.

Finally, as a part of longer-term projects, this study opened up new research avenues for:

- The development of the field "user-calibration" approach;
- The development of a mobile sensing platform for noise exposure assessments.

The objective of the field "user-calibration" approach would be to limit the need for laboratory calibration measurements and professional reference measurement systems. A proposed approach, called *Starbuck*, illustrated and described (in French) in Annex I-2, is based on the measurement methodology and the calibration algorithms design methods developed for this study. The concept is to use a calibrated mobile phone as the reference in order to field calibrate an un-calibrated phone. Both frequency response and noise level correction measurements are conducted with the phones (or the external devices) side by side amidst the noise sources present in the field. The design and implementation of the calibration algorithms is performed by the calibrated phone and the field "user-calibration" process ends with the transfer and the implementation of the calibration data (digital filter and noise level corrections) into the phone being calibrated. The proposed approach would require the development of automatic methods for the design and implementation of the calibration algorithms. Laboratory measurements could be conducted in order to evaluate the quality of the proposed calibration approach and the accuracy of "field calibrated" mobile phone measurements.

The objective of a mobile sensing platform for noise exposure assessments is to provide a practical tool to accurately assess the noise exposure. It would require the development of a mobile sensing platform which includes a mobile phone app and a web server application that manage the analysis and the visualization of the phone data. The implementation of such a platform has been well documented by Ruge *et al.* (2013) and Stevens (2012) and a preliminary web application was developed by the author based on the web-based management system Pumilio, Villanueva-Rivera and Pijanowski (2012).

One of the great advantages of using mobile phones for measuring noise exposure is being able to optimize the use of mobile phone user-interaction and embedded mobile phone sensors in order to improve the quality of noise exposure assessment. While the proposed user-defined adjustment requires the user involvement to select the most appropriate calibration, a method variant could include context classification algorithms that assess the acoustical field and the mobility of the wearer using the microphone signal and other sensors embedded in the phone, with no or minimal user involvement. Moreover, for outdoor measurements, geo-located data can be easily measured in addition to the noise levels, an analysis of the measurement could allow to create noise exposure mapping, which opens up to the following research work:

- The creation of noise maps based on a spatial interpolation of punctual noise measurements. Based on the research carried out by Rana *et al.* (2013) for mobile phone environmental noise mapping, research could focus on the particularities of the occupational noise exposure measurements;
- Noise exposure assessment with the use of tracking technologies. As presented in Annex V, recent methods have used tracking technologies to monitor workers' displacements to evaluate noise exposure. A research work could conduct a field study on similar methods using the mobile phone platform and geolocation technologies available on mobile phones.

Finally, pursuing the efforts to put this research into practice, there is a need to develop a platform that would provide more than only a standardized approach to noise exposure assessment. Most audiences targeted for a noise exposure platform using mobile phones would not need the noise exposure measurement to be as accurate as those required for standards. As discussed in detail in Annex IV, there are other approaches than standardized noise exposure methods that allow one to determine if a noise exposure presents risks of NIHL; simplified noise levels measurements together with noise exposure databases and/or activity analysis can provide a sufficiently accurate evaluation of the overall noise exposure to identify obvious risks of NIHL and lead to the implementation of a noise reductions program. A future research study could consist in implementing these non-standardized approaches as features of the mobile sensing platform and evaluate their effectiveness in a field study.

# CONCLUSION

This research work was the first in its kind to investigate a calibration approach for mobile phones that integrates corrections for microphone placement errors and considers the use of wearable external microphones. Measurements were carried out using several mobile phones of the same model, with a built-in microphone and two additional external devices: an earpiece and a headset with an in-line microphone. This thesis investigated the mobile phone's electro-acoustical limitations and the procedure for calibration measurements. The study also sought to determine the effect of noise exposure characteristics on the accuracy of calibrated mobile phone noise exposure measurements. The proposed mobile phone calibration approach, investigated in the study, includes a frequency-dependent correction using a digital filter and noise level-dependent correction that depends on the measured phone C-weighted noise level minus A-weighted noise level, used as an indication of the noise spectral balance.

High-pass filter-like audio processing integrated in the phone and nonlinearities of the microphone's frequency response highlighted the need for a frequency-dependent calibration. External microphone measurements showed that the noise level saturation observed at high noise levels for the measurements with the built-in microphone was mainly due to the high sensitivity of the built-in microphone and the saturation of the phone hardware components that process the microphone signal. A frequency distortion due to the signal saturation was observed, highlighting the need for a calibration that is only slightly or not at all sensitive to frequency distortion. The use of an external device within an embedded electrical gain reduction, achieved with a voltage divider, has proved to be the best approach to reduce the device's sensitivity and prevent a saturation of the signal when applicable.

From the results of noise levels measurements conducted using the measuring app with and without the frequency-dependent algorithm, it was concluded that the frequency-dependent calibration generally improved the noise level measurements but that alone was not sufficient to compensate for the overall A-weighted errors and the effect of saturation that occurred with the built-in microphone measurements. The proposed calibration algorithms were supported by an entry-level phone model and the processing time required to compute the calibrated noise levels met the requirements specified in the study. While the implementation in the app of the IIR filters highlighted the phone's limitation to handle very high order IIR filters, the implementation of the noise level corrections showed a limitation associated with the app software and in particular the storage capacity of the lookup table containing the noise level corrections.

The following sources of errors and uncertainties were identified based on the analysis of the validation measurements, they are associated with:

- The measurement repeatability;
- The inter-unit variability;
- The presence or the absence of signal saturation;
- The differences in spectral content between the noise sources used for the calibration and the noise sources used for the validation measurements;
- The differences in acoustical field between the calibration and the validation measurements;
- The microphone placement relative to the source;
- The microphone placement relative to the wearer.

While the standard deviations associated with the repeatability of noise level measurements were less than 0.1 dB(A) for the measurements with the earpiece and the headset regardless of the noise levels, the standard deviation of the built-in microphone measurements increased from 0.1 dB(A), for noise levels between 80 and 100 dB(A), to 0.4 dB(A) at 105 dB(A) due to saturation and the deviations associated with the noise level correction algorithm.

The inter-unit variability of the built-in microphone measurements highlighted one "outlier" phone unit at 105 dB(A) and large standard deviations: between 1.5 and 3.9 dB(A) for the standard deviation over four units including the outlier (measured in the semi-anechoic chamber). These results showed that the inter-unit variability was more likely due to the built-in microphone rather than to the phone's hardware and software components. For the mobile phones under test and their use with the built-in microphone, it was concluded that a calibration specific to each phone unit was the most appropriate calibration paradigm in order to obtain accurate noise exposure measurements. Regarding the use with the earpiece, based on large (3 dB) standard deviation associated with the inter-unit variability of the microphone earpiece, it was concluded that a calibration specific to each earpiece unit was the most suitable calibration paradigm. Considering the small inter-unit variability of the phone acting as an acquisition system, below 0.4 dB(A), a calibration specific to a particular model would be acceptable only if the device's microphone had very little inter-unit variability, which seems to be the case for the products from leading manufacturers of mobile phones and external audio devices.

Analysis of the validation measurements showed that for the headset and the earpiece, whose signal did not saturate at high noise levels, the proposed calibration significantly improved the accuracy of the noise level measurements in both acoustical fields, with better results in the diffuse field and with ATF positions causing little or no acoustical shadowing. The built-in microphone validation measurements highlighted the limitations of the calibration method at handling the signal saturation in a diffuse field. Nonetheless, the built-in microphone calibration significantly improved the accuracy of the noise level measurements for noise levels below 100 dB(A). The measurements of "real-world" noise sources highlighted one major limitation of the current noise level corrections algorithm regarding the interpolation of the measured noise-level corrections.

Cross-calibration measurements revealed that differences between the acoustical field of the calibration environments and the measurement location is a major source of error of the noise level measurements. A "user-defined adjustment", to be considered in addition to the calibration, was determined to minimize the errors associated with the acoustical characteristics of the measurement location and the microphone placement with regards to the source. The approach consists in questioning the phone-user about the measurement characteristics in order to determine which noise level corrections to implement between the diffuse-field and free-field noise level corrections.

Major technical contributions of the study bear on the design and implementation of a frequency response linearization with a digital filter and a noise level-dependent calibration algorithm as a function of the C-A. It includes:

- A Java™ and Android-based app software;
- Matlab scripts for the analysis of the phone measurement files, the design of a IIR filter and the interpolation of noise level corrections.

Regarding the scientific contributions, the methodology of the study and the analysis of the investigations provide the basis for a standardized and unique factory default calibration approach intended to be implemented in any mobile phone and with the aim of eliminating current confusion. Below are the main conclusions that were drawn regarding the calibration measurements methodology:

- The design of the frequency-dependent calibration requires frequency response measurements in a free-field with the device being tested on a stand;
- The design of a noise level-dependent calibration requires measurements of noise level corrections in both diffuse and free-field with the external device located on an ATF;
- Close attention should be payed to the effects of the room acoustics on the calibration noise sources spectrum so that the C-A values measured for these sources are as close as possible to the C-A values of the original signals;
- Close attention should be payed to microphone orientation and placement, especially for earpiece-type devices mounted in the vicinity of the ear.

From the results of the design of the digital filters for the frequency-dependent calibration, four major conclusions were drawn:

- The fitting of the devices' transfer function was better achieved (and with less coefficients) with IIR filters than with FIR filters;
- High coherence values of the calculated transfer functions were necessary in order to improve the design of IIR filters;
- Frequency response measurements in a free-field may lead to a better design of IIR filters than those from a diffuse field;
- For the IIR filter associated with the earpiece, the filter design method used in this study require a transfer function from measurements conducted on a stand rather than a transfer function from measurements conducted on the ATF.

Based on the results of the study, several recommendations for future works were determined including:

- A series of factory calibration measurements with a larger number of mobile phones and external device models and conducted with human subjects in order to investigate phone limitations and inter-unit variability within a broader scope and validate a calibration procedure with human subjects;
- A field validation study in order to investigate errors associated with measurements in "real-world" environments and quantify the values of the uncertainties due to the instrumentation and the microphone location required in the noise exposure standards.

Finally, the following long-term projects stemming from this research would be:

- The development of a field "user-calibration" approach that would limit the need for laboratory calibration measurements;
- The development of a mobile sensing platform for noise exposure assessments that would provide a larger audience with a practical tool to accurately assess the noise exposure by taking advantage of embedded mobile phone sensors and geolocation technologies together with a web-based data analysis.

The main contribution towards occupational health and safety is that the proposed approach enables the use of mobile phones for monitoring individual noise exposure. It also opens up a realm of a wide range of hearing conservation approaches ranging from the evaluation of noise reduction actions to in-ear individual noise exposure assessments.

Investigating the limitations of mobile phones as noise exposure instruments is an important step towards the expansion of their use. While preventive interventions and users involvement were seen to be essential in hearing conservation programs, Rabinowitz *et al.* (2011) and Goelzer *et al.* (2001), it is hoped that the findings in this research will help promoting mobile phones as prevention and training tools, helping to raise awareness regarding the risks of NIHL. Overall, despite the fact that mobile phone measurements may not be as accurate as standardized noise exposure measurements, standardized and accurate noise exposure measurements are not essential in the process of reducing NIHL and as summarized in the following quote from Beat W.Hohmann (2008):

> "It is not the detailed noise measurement (nor the study of prescriptions how these measurements should be done) that protects employees against noise-induced hearing loss but rather the measures that are taken!"

# ANNEX I

# PUBLICATIONS AND PRESENTATIONS

## 1. 2012 EREST Poster Contest: "Mesures de l'exposition sonore des travailleurs avec des téléphones intelligents"

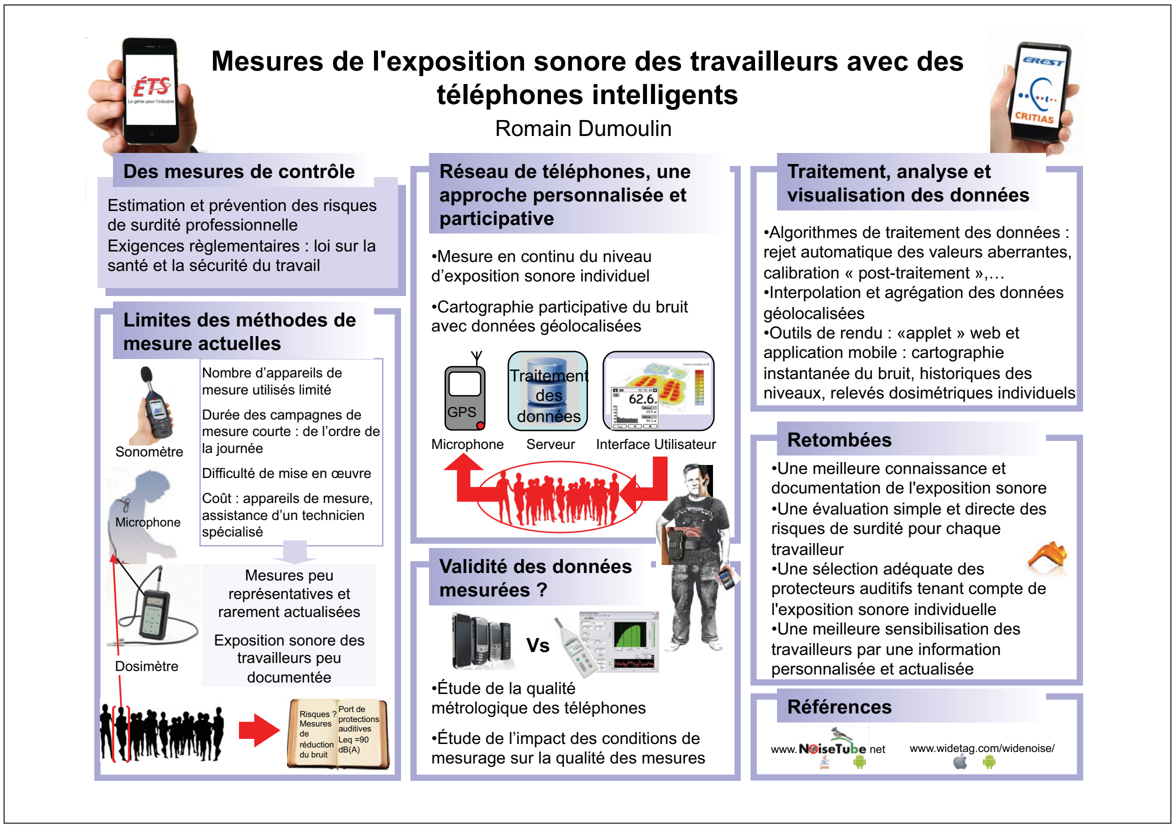


Figure-A I-1 Poster "Measurements of workers' noise exposure with smartphones"

## 2. 2013 EREST Poster Contest: "Propagation participative des valeurs de calibration"


Figure-A I-2 Participatory propagation of calibration values

### 3. 80th ACFAS congress, May 2012 - Abstract and oral presentation (in French)

**Preuve de faisabilité de l'utilisation de téléphones mobiles pour la mesure continue et personnalisée de l'exposition sonore des travailleurs au Québec**

Les mesures d'exposition sonore ont pour objectif d'évaluer les risques pour la santé auditive avant de déclencher si besoin des actions de réduction du bruit et un programme de prévention. Les campagnes de mesures ont comme principaux inconvénients leur cout et les difficultés de mise en oeuvre associées. Dans ce contexte, les nuisances sonores peuvent parfois être peu ou pas documentées avec des relevés dosimétriques individuels rares et peu actualisés. Le projet présenté lors de la communication tente de répondre à cette problématique avec l'utilisation de téléphones mobiles "intelligents" pour une mesure continue et personnalisée de l'exposition sonore. Les retombées potentielles du projet sont multiples : une évaluation simple des risques de surdité pour chaque travailleur, une meilleure sensibilisation grâce à une information personnalisée et actualisée, une sélection adéquate des protecteurs auditifs tenant compte de l'exposition individuelle. Dans un premier temps, les résultats de la recherche portant sur la validation de l'utilisation des téléphones comme dosimètre seront présentés. Dans un deuxième temps, après la présentation d'une expérience similaire, les enjeux liés à la transférabilité au milieu de la santé et sécurité au travail seront discutés.

## 4. Canadian Acoustics Week in Banff, October 2012- Proceeding and oral presentation

### ON THE USE OF SMARTPHONES FOR OCCUPATIONAL NOISE MONITORING: INSTRUMENTATION

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#### ABSTRACT

This paper presents an on-going research effort that focuses on a smartphone-based occupational noise monitoring platform. A laboratory calibration method for smartphones and embedded devices, together with an innovative "field" calibration are detailed. The evaluation of uncertainties associated with the use of smartphones for noise level measurement is discussed with regards to the main individual uncertainty components.

#### 1. INTRODUCTION

Although noise induced hearing loss represents the number one occupational disease, individual workers' noise exposure levels are still rarely precisely known and infrequently tracked. Indeed, standardized noise exposure campaigns have as their principle disadvantages the cost of instrumentation and the practical difficulties associated with real world implementation. In opposition to these procedures, informal noise surveys carried out with basic and inexpensive sound level meters are not necessarily precise or accurate enough.

The *WikiLeq* project [1] proposes the use of smartphones as an alternate solution. The first step of the project focuses on the evaluation of the measurement quality through the assessment of uncertainties associated with the instrumentation. In a second step, the uncertainty associated with time and spatial sampling strategies for noise exposure assessment will be carefully evaluated.

#### *2.* ANDROID IMPLEMENTATION

*WikiLeq* is an open source framework for monitoring occupational noise based on the NoiseTube project [2]. It combines two simultaneous approaches: the first one features a personal full work shift dosimetric assessment, while the second features a participative sound pressure levels mapping.

An Android™ (v2.3.5) application has been developed for the personal full work shift dosimetric assessment: A-weighting and real-time octave band filters (63 to 8,000 Hz) have been implemented for a 16-bits audio stream acquired at 22,050 Hz. This application requires the user to define what type of microphone device is used and where it will be located on the user's body; an associated *calibration adjustment* is determined and applied to the measured $L_{eq}$. One-second octave-band equivalent level, $L_{eq,1s}$ , are then computed and tagged with GPS data. A cumulative long-term $L_{eq}$ is displayed within the application and will be in near future presented with the associated expanded measurement uncertainty (detailed in Section 4). Finally, the locally stored data is sent to the *WikiLeq* server for data aggregation required for the participative sound pressure levels mapping.

#### 3. CALIBRATION PROTOCOLS

**3.1. Laboratory calibration**

This procedure, based on IEC 1183 standard [3], aims at separating the diffuse field sensitivity levels associated with the directional characteristics of a device from the one associated with the effects of its mounting position. The resulting *random-incidence calibration value*, regroups these two effects, and will be determined for a wide range of noise levels for one specific microphone device among supported by the WikiLeq application such as the phone embedded microphone, the "in-line" microphone on headphone cord and the microphone of a Bluetooth® earpiece.

- Random Incidence Microphone Placement Error

In a reverberation room, the reference microphone measurements, conducted on a head and torso simulator (HATS) at different mounting positions are compared to measurements done with the same microphone at the center-of-head position without the mannequin. Acoustical reflections and mannequin shielding effects lead to a random-incidence microphone placement error, $\varepsilon_{mp}$ , that can be measured for every octave band at typical microphone positions: on the belt holster, in the breast pocket, on an "in-line" headphone cord and on top of the shoulder, as per ISO 9612 standard [4].

- Random-incidence sensitivity levels

The random-incidence sensitivity levels, $G_{RI}$, are calculated for each octave band from Eq. 1 below and measured in a semi-anechoic room. The free-field sensitivity level, $G_F$, is measured for a reference direction of sound incidence and directivity factor, γ, assessed from an IEC 1183 procedure.

$$G_{RI} = G_F - 10 \log(\gamma) \qquad (1)$$

- Calibration adjustment

The obtained $G_{RI}$ values are stored in the *WikiLeq* application calibration module and will be added to $\varepsilon_{mp}$ to obtain a so-called octave-band *calibration adjustment* specific to the microphone device used and its mounting position.

**3.2. Field calibration proposed approach**

A laboratory calibrated smartphone will now be used to calibrate an uncalibrated microphone device in the field by assessing its free-field sensitivity levels with the following

Figure-A I-3

proposed approach: the calibrated and uncalibrated phones are physically brought close together to be immersed in the same sound-field and a real-time audio recording is performed. A dual channel FFT analysis, implemented in the Android "app", will estimate the transfer function between the two microphone devices and compute a free-field sensitivity levels, $G_F$, for the device under field calibration. The normalized random error for the frequency response magnitude is calculated from the coherence function in order to evaluate the quality of that field calibration. The values of $G_F$, are then stored in the newly calibrated phone app with an associated "field calibration uncertainty" that quantifies the quality of the proposed field calibration. An average directivity factor, $\overline{\gamma}$, for the three types of microphone device is calculated. The figure illustrates the calculation of the *calibration adjustment*.

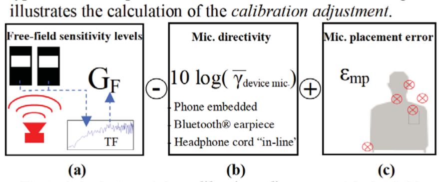


**Fig.1. Calculation of the *calibration adjustment* with the field calibration values; assessing free-field mic. sensitivity relative to calibrated device (a), then accounting for mic. directivity (b) and mic. placement position (c).**

## 4. INSTRUMENTATION UNCERTAINTIES

### 4.1. Main uncertainties considered

Prior published analysis on noise dosimeter and sound level meter measurements uncertainties has been revisited for the envisioned use of a smartphone. For a large population of IEC-compliant noise dosimeters, 4 main uncertainties [5] are given: microphone placement errors, frequency response errors, linearity and sensitivity errors. On top of these, the uncertainties associated with the *WikiLeq* lab and field calibrations as well as the long term environmental and aging drifts need to be considered.

- Microphone placement error is partially addressed in the *calibration adjustment* calculations. In a free-field situation (with a source at a particular angle of incidence) the microphone placement error will be underestimated [5]. It is reduced when the worker is mobile with respect to the noise source [5].
- Frequency response uncertainty is principally influenced by the data acquisition hardware (microphone, pre-amplifier,…) since A-weighting and octave-bands filters are digitally implemented. The quality of the laboratory calibration process impacts significantly this uncertainty.
- Linearity and sensitivity uncertainties are due to the discrepancies between the measured sound pressure level and the reference sound pressure level for a 30 dB range over 90 dB sound pressure level (at which sensitivity is assessed). Again, the quality of the laboratory calibration process impacts significantly this uncertainty while it rises naturally at higher noise levels because of the stalling "slope" of the calibration response curve.
- Laboratory calibration error, $\varepsilon_{mp}$ , may lead to an error since it is measured without considering the directivity of the microphone under calibration. Uncertainties associated with the "laboratory" measurements of the sensitivity levels and directivity factors must also be taken into account.
- Field calibration error includes the above-mentioned laboratory calibration error and microphone placement error, as well as the error due to the use of an averaged directivity factor and the uncertainties associated with the dual channel FFT analysis applied.
- Long term environmental and aging drifts error may be taken at first from published work: Electret and MEMS microphones showed a negative correlation between sound level and temperature with a global error around 1 dB [6], while the variability from different phones of the same model was determined as negligible [7].

### 4.2. Discussion about the evaluation of uncertainties

The determination of these main individual uncertainty components aims to evaluate a practical value of the instrumentation error for the overall measured noise level. In ISO 9612 [4], the standard uncertainties associated with the instrumentation and the measurement position are defined for standardized instrument and are based on empirical data. These empirical data must be used, since the tolerance limits given in IEC 1252 [8] would lead to an overestimation of the instrumentation uncertainties [4]. The practical approaches for the assessment of each of these uncertainty components are still to be developed and preferably using "hands-on" approaches as in [5] and [9] for the specific constrains of the proposed use of smartphone-based instruments. For example, based on the evaluation tests defined in IEC 1252 as reference, the sinusoidal signals source should be modified for more "real world" industry noises.

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Figure-A I-4

## 5. ICA 2013 Montreal, July 2013- Proceeding and oral presentation

# 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, $L_{\mathrm{eq,1sec}}$. Audio processing features available on Android devices such as automatic gain control are disabled. $L_{\mathrm{eq}}$ 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.

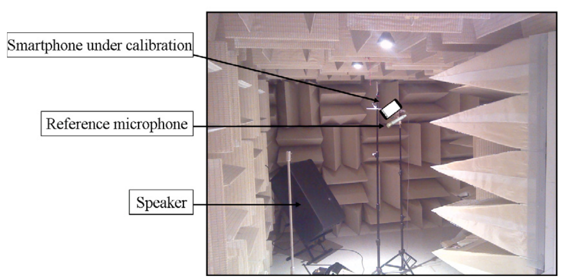


**FIGURE 1:** Setup of the calibration measurement in the anechoic chamber showing the smartphone under calibration, the reference microphone and the powered speaker

### 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 :

$$Lp_{\text{ A,correction}} = Lp_{\text{A,ref}} - Lp_{\text{A,phone}}. \quad (1)$$

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

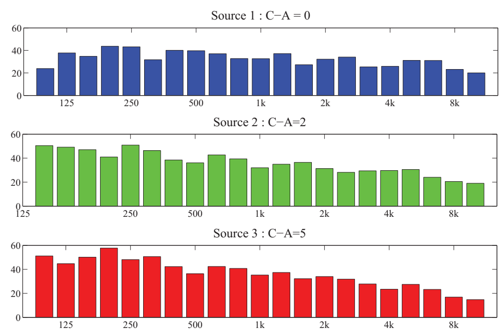


**FIGURE 2:** Noise spectrum of the Source 1, 2 and 3 with C-A value respectively 0, 2 and 5 dB at 85 dB(A)

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.

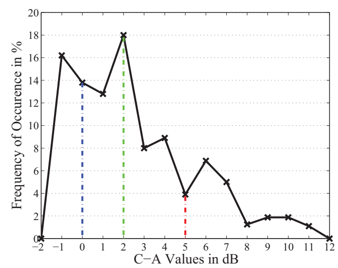


**FIGURE 3:** Histogram of the C-A values of NIOSH100 noise source database. The C-A of the noise sources used in this study are -1, 2 and 5 dB

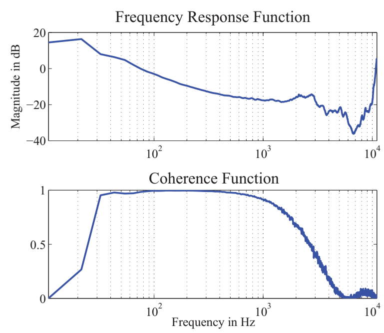


**FIGURE 4:** Frequency response function and coherence between a smartphone and the reference measurement system with dual channel FFT analysis

### 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.

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

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

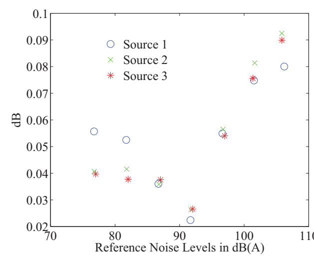


**FIGURE 5:** Uncertainty associated with the dB(A) phone measurement,$u_{Lp_{A,phone}}$ in dB

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.

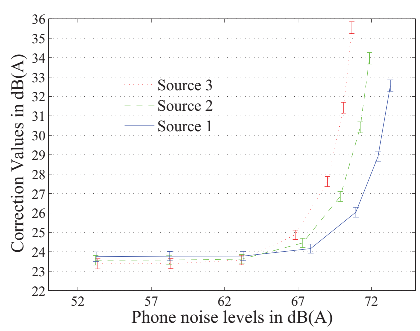


**FIGURE 6:** Correction values in dB(A) as a function of the phone noise levels and their associated expanded uncertainties in error bars

## 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, $Lp_{\mathrm{A,phone}}$ and the phone C-A values, $C-A_{\mathrm{phone}}$. 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

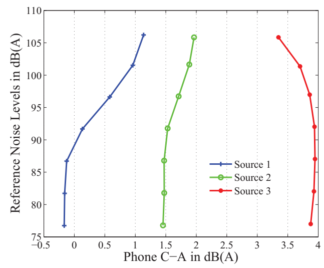


**FIGURE 7:** Reference noise levels in dB(A) as a function of phone C-A in dB(A)

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

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

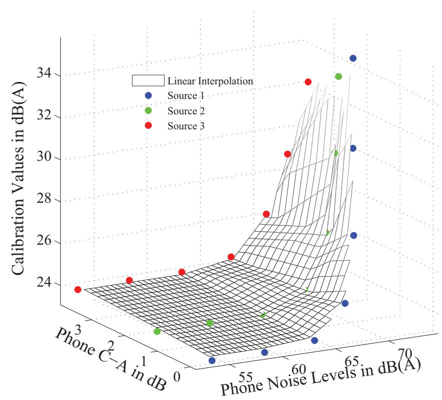


**FIGURE 8:** Interpolated correction values calculated with a linear interpolation and within the measured correction values for sources 1, 2 and 3

## Discussion

The determination of the uncertainty associated with a calibrated phone measurement $Lp_{\mathrm{\ A,calibrated\ phone}}$ 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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## ANNEX II

## NOISE LEVEL AND NOISE EXPOSURE DESCRIPTORS

The sound pressure level (SPL) is a logarithmic ratio of the effective sound pressure on a specific reference sound pressure value in deciBel (dB) calculated using Equation A II-1. The reference sound pressure, $p_{ref}$, corresponds roughly to the threshold of human hearing.

$$L_p = 20 \log_{10} \left( \frac{p_{rms}}{p_{ref}} \right) \ dB \tag{A II-1}$$

With $p_{ref}$, the reference sound pressure of 20 $\mu$Pa and $p_{rms}$, the root mean square (RMS) sound pressure being measured.

The frequency weightings, A and C, are an approximation of the inverted and normalized equal loudness contours. They aim to account for the loudness sensitivity of the human ear. The A-weighting is based on the 40-phon of the Fletcher and Munson contour which corresponds to relatively low sound pressure levels (1 kHz tone at 40 dB and 100 Hz tone at 60 dB). The C-weighting follows the frequency sensitivity of the human ear at high sound pressure levels, it is relatively flat, and therefore includes much more of low-frequency content than the A-weighting. Although the A-weighting follows the frequency sensitivity at low noise levels, current noise exposure instruments' standards require the use of A-weighting curve for the measurement of high noise levels.

The equivalent continuous sound level commonly referred to as $L_{eq}$ is the sound pressure level of an imaginary continuous signal, within a given time interval, that would produces the same energy as a measured fluctuating sound pressure level. So-called "short" $L_{eq}$ are usually calculated over an interval between 0.125 to 1 second. An "overall" $L_{eq}$ corresponds to the equivalent continuous sound level over the total duration of a measurement. Figure II-1 illustrates a measurement fluctuating noise level, overall $L_{eq}$ and short $L_{eq}s$

Noise exposure descriptors are calculated from A-weighted sound levels and the duration of noise exposure.

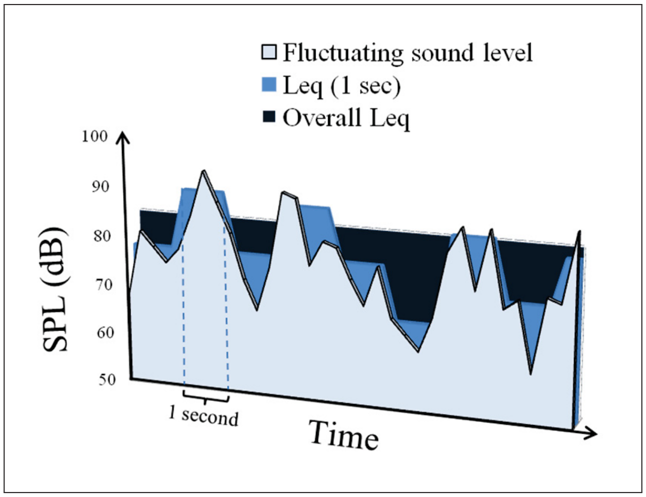



Figure-A II-1 Fluctuating sound pressure level,
Overall $L_{eq}$ and short $L_{eq}s$

**A-weighted noise exposure level normalized over 8 hours,** $L_{EX.8h}$

$L_{EX.8h}$ is the equivalent continuous sound level normalized over a working day of 8 hours. The international Standard Organization standard 9612 "Determination of occupational noise exposure — Engineering method", ISO (2008), defines $L_{EX.8h}$ equation as:

$$L_{EX.8h} = L_{p.A.eqT_e} + 10\log_{10}\left(\frac{\overline{T_m}}{T_0}\right)\ dB(A) \tag{A II-2}$$

where:

- $L_{p.A.eqT_e}$ is the A-weighted equivalent continuous sound pressure level over the effective duration of the working day;
- $T_e$ is the effective duration of the working day;
- $T_0$ is the reference duration, $T_0 = 8hours$.

Depending on the sampling strategy used, $L_{EX.8h}$ can also be calculated from other equations than stated above (A II-2). It is currently the most commonly used noise exposure descriptor both in regulations and standards. When the duration of the measured noise exposure is other than 8 hours, the $L_{EX.8h}$ is calculated using an exchange rate. The exchange rate is the amount by which $L_{EX.8h}$ may increase if the exposure time is halved. An exchange rate of 3 dB means for a halved duration of the noise exposure, $L_{EX.8h}$ is reduced by 3 dB. Although the 3 dB exchange rate is the most widely used, a 5 dB exchange rate is still required by the regulation of a few countries and organizations. If the daily noise exposure varies during a given week, a weekly noise exposure level, $L_{EX.w}$, calculated over 40 hours can be used.

**Percentage of the permissible daily noise dose**

The percentage of the permissible daily noise dose is defined in equation (A II-3). 100% of the dose corresponds to the permissible noise level over 8 hours. Although, the noise dose is not widely used, it is still required by several organizations such as the Occupational Safety and Health Administration, OSHA (1983).

$$D(Q) = 100 \times \left(\frac{T}{T_c}\right) \times 10^{\frac{L_{p.A.eqT_e} - Lc}{q}} dB \qquad \text{(A II-3)}$$

Where:

- $D(Q)$ is the percentage of the permissible daily noise dose;
- $L_{p.A.eqT_e}$ is the A-weighted equivalent continuous sound pressure level over the effective duration of the working day;
- $Lc$ is the permissible exposure level in dB(A);
- $Qc$ is the exchange rate in decibels (3,4, or 5);
- $q$ is $Qc/\log(2)$ i.e.(10, 13.29, or 16.61);
- $T$ is the effective duration of the working day in hours;
- $Tc$ is the criterion duration: 8 hours.

**Exposure points**

Noise dose can also be expressed in exposure points. They are calculated using equation (A II-3) but are expressed without a percentage. 100 exposure points correspond to the permissible exposure level ($L_{EX.8h}$) in dB(A). They are usually presented in a table with a range of noise levels on one axis and durations of exposure on the other. Figure II-2 adapted from L. Thiéry et P. Canetto (2009) presents a table of exposure points for a permissible exposure level of 85 dB(A), an exchange rate of 3 dB and a criterion duration of 8 hours.

**The A-weighted sound exposure**

The A-weighted sound exposure, $E_{A,T}$, is expressed in pascal squared seconds,$Pa^2.s$ (PASQUES) or in pascal squared hours,$Pa^2.h$. It corresponds to the transformation of decibels into acoustic energy. The sound exposure can be determined from A-weighted sound pressure levels using the equations (A II-4) and (A II-5) from Bruce *et al.* (2011).

$$p_{exp}{}^2 = 10^{\frac{L_p}{10}} \times p_{ref}{}^2 \; (Pa^2.s) \tag{A II-4}$$

$$E_{A,T} = p_{exp}{}^2 \times T \; (Pa^2.s) \tag{A II-5}$$

where:

- $p_{exp}{}^2$ is the square of exposure sound pressure;
- $p_{ref}{}^2$ is the square of exposure sound pressure $20\mu$ Pa;
- $L_p$ is the A-weighted sound pressure level;
- $E_{A,T}$ is A-weighted sound exposure;
- T is the length of exposure in seconds.

A-weighted sound exposure can also be directly calculated from $L_{EX.8h}$ using:

$$E_{A,T} = \left(p_{ref}{}^2 \times T_c\right) \times 10^{\frac{L_{EX.8h}}{10}} \; (Pa^2.h) \tag{A II-6}$$

where:

| Noise Levels | Exposure Duration of the activity/task | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| dB(A) | 8h | 4h | 2h | 1h | 30 min | 15 min | 10 min | 5 min | 1 min |
| 75 | 10 | 5 | 3 | 1 | 1 | 0 | 0 | 0 | 0 |
| 76 | 13 | 6 | 3 | 2 | 1 | 0 | 0 | 0 | 0 |
| 77 | 16 | 8 | 4 | 2 | 1 | 1 | 0 | 0 | 0 |
| 78 | 20 | 10 | 5 | 3 | 1 | 1 | 0 | 0 | 0 |
| 79 | 25 | 13 | 6 | 3 | 2 | 1 | 1 | 0 | 0 |
| 80 | 32 | 16 | 8 | 4 | 2 | 1 | 1 | 0 | 0 |
| 81 | 40 | 20 | 10 | 5 | 3 | 1 | 1 | 0 | 0 |
| 82 | 50 | 25 | 13 | 6 | 3 | 2 | 1 | 1 | 0 |
| 83 | 64 | 32 | 16 | 8 | 4 | 2 | 1 | 1 | 0 |
| 84 | 80 | 40 | 20 | 10 | 5 | 3 | 2 | 1 | 0 |
| 85 | 100 | 50 | 25 | 13 | 6 | 3 | 2 | 1 | 0 |
| 86 | 130 | 64 | 32 | 16 | 8 | 4 | 3 | 1 | 0 |
| 87 | 160 | 80 | 40 | 20 | 10 | 5 | 3 | 2 | 0 |
| 88 | 200 | 100 | 50 | 25 | 13 | 6 | 4 | 2 | 0 |
| 89 | 250 | 130 | 64 | 32 | 16 | 8 | 5 | 3 | 1 |
| 90 | 320 | 160 | 80 | 40 | 20 | 10 | 7 | 3 | 1 |
| 91 | 400 | 200 | 100 | 50 | 25 | 13 | 8 | 4 | 1 |
| 92 | 510 | 250 | 130 | 64 | 32 | 16 | 11 | 5 | 1 |
| 93 | 640 | 320 | 160 | 80 | 40 | 20 | 13 | 7 | 1 |
| 94 | 800 | 400 | 200 | 100 | 50 | 25 | 17 | 8 | 2 |
| 95 | 1000 | 510 | 250 | 130 | 60 | 32 | 21 | 11 | 2 |
| 96 | 1300 | 640 | 320 | 160 | 80 | 40 | 27 | 13 | 3 |
| 97 | 1600 | 800 | 400 | 200 | 100 | 50 | 33 | 17 | 3 |
| 98 | 2000 | 1000 | 510 | 250 | 130 | 60 | 40 | 21 | 4 |
| 99 | 2500 | 1300 | 640 | 320 | 160 | 80 | 50 | 27 | 5 |
| 100 | 3200 | 1600 | 800 | 400 | 200 | 100 | 70 | 33 | 7 |
| 101 | 4000 | 2000 | 1000 | 500 | 250 | 130 | 80 | 40 | 8 |
| 102 | 5100 | 2500 | 1300 | 630 | 320 | 160 | 110 | 50 | 11 |
| 103 | 6400 | 3200 | 1600 | 800 | 400 | 200 | 130 | 70 | 13 |
| 104 | 8000 | 4000 | 2000 | 1000 | 500 | 250 | 170 | 80 | 17 |
| 105 | 10000 | 5100 | 2500 | 1300 | 630 | 320 | 210 | 110 | 21 |
| 106 | 13000 | 6400 | 3200 | 1600 | 800 | 400 | 270 | 130 | 27 |
| 107 | 16000 | 8000 | 4000 | 2000 | 1000 | 500 | 330 | 170 | 33 |
| 108 | 20000 | 10000 | 5000 | 2500 | 1300 | 630 | 420 | 210 | 40 |
| 109 | 25000 | 13000 | 6400 | 3200 | 1600 | 790 | 530 | 270 | 50 |
| 110 | 32000 | 16000 | 8000 | 4000 | 2000 | 1000 | 670 | 330 | 70 |
| 111 | 40000 | 20000 | 10000 | 5000 | 2500 | 1300 | 840 | 420 | 80 |
| 112 | 51000 | 25000 | 13000 | 6300 | 3200 | 1600 | 1100 | 530 | 110 |
| 113 | 64000 | 32000 | 16000 | 8000 | 4000 | 2000 | 1300 | 670 | 130 |
| 114 | 80000 | 40000 | 20000 | 10000 | 5000 | 2500 | 1700 | 840 | 170 |
| 115 | 100000 | 51000 | 25000 | 13000 | 6300 | 3200 | 2100 | 1100 | 210 |
| 116 | 125000 | 64000 | 32000 | 16000 | 8000 | 4000 | 2700 | 1300 | 270 |
| 117 | 160000 | 80000 | 40000 | 20000 | 10000 | 5000 | 3300 | 1700 | 330 |
| 118 | 200000 | 100000 | 51000 | 25000 | 13000 | 6300 | 4200 | 2100 | 420 |
| 119 | 255000 | 125000 | 64000 | 32000 | 16000 | 8000 | 5300 | 2700 | 530 |
| 120 | 320000 | 160000 | 80000 | 40000 | 20000 | 10000 | 6700 | 3300 | 670 |

$L_{ex,8h} < 80$ dB(A)

$80 < L_{ex,8h} < 85$ dB(A)

$L_{ex,8h} > 85$ dB(A)

Figure-A II-2 Exposure points, adapted from L. Thiéry et P. Canetto (2009)

- $L_{EX.8h}$ is the A-weighted noise exposure level normalized to a nominal 8 hours working day;
- ${p_{ref}}^2$ is the square of exposure sound pressure: $20\mu$ Pa;
- $T_c$ is the criterion duration: 8 hours.

The main advantage of this metric is its ease of use. Unlike the sound pressure levels that require the use of a logarithmic operations, A-weighted sound exposure can be simply summed. The metric is recommended by several occupational and safety agencies such as the Health and Safety Executive (HSE) in England or the French Institute for Research and Security (INRS) and required in the standards ISO (1999) and ANSI (1996).

# ANNEX III

## NOISE EXPOSURE INSTRUMENTATION

### 1. How they work

Noise exposure instruments include sound level meters (SLMs), integrating sound level meters and noise dosimeters. This section provides an overview of how noise exposure instruments work with regards to the "noise measuring" features.

**Sound level meter and integrating sound level meter**

An omni-directional condenser microphone converts the sound pressure into an electric signal. A and C-weighting filters are then applied to audio signal. An RMS detector extracts the amplitude of the pre-amplified and frequency-weighted signal and averaged it over time. The basic sound level meter, also called "conventional" sound level meter comes with the "Fast" and "Slow" time averaging that respectively have an exponential time-constant of integration of 0.125 second and 1 second. Exponential time weighting originates from previous technical limitations when analogue circuits didn't allow computation of the true time-varying sound pressure over a time interval. Nowadays, the fast and slow time-averaging remain applied and are still required by several regulations.

Integrating sound level meters differentiate themselves from conventional SLMs as they measure equivalent continuous sound level ($L_{eq}$) with no-time-weighted averaging. After the RMS detection, sound pressure levels in dB are calculated using equation (A II-1). The integration duration varies depending on the type of measurement and is set by the user. Short $L_{eq}$ (0.125 second to 1 second long) are usually used to store and display the sound level data. An "overall" $L_{eq}$ corresponds to the equivalent continuous sound level over the total duration of a measurement, it can be computed from short $L_{eq}s$. Finally the SPL are displayed and stored in memory for some of the more sophisticated and expensive SLMs.Figure III-1 illustrates the main components of integrating SLM and basic SLM. The audio signal processing in the first sound level meters were all analogue electronics with a movable needle that displayed the SPL.

Today, most of the SLMs are digital electronic devices, the audio processing concepts remain the same except that the signal is fed to an analog-to-digital converter and the audio processing is digital.

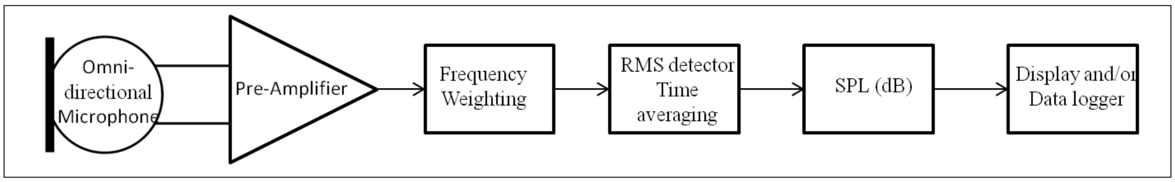



Figure-A III-1    Simplified block diagram of a sound level meter

**Noise dosimeter**

A noise dosimeter is a type of sound level meter that is specifically designed for measuring the noise exposure of an individual over a long period of time. Noise dosimeters feature the calculation of noise exposure metrics based on the sound pressure level, the measurement duration and others parameters specified by noise exposure regulations.

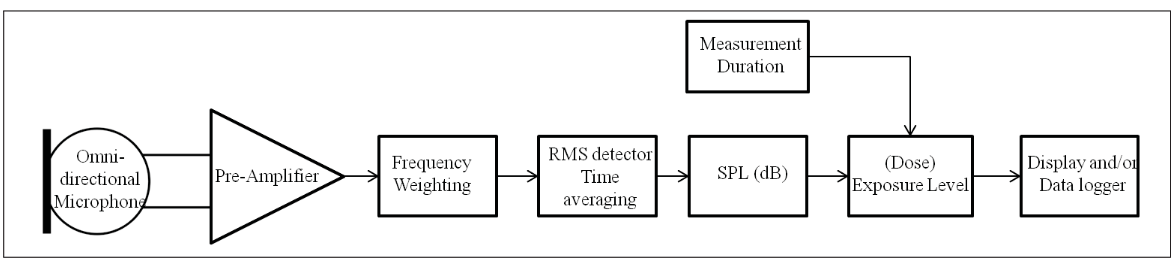



Figure-A III-2    Simplified block diagram of a noise dosimeter

## 2. Electro-acoustical characteristics and requirements

Table III-1 summarizes the standards' requirements for the main electro-acoustical characteristics. In ANSI (2007a), the requirements for the frequency and directional characteristics corresponds to the ANSI (2007b) tolerances for a Type-2 sound level meter. Generally, the requirements of the IEC an ANSI standards are compatible however they may differ in some details. For example, IEC (2003a) specifies that sound level meters are calibrated or an acoustic free field while ANSI (2007a) requires a random incidence calibration.

Tableau-A III-1 Requirements of noise instrumentation standards for the main characterisitcs

| Standard | Frequency response | Dynamic Range | Level linearity | Directivity |
|---|---|---|---|---|
| ANSI S1.43: 1997 | In a random sound field -Electrical and acoustical tests: 20 to 10 kHz. See III-3 | Type1: At least 60 dB, Type2: 50 dB | Type1:±0.7, Type2:±1 dB | 1)Variations ±22.5° from a angle of incidence. 2)Any angle of incidence |
| IEC 61672-Part 1 | Electrical or acoustical (Closed coupler, free or diffuse sound field) tests | At least 60 dB | Level linearity error: Class1 : ±1.1 dB, Class2 : ±1.4 dB | Variations ± 30, 90 and 150° from reference direction |
| ANSI 1.25 1991 [1] | Identical to Type2 ANSI S1.4: 1983 - In a diffuse sound field-Electrical and acoustical tests : 20 to 10 kHz | At least 50 dB | ±1 dB over the operating range | Identical to Type2 ANSI S1.4: 1983 . 1)Variations ±22.5° from a angle of incidence. 2)Any angle of incidence |
| IEC 61252: 1993 [2] | Relative to response at 1kHz - In a free field - Without an observer | "Sound level range shall extend at least from 80 dB to 130 dB" | -21 % to +26 % of the calculated sound exposure | No specifications for the response to sounds from various directions. |

[1] Directional and frequency responses tolerances are added
[2] Characteristics are evaluated using sound exposure in pascal-squared hours

Figure III-3 illustrates the frequency weightings' tolerance limits for Type-1 and 2 SLMs, from ANSI (2007b) and IEC (2002).

## 3. Evolution of noise dosimeters and current market overview

As stated by Alan Marsh (2012), the sound level meter together with the decibel unit were developed in 1928 by engineers from the Bell Telephone Laboratory and Johns-Manville for the

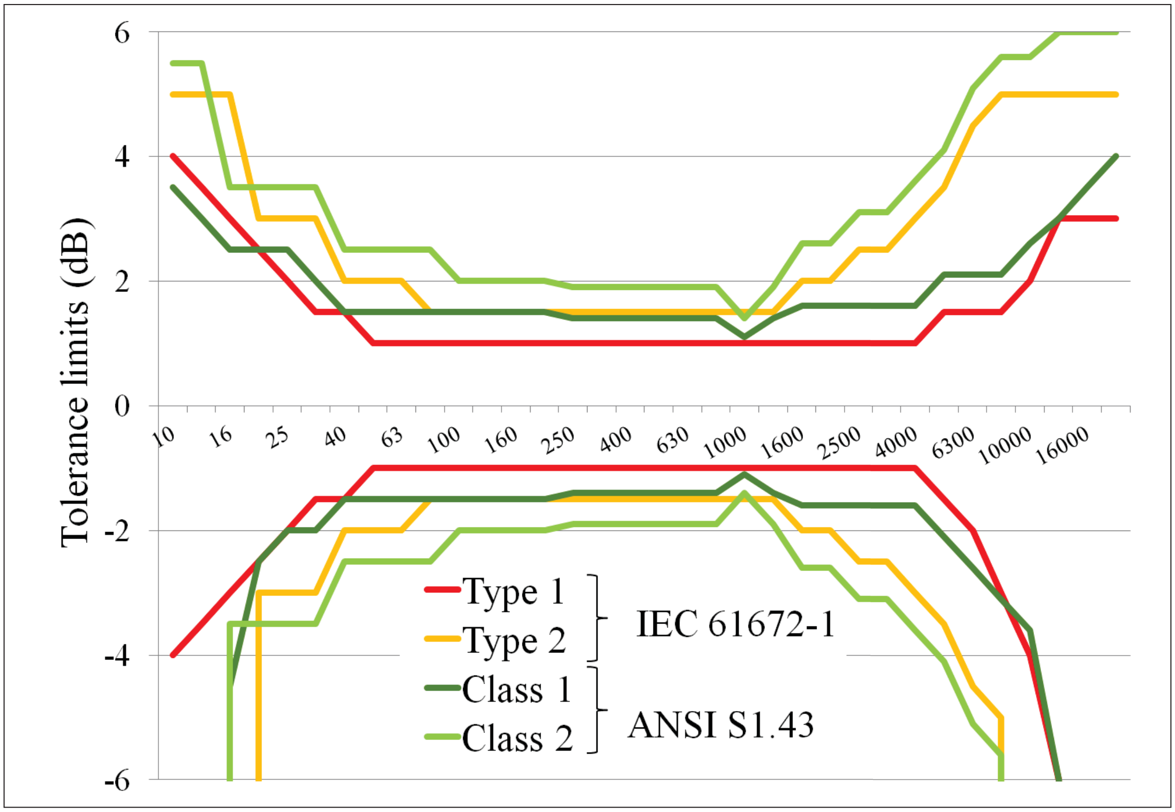



Figure-A III-3 Sound level meter frequency weightings' tolerance limits from ANSI (2007b) and IEC (2002)

New York City Noise Abatement Commission. The sound level meter was actually a collection of equipment weighing 25 kilos and all filled in a truck. In 1936, the first standard for the performance of a sound level meter was published by the recently-funded Acoustical Society of America. According to Giardino *et al.* (1976) and John P. Seiler (2008), in the 50s, the first commercial and portable sound level meters was manufactured by the General Radio Company and the first patents for a noise dosimeter appeared in 1955 and in 1956. In the 60s the first commercial noise dosimeters appeared together with new occupational noise regulations. According to Giardino *et al.* (1976), the noise surveys initially conducted with sound level meters were seen as a "tedious and time-consuming procedure", therefore the noise dosimeter was developed as a SLM that could be portable and directly worn by the person being tested in order to avoid errors caused by the SLM operator. The first noise dosimeter standard, ANSI S1.25-1978, marks the arrival of a new generation of dosimeters that supports field calibration and comes with a deported microphone. As stated by John P. Seiler (2008), the advent of the personal computer (in the 80s) has provided tools for the measurement analysis and visualization and the evolution of digital electronics has allowed manufacturers to increase the data storage capacity and the number of features in the dosimeters. In 1993, the first international standard for noise dosimeter, IEC (1993), proposed a new appellation for the noise dosimeter: personal sound exposure meter. Brauch (2008) identified four types of noise dosimeters in the history of its development:

- **Traditional dosimeters** are the original and most often used noise dosimeters. Their design originates from the 70s devices, with a small unit and a wired microphone carried by the worker. Design goals and electro-acoustic features of traditional dosimeters have not changed very much since the 70s. The more recent features improved the user-interface with PC-based tools for measurement download, analysis, visualization and data storage;
- **Integrated form factor dosimeters** are miniaturized instruments, intended to be shoulder mountable with intentionally limited internal display and controls. Typical examples are the doseBadge® from Cirrus Research or the dB Badge® from Casella;
- **Super dosimeters** are traditional dosimeters that integrate extra features such as frequency analysis, audio recordings or multi-channel measurements. Typical examples are the DC112® from CESVA, the SV 102® from Svantek and the QuietDose® from Howard Leight. The 2-channel noise "super dosimeters" allow microphone-in-real-ear measurements and evaluation of the HPDs attenuation, used in the continuous monitoring approach;
- **Dose indicators** are inexpensive noise dosimeters that provide a basic estimation of the noise dose with a limited accuracy since they don't comply with the standard requirements. They are used as a training or educational tool for hearing awareness program. They are as small or smaller than the "integrated form factor" type and they use flashing lights to display exposure risk. Examples are NI-100® from 3M, the PocketEar® from SoundEar A/S and the ER-200® from Etymotic.

Brauch (2008) introduces the FSC index that is a combination of the number of features of dosimeters (F), the size and complexity (S) and the cost (C). Figure III-4, adapted from Brauch (2008), places the recent dosimeter types with their FSC index. The noise dosimeter development is lead by several manufacturers including:

- Bruel & Kjaer (Denmark);
- Casella CEL Ltd.(United Kingdom);
- Cirrus France Ltd. (United Kingdom);
- Pulsar Instruments plc (United Kingdom);
- Quest Technologies Inc. (USA);
- 01dB-Metravib (France).

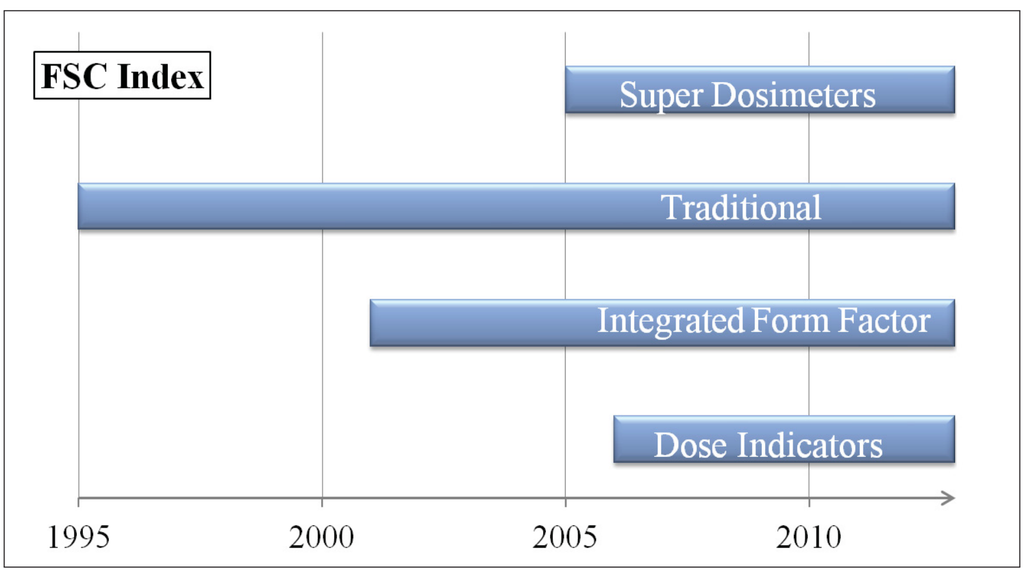



Figure-A III-4 Recent trends in noise dosimeter development

Brauch (2008) characterizes the noise dosimeter market in the US as a "replacement market". According to Brauch (2008), the two major reasons that explain the decrease of the overall demand for noise dosimeters are the "decreased industrialization" and the decreased health and safety budget. Since the first noise dosimeter in the 60s, several type of dosimeters have been developed in response to the different market needs and to the evolution of standards requirements, recent trends in noise exposure assessment require the use of elaborated "super" dosimeters.

## ANNEX IV

## NON-STANDARDIZED METHODS FOR THE DETERMINATION OF THE OCCUPATIONAL NOISE EXPOSURE

### 1. Three-levels approach

To assess the occupational noise exposure risk, L. Thiéry et P. Canetto (2009) recommended a progressive 3-levels approach:

- Level 1 relies on estimations using rules that do not require any noise measurement and that are based on communication tests or noise exposure databases;
- Level 2 relies on simplified evaluations based on short-duration noise measurements and exposure duration data;
- Level 3 relies on standardized methods including a specific sampling strategy

Figure IV-1, translated from L. Thiéry et P. Canetto (2009), illustrates the interactions between the three levels of the noise exposure risk evaluation. The noise exposure values and noise exposure reduction actions illustrated in the figure are based on the French noise exposure regulation, France (2008), for which the lower and the upper exposure action values are 80 and 85 dB(A) respectively and the permitted noise exposure level is 87 dB(A). U corresponds to the expanded uncertainty of the measured A-weighted equivalent continuous sound pressure level. The approach aims to reduce the cost and effort of the noise exposure assessment. The first two levels help identify the most obvious situations: either low noise exposure with no risk, or a high noise exposure that implies an obvious risk. During the first two levels of the approach, if a noise exposure risk is obvious, a noise reductions program is directly implemented without conducting standardized measurements, therefore saving time and money.

Malchaire (2000) proposed a progressive 3 stage strategy, "for prevention and control of the risks due to noise" that aims to focus on preventive and noise control solutions rather than only

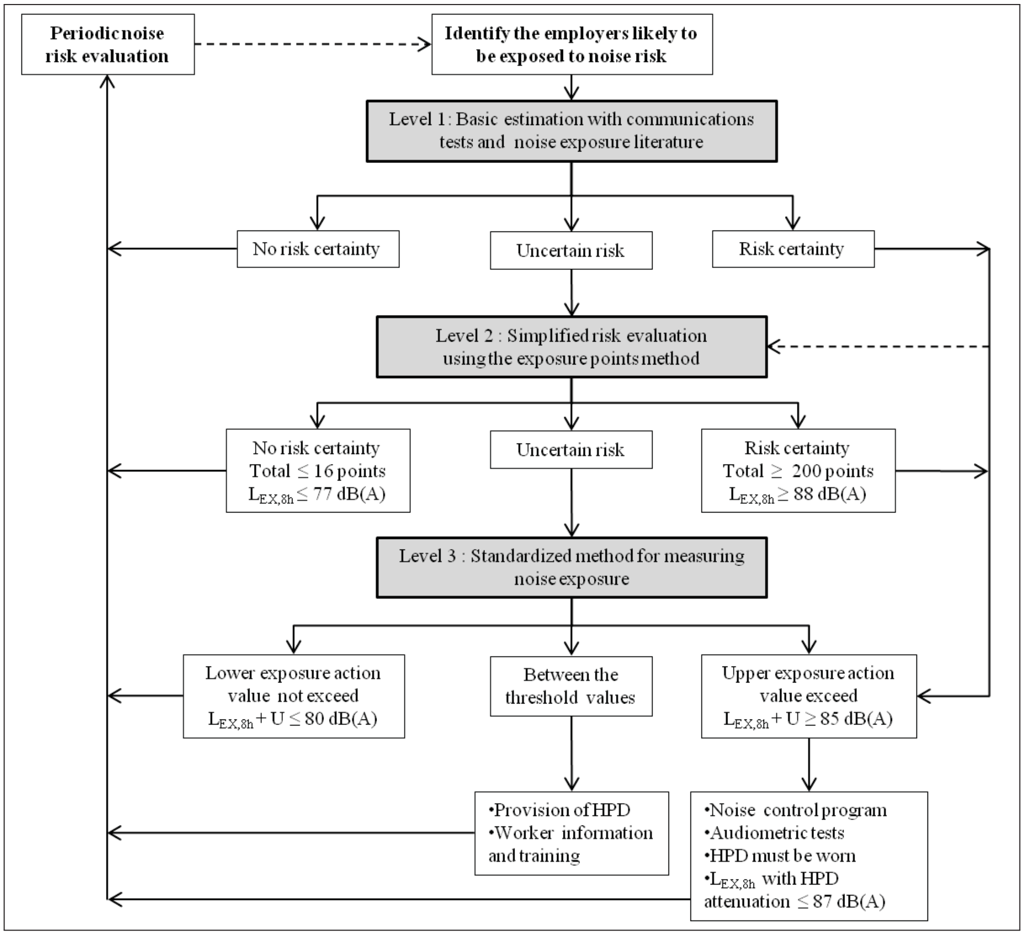



Figure-A IV-1 Translated from L. Thiéry et P. Canetto (2009), noise exposure risk evaluation with the 3 levels approach proposed by INRS

noise exposure assessment. First, the observation stage is based on quick and straightforward investigations from employees and does not require any specialist involvement or any acoustic knowledge. Second, the analysis stage aims to find technical solutions that may require noise exposure measurements and involvement of specialists to identify technical solutions. Third, if needed, the expertise stage may imply expert involvement. Both approaches proposed by Malchaire (2000) and L. Thiéry et P. Canetto (2009) are participatory approaches where workers' involvement is essential. The OSHA (2013) online "Noise and hearing conservation" documentation describes two additional preliminary steps that should be performed prior to any noise monitoring program: "Indications of a Problem" which is similar to the Level 1 of the L. Thiéry et P. Canetto (2009) approach with communication tests and the "Walkaround

Survey" which is a simplified evaluation of noise exposure very similar to Level 2 of the L. Thiéry et P. Canetto (2009) approach.

Basic evaluations based on communication tests and noise exposure databases are presented in section 2 and simplified evaluations are discussed in further detail in section 3.

## 2. Basic evaluation

The basic evaluation aims to provide easy and free-measurement tests for evaluating noise levels and identify high risk employees.

**Communication tests**

Communication tests allow the approximation of noise levels based on the difficulty of communicating in a noisy place. Table IV-1 summarizes several communication tests found in the literature with their associated noise level and the hearing loss risk.

**Noise exposure database**

Noise exposure databases usually contain noise exposure values by occupational category or the sector of activity. According to Hohmann (2008), the Swiss National Accident Insurance Fund has developed a noise database intended for the small and medium-sized enterprises. The database covers a large variety of industries and contains both noise levels data (with $L_{eq.A}$ values) and noise exposure data (with $L_{EX.8h}$ values). The noise data also comes with recommended hearing conservation actions. Noise level database when combined with exposure duration data, can be used as a simple method for the evaluation of noise exposure. Several noise level databases have been documented in the literature:

- Noise level data collected by NIOSH (1998) presents the proportion of workers by occupational category and economic sub-sector exposed to noise levels greater than 85 dB(A);
- According to Concha-Barrientos M, Campbell-Lendrum D (2004), the Canadian Center for Occupational Health and Safety (CCOHS) used to provide a noise level database for

Tableau-A IV-1 Communication tests for evaluating noise level with their associated noise level and hearing loss risk

| Test description | Noise level | Hearing-loss risk | Reference |
|---|---|---|---|
| Having to raise their voices to carry out a normal conversation when about 2m apart for at least part of the day | | Probably need to do something about the noise | HSE |
| Having to shout or having a lot of difficulty to be understood by someone at less than 1m | $L_{eq} > 90dB(A)$ | Certain risk | L. Thiéry et P. Canetto (2009) |
| Having to shout or having a lot of difficulties to be understood by someone at less than 2m | | Incertain risk | |
| Being able to communicate normally with someone at 0.5m | | Certain no-risk | |
| Having to shout to be clearly understood by someone at 1m | $L_{eq} > 82dB(A)$ | | BC Worksafe (2007) |
| Having to shout to be clearly understood by someone at 0.5m | $L_{eq} > 88dB(A)$ | | |
| Speaking "loud" to be understood at a distance of 0.5m | 70 | High discomfort | Malchaire (2000) |
| Speaking "very loud" to be understood at a distance of 0.5m | 85 | Low risk | |
| Shouting to be understood at a distance of 0.5m | 90 | Medium risk of hearing loss | |
| Maximum shouting | 100 | High risk | |

a large variety of workplaces, occupational categories and activities, unfortunately, at the time of writing, the noise database was no longer available.

Recent studies such as Choi *et al.* (2012), Sjöström *et al.* (2013) have led to the development of a specific noise exposure database called Job-Exposure matrix (JEM) that contains noise exposure data for several types of job families.

## 3. Simplified evaluation

As illustrated in Figure IV-1, the simplified evaluation is conducted if the evaluation of the hearing loss risk is uncertain. The approach aims to provide an easy-to-use evaluation of the overall noise exposure and a classification of the different phases of a working day, based on noise level measurements and exposure duration data. The working day is divided into different tasks and a number of exposure points is determined for each task. For each task, the number of exposure points is obtained based on a noise level in dB(A) and the task exposure duration and using an exposure points table (Figure II-2). The addition of each task exposure points gives an estimation of the daily noise exposure with 100 exposure points that corresponds to the permissible exposure level ($L_{EX.8h}$) in dB(A). The main advantage of the simplified evaluation is the ease of use: exposure points can be simply added without using the decibel notation.

With the same goal of simplicity, the "walkaround survey" recommended in OSHA (2013) consists in mapping the workplace with noise levels measured at different locations and estimating the noise exposure based on the noise map and the employees' locations during the day. The modest sampling associated with the simplified evaluation limits the accuracy of the estimated noise exposure and if the results of the evaluation get too close to the regulatory limits, one cannot conclude the degree of non-compliance and in this case, standardized measurements are conducted.

# ANNEX V

## NOISE EXPOSURE AND SPATIAL SAMPLING WITH TRACKING TECHNOLOGIES

Looking at occupational noise practices, noise maps are mostly used as visualization tools to help localize the noisiest sources and monitor noise emission from machines or processes. Based on ambient noise levels at fixed locations or on workplace acoustic simulations, noise maps remain limited at accurately evaluating noise exposure. In practice, their main disadvantages is that they can be time-consuming and they require dedicated softwares.

In addition to noise mapping, spatial sampling methods like the OSHA "Walkaround survey", described in section 3, also take into account the worker's locations and the noise level variations along the workday. Ambient noise levels may differ greatly from noise dosimeters measurements. Moreover, surveyors' observations or worker's questionnaires used to assess workers' locations during the measurement may introduce errors. This issues restrain the use of spatial sampling for assessing accurately personal noise exposure and probably explained why no measurement standard describes spatial mapping.

Recently developed methods use tracking technologies to monitor workers' displacements and from them, evaluate the noise exposure based on fixed noise measurements. The main advantages of these methods are that they do not interfere with the workers' activity (compared to standardized methods) and they reduce time and costs of the collection and analysis of noise measurements and workers' activities.

Huang *et al.* (2010) used a radio frequency identification (RFID) technology system to records workers' real-time location. The layout of a steel manufacturing plant was split into "zones" and noise instruments were set up at the center of each zone. Each time a worker went in and out of a "zone", the system recorded the time of entrance and exit, the duration spent in the zone and the noise levels measured by the noise sensing unit associated with the zone. The accuracy of the RFID method to evaluate time activity pattern was compared to methods using surveyors observations and workers' questionnaires. Based on a study of 4 days with 8 workers, Huang *et al.* (2010) stated that the RFID system provided an accurate monitoring of the worker activity as the estimation of the time activity pattern with the RFID method was greater than with the questionnaire method. Huang *et al.* (2010) showed that the noise exposure ($L_{EX.8h}$) evaluated from the RFID method differs from the traditional full-day noise exposure assessments (based on noise dosimeters) by 1.2 dB(A). They conclude that : " for the microenvironment with stable noise, an accurate monitoring of the worker TAP [time activity pattern] will lead to accurate estimation of worker's noise exposure dose".

A patent by Devinant (2008) describes both a device and a method that evaluate a person's noise exposure using noise exposure duration data, fixed noise level measurements. The entrance and exit of a person in a noisy location is determined using an RFID technology or human recognition systems. The noise exposure calculation is based on the person's duration exposure and noise levels measured by noise sensors located in the place but the patent describes other factors that can also be considered such as:

- The ears recovery based on the person's hearing health background;
- The use of earplugs ;
- The use of portable audio player;
- The difference of location between the person surveyed and the noise sensing unit.

Although the system is presented by Devinant (2008) as accurate and reliable, the patent does not provide experiment results.

# ANNEX VI

## NOISE LEVEL CORRECTION ALGORITHM

```
public float findInCalibrationTableA(float leqA, float leqC) {
        float C_Ap = leqC - leqA;
        int auxc = (int)(C_Ap*10);
        C_Ap = auxc/10f;//round 1 decimal
       %xmin, ymin, xmax, ymax correspond to the minumum and maximum ...
          dBA and C-A values in the lookup table
        int  index=(int) ((leqA-xmin)*10);
        int  indey=(int) ((C_Ap-ymin)*10);
    % indey and index correspond to the coordinates of  lookup table
   % indeyMax and indexMax corespond to the number of dBA values  ...
      andC-A values  in the lookup table
   %caliA[indey][index] is the lookup table, stored  in the java ...
      class as a variable
            if (index < 0){
                if (indey<0) {leqAcal = leqA+caliA[0][0]; }
                else {
                        if (indey> indeyMax){leqAcal = ...
                           leqA+caliA[indeyMax][0];}
                        else {if (indey≤ indeyMax){leqAcal = leqA + ...
                           caliA[indey][0]; }}}}

            if  (index  > indexMax) {
                if (indey< 0) {leqAcal = leqA+caliA[0][indexMax]; }
                else {
                    if (indey> indeyMax){ leqAcal = ...
                       leqA+caliA[indeyMax][indexMax];}
                    else {if (indey≤ indeyMax){leqAcal = ...
                       leqA+caliA[indey][indexMax]; }}}}
            if (index ≥ 0 && index  ≤ indexMax){
                if (indey< 0) {leqAcal = leqA+caliA[0][index]; }
```

```
                else {
                if (indey> indeyMax) {leqAcal = ...
                   leqA+caliA[indeyMax][index]; }
                else {
                if (indey≥ 0 && indey ≤ indeyMax){ leqAcal = ...
                   leqA+caliA[indey][index]; }}}}
        return leqAcal;
          }
```

## ANNEX VII

## INTERPOLATION OF NOISE LEVEL CORRECTIONS, VISUAL EVALUATION OF THE INTERPOLATION METHODS

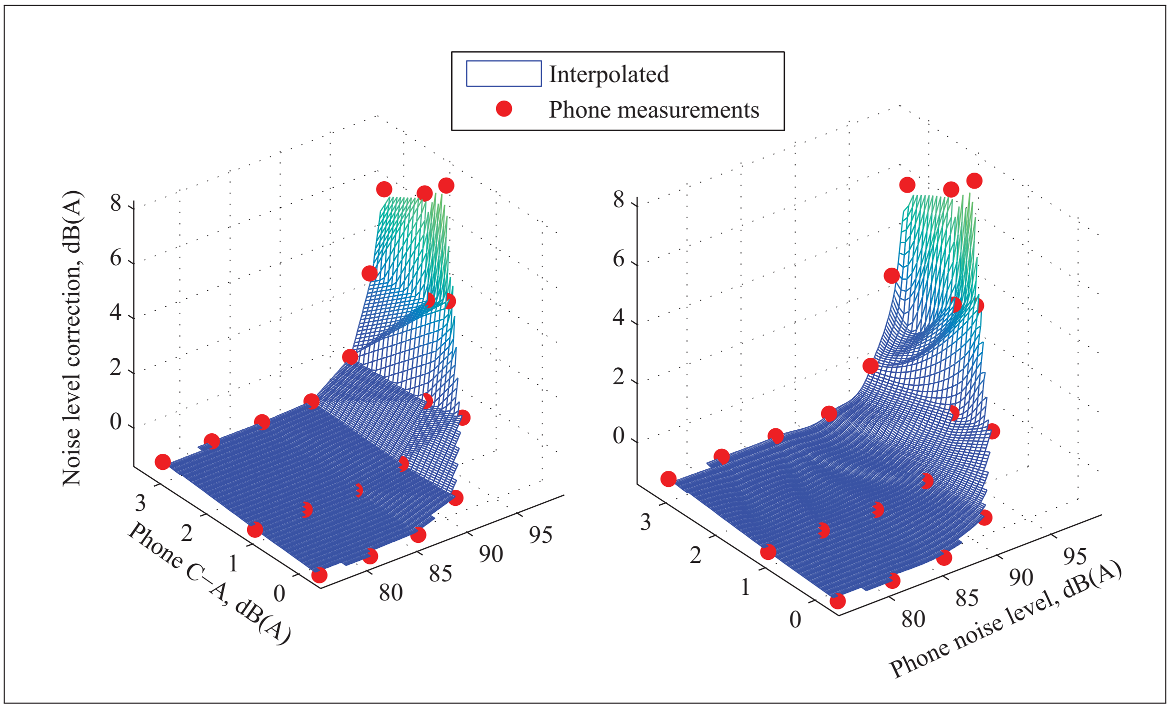



Figure-A VII-1 Built-in microphone measured noise level correction values (in red) and interpolated values with the *griddata* MATLAB function and the *linear* and *cubic* methods

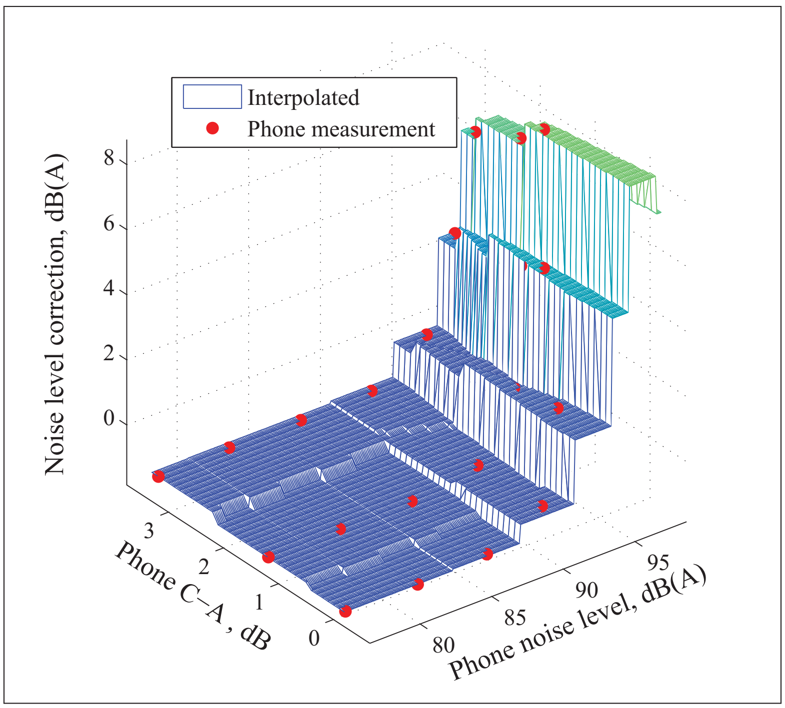



Figure-A VII-2 Built-in microphone measured noise level correction values (in red) and interpolated values with the *griddata* MATLAB function and its *nearest* method

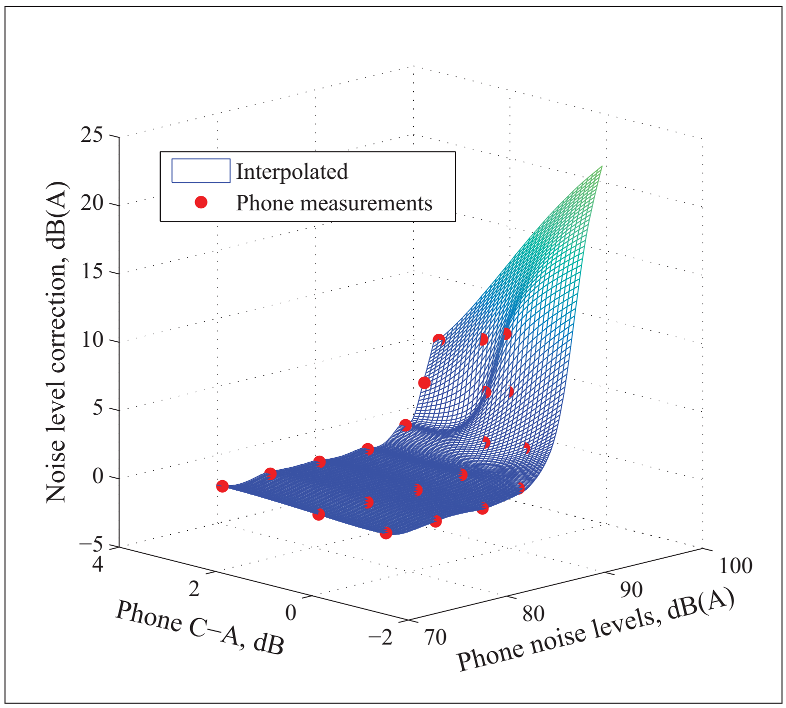



Figure-A VII-3 Built-in microphone measured noise level correction values (in red) and interpolated values with the *griddata* MATLAB function and its *v4* method

# ANNEX VIII

## NOISE LEVEL CALIBRATION MEASUREMENTS

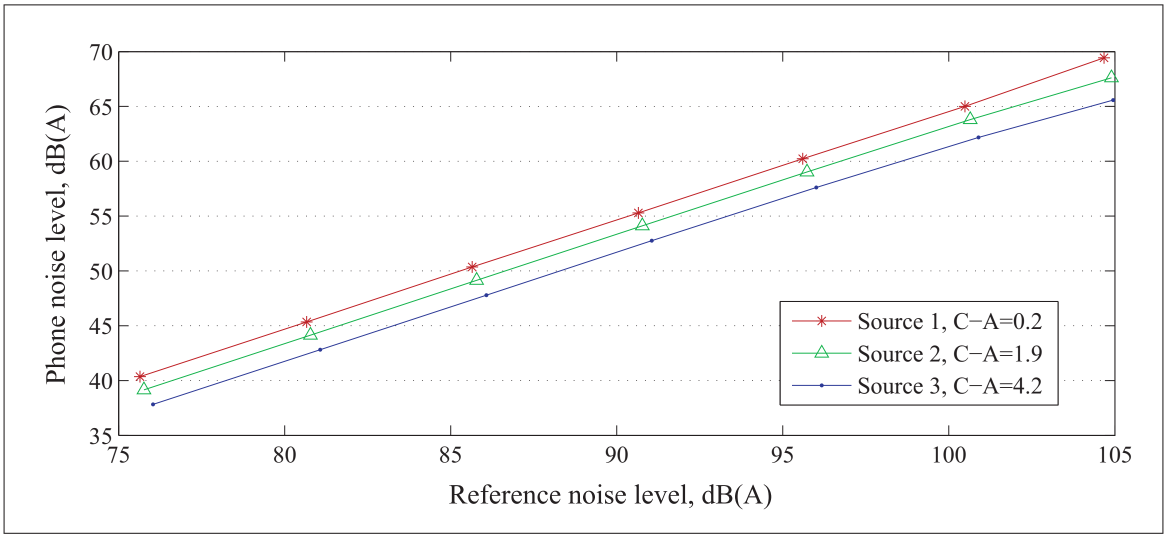



Figure-A VIII-1 Uncalibrated mobile phone noise levels measured with the earpiece, as compared with the reference noise levels while measuring Source 1, 2 and 3 in the semi-anechoic chamber

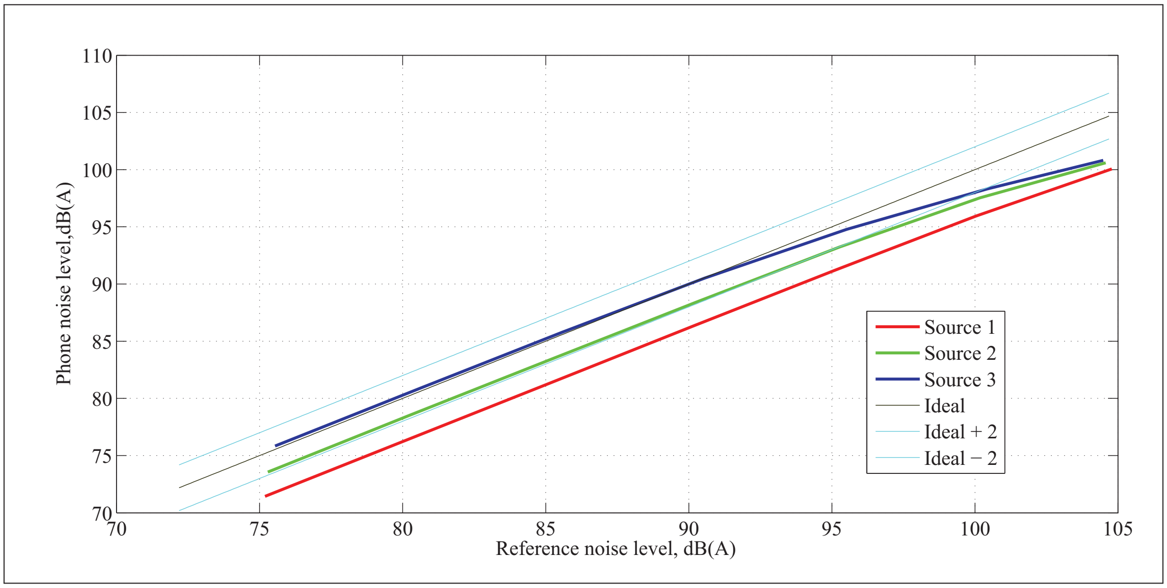



Figure-A VIII-2 Phone noise levels measured with the earpiece, as compared with the reference noise levels while measuring Source 1, 2 and 3 in the semi-anechoic chamber with the phone implementing the frequency-dependent calibration algorithm

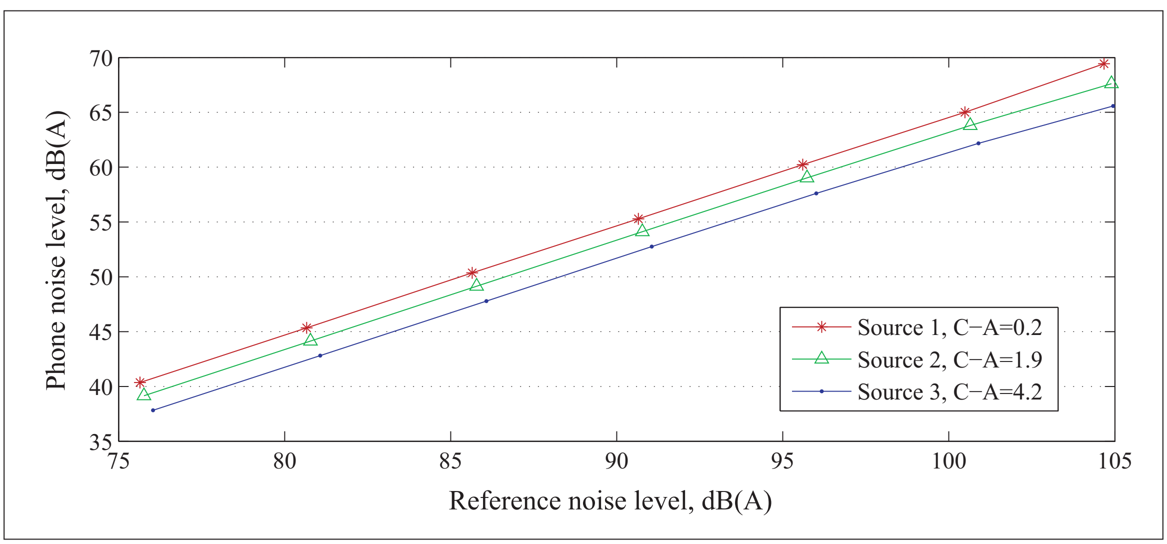



Figure-A VIII-3 Uncalibrated mobile phone noise levels measured with the headset, as compared with the reference noise levels while measuring Source 1, 2 and 3 in the semi-anechoic chamber

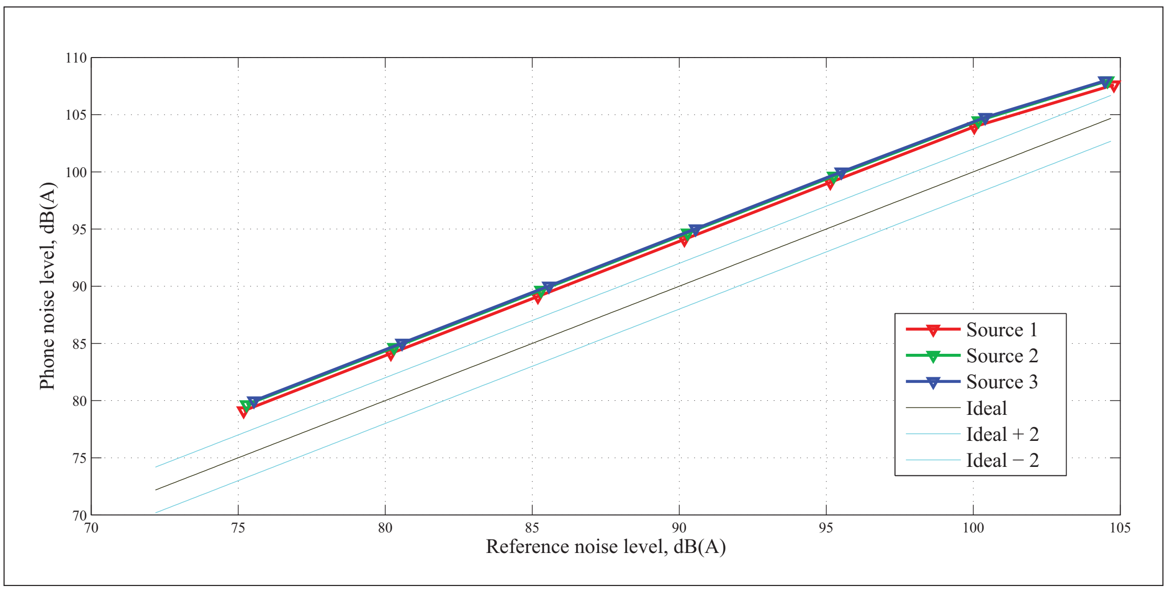



Figure-A VIII-4 Phone noise levels measured with the headset, as compared with the reference noise levels while measuring Source 1, 2 and 3 in the semi-anechoic chamber with the phone implementing the frequency-dependent calibration algorithm

## ANNEX IX

## NOISE LEVEL VALIDATION MEASUREMENTS

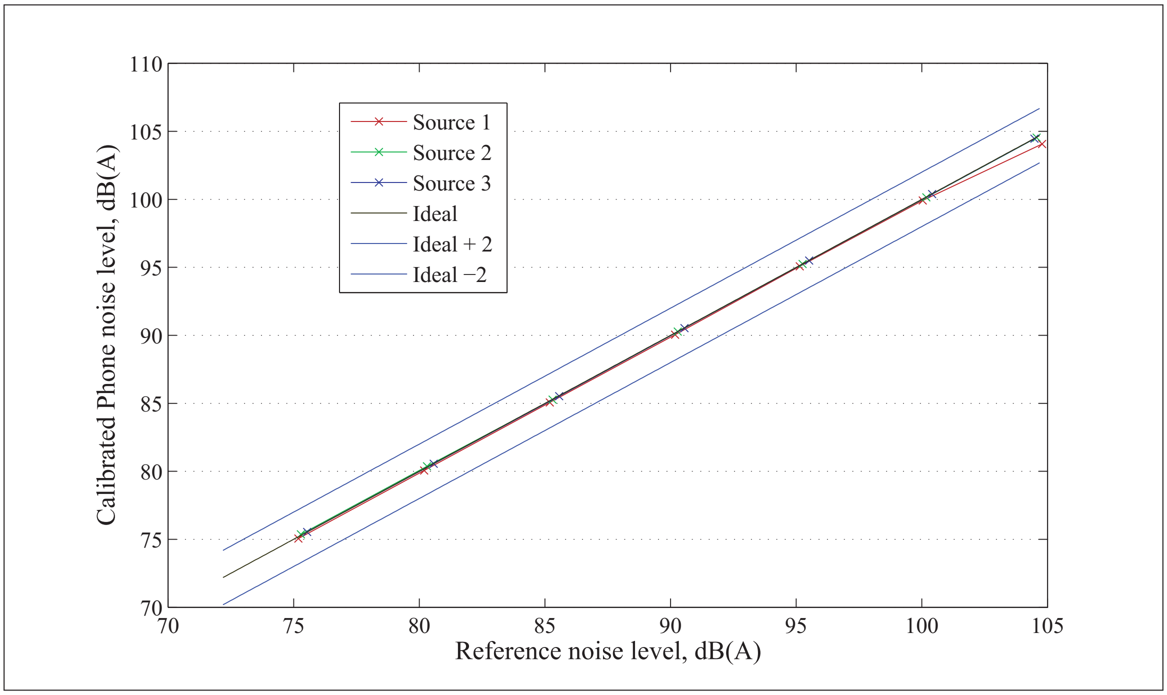



Figure-A IX-1 Calibrated noise levels in dB(A), measured with the headset microphone, right after the calibration measurement

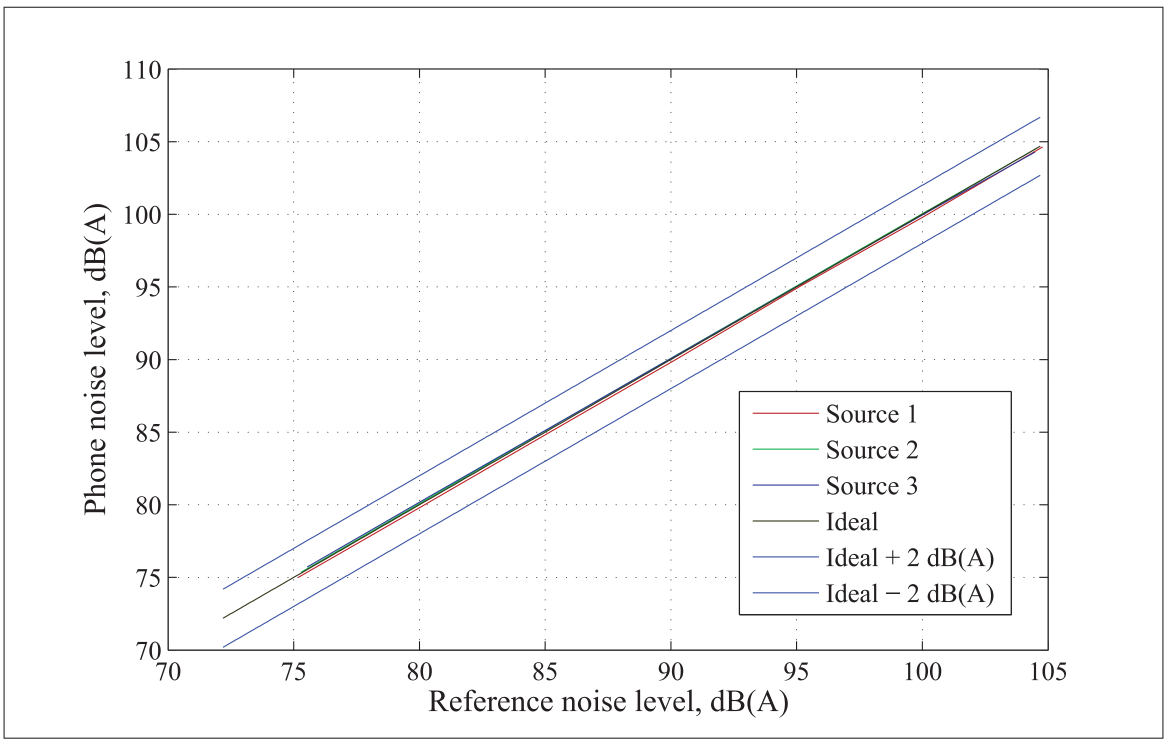



Figure-A IX-2 Calibrated noise levels in dB(A), measured with the headset microphone, right after the calibration measurement

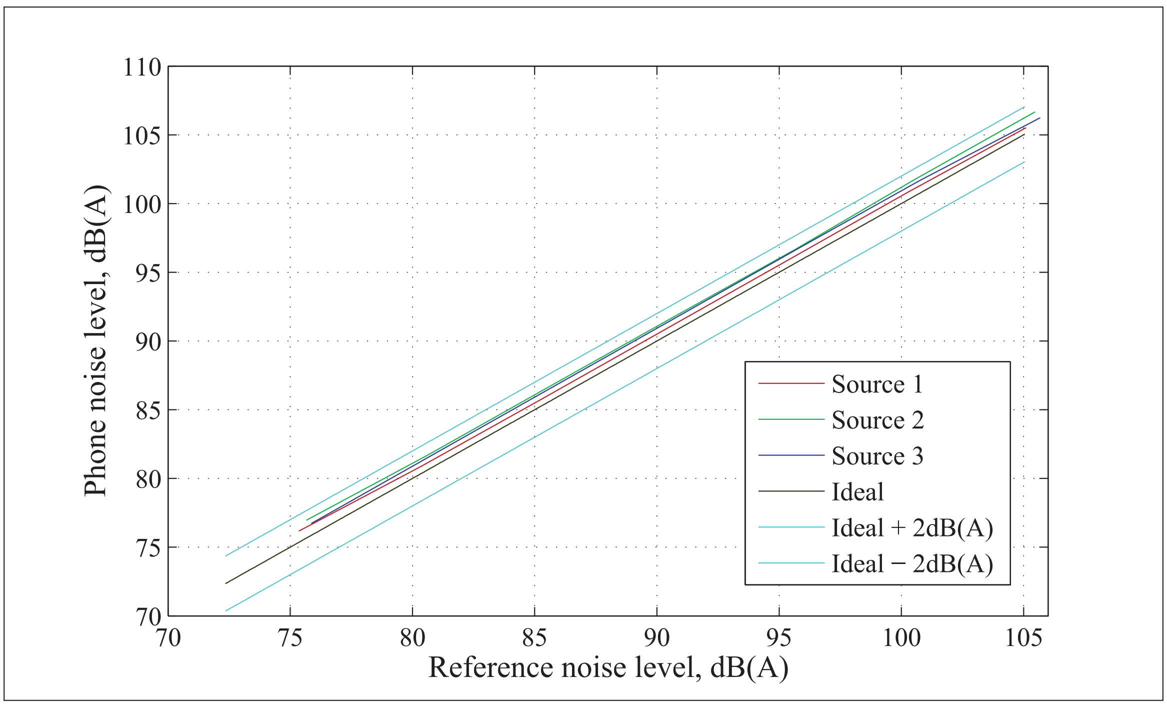



Figure-A IX-3 Calibrated noise levels in dB(A), measured with the headset microphone, right after the calibration measurement

# ANNEX X

# MATLAB SCRIPTS, CALIBRATION MEASUREMENTS AND ANALYSIS

## 1. Frequency-dependent algorithms

```
%%  FIR design Script
     % firls
 %(FIR)
% H3m is the results of the calculation of the transfert function
% vector of complex numbers
% fm is the vector frequencies associated with H3m
H3m = H3m1'; fm=fm1;
% To improve the fitting :
% The very low frequency content is not considered
% The first frequencies are skipped with:
% DeleteBegin, it must be an even number! usually between 7 and 11
DeleteBegin=11;
an = (fm(1,DeleteBegin:end)./max(fm(1,DeleteBegin:end)));
% nbcoefs determines the number of coefficients of the designed filter
% even number msut be used !
nbcoefs = 21;
% bs, vector that contains the coefficients
bs = firls((nbcoefs-1),an,abs(H3m(1,DeleteBegin:end)));
% display
[ht,ft] = freqz(bs,1,1024,Fs);
plot1=semilogx(ft,20*log10(abs(ht))),hold on;figure(gcf);
plot2 ...
   =semilogx(fm(1,DeleteBegin:end),20*log10(abs(H3m(1,DeleteBegin:end))));
                 legend('firls', 'TF');
set(plot1,'Color',[0.749 0 0],'DisplayName','filter');
set(plot2,'Color',[0 0.4902 0],'DisplayName','TF built-in phone 1');
```

```
% From matlab FIR coefficients to  java (for import to  the Android app)
format long
datName = 'coefs.txt';
seperator1 = ',';
seperator2 = '\n';
datei = fopen(datName,'w');
%coefs : bs in matlab
fprintf(datei,'new float[] {');
for z=1:size(bs,2)
        pp=('bs(1,z)');
        var = eval(pp);
        if isnumeric(var) == 1
            var = num2str(var,16);
            fprintf(datei,var);
            fprintf(datei,'F');
            if z<size(bs,2)
            fprintf(datei,seperator1);
            end
        end
end
  fprintf(datei,seperator2);
  fprintf(datei,'}));');
  fprintf(datei,seperator2);
  fclose(datei);
```

```
% TF calculation and  IIR design
% H3m1 is the results of the calculation of the transfert function
% fm1 is the vector frequencies associated with H3m

%pre-processing before the calculation of the TF
 [phone ref]= myfuns.cale_vect(mes_phone,mes_ref);
  % TF calculation
[fm1,fbo1,H3m1,H51,C3m1,C51] = wavtotrans(phone',ref',Fs,2048);
```

```
% IIR design
ordre = 12;
cut=370;
begin=9;
ang = (2*pi().*fm1)./Fs;
[b,a] = invfreqz(H3m1(begin:end-cut),ang(begin:end-cut),
                        ordre,ordre,[],'iter','tol');
[ht,ft] = freqz(b,a,2048,Fs);
semilogx(ft,20*log10(abs(ht)),fm1, 20*log10(abs(H3m1)));figure(gcf);
legend('Frequency response of calculated filter', 'transfer function ...
   measured')
xlim([60 16000]);
```

```
% From matlab IIR coefficients to  java (for import to  the Android app)
format long
datName = 'coefs.txt';
seperator1 = ',';
seperator2 = '\n';
datei = fopen(datName,'w');
%coefs a
fprintf(datei,'new float[] {');
for z=1:size(a,2)
        pp=('a(1,z)');
        var = eval(pp);
        if isnumeric(var) == 1
            var = num2str(var,16);
            fprintf(datei,var);
            fprintf(datei,'F');
            if z<size(a,2)
            fprintf(datei,seperator1);
            end
        end
end
  fprintf(datei,'}');
```

```
  fprintf(datei,seperator1);
  fprintf(datei,seperator2);
  %coefs b
fprintf(datei,'new float[] {');
for z=1:size(b,2)
        pp=('b(1,z)');
        var = eval(pp);
        if isnumeric(var) == 1
            var = num2str(var,16);
            fprintf(datei,var);
            fprintf(datei,'F');
            if z<size(b,2)
            fprintf(datei,seperator1);
            end
        end
end
  fprintf(datei,'}));');
  fprintf(datei,seperator2);
  fclose(datei);
```

## 2. Noise level-dependent algorithms

```
% Interpolation of noise level corrections from the phone A-weighted ...
    and C-weighted noise levels
% sort the values by the dBA values
sortmatrix= [CorrA CorrC dBAp dBCp (dBCp-dBAp)];
sortmatrix = sortrows(sortmatrix , 1);
X=sortmatrix(:,3); % 3:dBAp, 4:dBCp
Y=sortmatrix(:,5); % C-A phone
Z=sortmatrix(:,1); % 1:corrA, 2:corrC
%Preparation for the interpolation method
[XI,YI] = meshgrid(round(min(X)*10)/10+3:.1:round(max(X)*10)/10,
     round(min(Y)*10)/10:.1:round(max(Y)*10)/10) ;
```

```
input = [X Y ];input=input';
% interpolation 3D
ZI = griddata(X,Y,Z,XI,YI,'v4'); Vqreuf = ZI;
% displays the interpolation and the measured noise levels
figure();
mesh(XI,YI,Vqreuf),hold on;
scatter3(X,Y,Z);
```

# ANNEX XI

# DATA SHEET OF THE EARPIECE MICROPHONE

# Data Sheet

RoHS 2002/95/EC

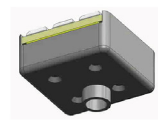
## microphone 66AF31

3600 - 3021183

Version:1 27-NOV-2009

### Description

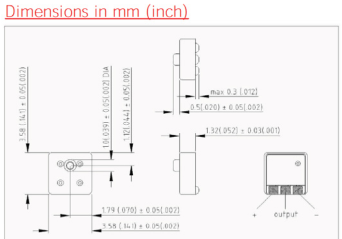
Miniature electret condenser microphone for hearing instruments with integrated capacitors and an integrated amplifier to decrease sensitivity for high frequency spurious signals.



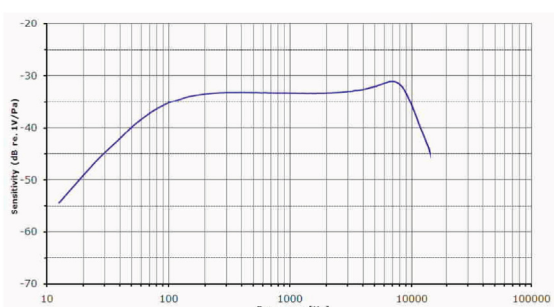
### Features

- Integrated cellular protection (superior EMI suppression)
- Low noise CMOS amplifier
- Better matching stability
- Reduced power supply feedthrough
- High dynamic range
- Performance parameter independent of supply voltage
- Improved vibration sensitivity

### Dimensions in mm (inch)




### Typical response curve




Sonion reserves the right to make changes at any time to improve reliability, function or design, in order to provide the best product possible.

SONION



Figure-A XI-1

# Data Sheet

RoHS 2002/95/EC

## microphone 66AF31

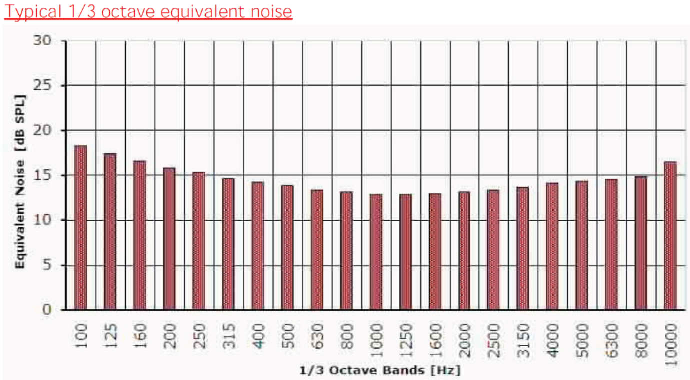
3600 - 3021183
Version:1 27-NOV-2009

### Specification

All parameters are specified at 0.9 V and 1 MOhm load impedance, AC-coupled with 1μF, unless specified otherwise.
Environmental conditions: 23 °C (73.4F), 50 % RH

| Parameters | | Min | Typ | Max | Unit | Comments |
|---|---|---|---|---|---|---|
| Sensitivity | @ 80 Hz | -6 | -3 | 0 | dB | re. 1 kHz value |
| | @ 1 kHz | -36.5 | -33.5 | -30.5 | dB | re. 1V per Pascal |
| | @ 7 kHz | 0 | 3 | 6 | dB | re. 1 kHz value |
| Peak frequency | | | 7 | | kHz | Approx. |
| Equivalent noise (A-weighted) | | | 27 | 29.5 | dB SPL | |
| Power supply feedthrough | | | -33 | -30 | dB | |
| Battery voltage range | | 0.8 | 0.9 | 3 | VDC | |
| Battery drain | | 28 | 30 | 35 | μA | |
| Output impedance | | 3.6 | 4.1 | 4.6 | kOhm | |
| Input-referred vibration sensitivity | | | 53 | 63 | dB SPL/g | 1 kHz ref. acc. in axial direction |
| Humidity coefficient of sensitivity | | | 0.02 | | dB/%RH | |
| Input-referred EMI noise | 0.8-0.96 GHz | | | 30 | dB SPL | according SMI 255, E=75 V/m |
| | 1.8-2.0 GHz | | | 30 | dB SPL | according SMI 255, E=50 V/m |
| Operating temperature range | | -17 | 23 | 63 | °C | |
| Storage temperature range | | -40 | | 63 | °C | |
| ESD protection level: Class 2 according to MIL-STD-750D, test method 1020,2. Apply protection in accordance with IEC 61340-5-1 and 61340-5-2. | | | | | | |

### Typical 1/3 octave equivalent noise




Sonion reserves the right to make changes at any time to improve reliability, function or design, in order to provide the best product possible.

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Figure-A XI-2

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