The development of a REAT test facility and an evaluation of hearing protector assessment methods

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Abstract

This thesis is concerned with assessing the acoustic performance of hearing protection devices (HPDs).

A facility was developed to assess HPDs in accordance with the real-ear attenuation at threshold (REAT) method described in AS/NZS 1270: 2002. The facility met all requirements of AS/NZS 1270: 2002 with the exception of the distortion requirements at low sound pressure levels.

AS/NZS 1270: 2002 was reviewed by comparison to international standards and the literature, with consideration of the REAT test facility development. The maximum background noise levels in AS/NZS 1270: 2002 are considered to be too high and the specifications at low sound pressure levels are considered to be impractical. Revised maximum background noise levels and an alternative specification for the assessment of low sound pressure levels are proposed.

The REAT, microphone-in-real ear (MIRE) and acoustical test fixture (ATF) HPD assessment methods were employed to assess conventional earplugs and earmuffs, a level-dependent earmuff, an active noise reduction (ANR) headphone and an abrasive blasting helmet using continuous noise and an insertion loss paradigm. The MIRE method showed the best agreement with the REAT method for conventional earmuffs. The ATF method was most useful for the assessment of the level-dependent earmuff and the ANR headphone at elevated noise levels.

A field assessment method for HPDs was explored by instrumenting a single cup of a pair of earmuffs. The prototype device was used to assess the effect of safety glasses and a thin woollen helmet liner worn beneath earmuffs. The implementation was used to identify the variation in earmuff attenuation with noise from various directions and estimate the real-ear attenuation of an earmuff worn in combination with common field artefacts.

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1. Introduction

Determining the total noise exposure of a person wearing an HPD requires an assessment of the incident noise and knowledge of how much noise the HPD attenuates. This thesis is concerned with determining the acoustic performance of HPDs (i.e. how much noise they attenuate).

The motivation for this work came from two sources. The first was from SAI Global (NZ) Ltd.[1] SAI Global (NZ) Ltd were interested in the development of an HPD test facility in accordance with AS/NZS 1270: 2002[2] [1] and were a sponsor of this work. The second source of motivation was from representatives of the Accident Compensation Corporation (ACC[3]). ACC representatives expressed interest in assessing the effectiveness of HPDs in field and laboratory settings. The development of an HPD test facility and the assessment of HPD effectiveness were identified as a suitable framework for a doctoral project.

This chapter comprises a literature review in Section 1.1, a summary of objectives in Section 1.2 and an outline of the thesis structure in Section 1.3.

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[1] SAI Global (NZ) Ltd. is a commercial testing laboratory in Christchurch, New Zealand.

[2] AS/NZS 1270: 2002 is a combined Australian and New Zealand standard which defines HPD requirements and specifies test equipment and procedures to assess the physical and acoustic performance of HPDs.

[3] The Accident Compensation Corporation (ACC) is a New Zealand Crown entity, solely responsible for no-fault injury prevention and compensation.

1.1 Literature review

1.1.1 Noise-induced hearing loss (NIHL)

Damage to the auditory system due to excessive noise exposure is commonly referred to as noise-induced hearing loss (NIHL). NIHL is normally classified as any one of (or a combination of) three changes in hearing due to noise exposure: temporary threshold shift, permanent threshold shift or acoustic trauma [2, 3]. Temporary and permanent threshold shifts are typically observed for noise exposures of 85 to 140 dBA [4]. Temporary threshold shifts are characterised by a full restoration of hearing thresholds; however, damage to the auditory system may still occur as a delayed degeneration of the cochlear nerve [5, 6], further degrading speech intelligibility than would be predicted based on auditory thresholds alone [7, 8]. Temporary and permanent threshold shifts depend on the exposure level, frequency and duration [9], but a maximum daily exposure limit ($\mathrm{L_{Aeq,8hr}}$) of 85 dB is generally accepted as a suitable criteria to avoid a temporary or permanent threshold shift. Acoustic trauma is defined as mechanical damage to the auditory system and typically occurs following exposure to a single event involving extremely intense noise (over 140 dB), such as a gunshot or explosion [10]. Any moderate to high noise exposure is likely to damage the human auditory system to some degree. Damage may also occur at low to moderate noise exposure by accumulation of insidious effects, but can be difficult to quantify.

NIHL is a significant occupational hazard despite widespread awareness and preventative workplace safety practices [11]. Industrial noise exposure is often the focus of NIHL studies, due to a combination of high noise intensity and long exposure times. Between 7 and 21 % of adult-onset hearing loss worldwide has been attributed to occupational noise exposure, depending on region and occupation [12]. Mining, manufacturing and construction are typically the most at-risk industries; however, NIHL is also prevalent to some degree in industries such as agriculture, medicine, military, the performing arts and transportation [13]. A study on occupational noise exposure in Auckland, New Zealand, found 40 % of production workers exceeded the daily maximum exposure limit ($\mathrm{L_{Aeq,8hr}}$ = 85 dB), compared with less than 15 % of non-production workers [14]. Furthermore, the literature on noise exposure and HPD use in New Zealand was found to be scarce [14]. An earlier study on the epidemiology of NIHL in New Zealand, found the total cost of compensation claims related to occupational NIHL was increasing at approximately 20 % per annum from 1995 to 2006, with over 50 % of occupational NIHL claims from agriculture and fisheries workers, plant and machine operators, labourers, and trade workers [15]. A lack of published work addressing NIHL issues in New Zealand was also reported by Thorne, et al. [15] concluding with: "*The substantial and* *increasing societal costs despite decades of NIHL control legislation suggests that current strategies addressing this problem are not effective, inadequately implemented, or both."* In New Zealand, compensation claims citing hearing loss from excessive noise exposure were estimated to total $ 514 million as of 30 June 2011, with an estimated additional $ 786 million for claims yet to be made prior to 1 July 1999 [16]. This liability has since been reduced by redefining hearing loss regulations, ensuring only hearing loss attributable to occupational noise exposure qualifies for compensation [17]. Beyond the financial cost to society, there are also societal effects due to NIHL such as social isolation [12] and personal disability [11]. More immediate effects of excessive noise exposure include sleep disruption and cognitive impairment [18, 19]. Currently, there is no cure for NIHL [3, 13, 20] and so prevention is the most effective form of mitigation.

1.1.2 Preventing NIHL

NIHL is preventable by reducing noise exposure. Methods to reduce noise exposure in Australasia are formalised in the AS/NZS 1269 [21] series of standards[4]. Other documents[5] are available from WorkSafe NZ[6], but this material is encompassed by the AS/NZS 1269 standards. The main criteria of the NIHL guidelines are:

- A maximum allowable daily noise exposure ($L_{\mathrm{Aeq,8hr}}$) of 85 dB.
- A maximum allowable overall sound pressure level of 115 dB.
- Impulsive noise must not exceed 140 dB ($L_{\mathrm{C,peak}}$).

The preferred methods to reduce occupational noise exposure include: engineering controls, such as treating the noise at source or the transmission path; and administrative controls, such as management of noisy processes or the noise exposure of personnel. The implementation of HPDs is considered a last-resort option in the effective management of excessive noise exposure; however, HPDs are often relied upon as a primary means of noise exposure mitigation due to their low cost and ease of implementation. When choosing or recommending an HPD, the noise exposure of the wearer should be below the exposure limit ($L_{\mathrm{Aeq,8hr}}$ = 85 dB) with consideration for the attenuation of the HPD; however, over protection can be dangerous due to loss of auditory cues [24]. Knowledge of the

[4] AS/NZS 1269 has parts 1 to 4. AS/NZS 1269-0: 2005 provides an overview of the series.

[5] *"Approved Code of Practice for the Management of Noise in the Workplace"* [22] and *"Noise-Induced Hearing Loss of Occupational Origin – A Guide for Medical Practitioners"* [23]. These documents were originally published by the former Occupational Safety and Health Service (OSH), which was part of the Department of Labour.

[6] WorkSafe NZ is a Zealand crown entity established in 2013. WorkSafe NZ regulates workplace health and safety in New Zealand and is part of the Ministry of Business, Innovation and Employment (MBIE).

various types of HPDs, how HPDs function and the various HPD assessment methods are necessary to make a suitable HPD selection [25].

1.1.3 HPD types

HPDs can be considered to be any device which reduces the noise exposure of the wearer. A conventional HPD can be thought of as a device which has no moving parts or electronics and solely relies on the materials of the HPD to attenuate noise. Earplugs and earmuffs are the most common types of conventional HPD. An earplug is inserted into the ear canal and seals to the ear canal wall. Some common types of earplug are roll-down foam, pre-moulded, custom-moulded or canal caps[7] [26]. An earmuff is a pair of rigid cups, connected by a sprung-loaded headband, that fit around the ears (circumaural[8]) and forms an acoustic seal on the head [27]. A common implementation of earmuffs is where the earmuff is fitted to a safety helmet, where the earmuff cups are held in place by short sprung loaded arms. Alternatively, the cups can be contained within the outer shell of a helmet. Helmets can also act as conventional HPDs by design or incidentally due to either partially or fully covering the head and ears. Helmets typically have a rigid outer shell with various lining materials. Some examples of helmets acting as HPDs are aviation and motorsport type helmets. There are also other technologies which can improve on the attenuation or practicality of conventional HPDs, referred to as non-conventional, augmented, and/or specialist HPDs. A general classification scheme for augmented HPDs, from [26, 28], has been used in this work (see Table 1-1). Specialist is used in AS/NZS 1270: 2002 and is defined in Section 1.1.7 below.

[7] A canal cap is a type of HPD with soft tips (foam or similar) which is inserted into the ear canal entrance and held in place by a lightly sprung headband.

[8] Earmuffs are typically circumaural but some active-noise reduction devices can be supra-aural but are more typical in music-listening type headsets. Active-noise reduction is defined in Table 1-1.

Table 1-1: Augmented HPDs.

General	Device type	Description
Passive HPDs (non-electronic)	Uniform attenuation	Incorporate acoustical damping and filtering giving essentially uniform attenuation over a range of frequencies (typically 125 to 8000 Hz). Also called flat attenuation HPDs.
	Passive amplitude-sensitive	Offer attenuation which varies with noise level using various acoustic or mechanical networks. Also called level-dependent.
	Passive wave resonance ducted	Typically a canal cap type HPD which relies on the quarter wave resonance principle to attenuate incident sound.
	Passive adjustable-attenuation	Level of attenuation can be changed by the user by selecting a filter or damper or inserting a valve into a vent.
	Dynamically adjustable-fit	Earplugs with user controlled fit. A balloon or similar is expanded in the wearer's ear canal to customise the fit.
Active HPDs (electronic)	Active noise reduction (ANR)	Reduction in sound pressure level via destructive interference of incident noise by production of a phase inverted sound. ANR is also known as active noise control or noise cancellation.
	Electronically-modulated sound transmission (EMST)	Transmits and can amplify sound beneath an HPD. If incident noise levels are too high they are not transmitted. Also called sound restoration or electronic amplitude sensitive devices.
	Electronic tactical communications and protection systems (TCAPS)	This type is based on a US military program. TCAPS can incorporate elements of EMST, ANR and radio communications.
	Verifiable attenuation and under-HPD dosimetry systems[9]	General category of devices where the attenuation of the HPD can be assessed whilst fitted to the participant.

1.1.4 How HPDs work[10]

An HPD reduces the noise exposure of a wearer by attenuating the noise that reaches the ear drum. There are four paths by which sound can be transmitted to the inner ear when occluded by an HPD: (1) bone conduction, (2) HPD vibration, (3) transmission through the HPD material and (4) air leaks. The transmission paths are illustrated in Figure 1-1.

[9] This type of HPD is further discussed in Section 1.1.9.

[10] Papers by Berger [29] and Henrique Trombetta Zannin and Gerges [30] were used to compile this section.

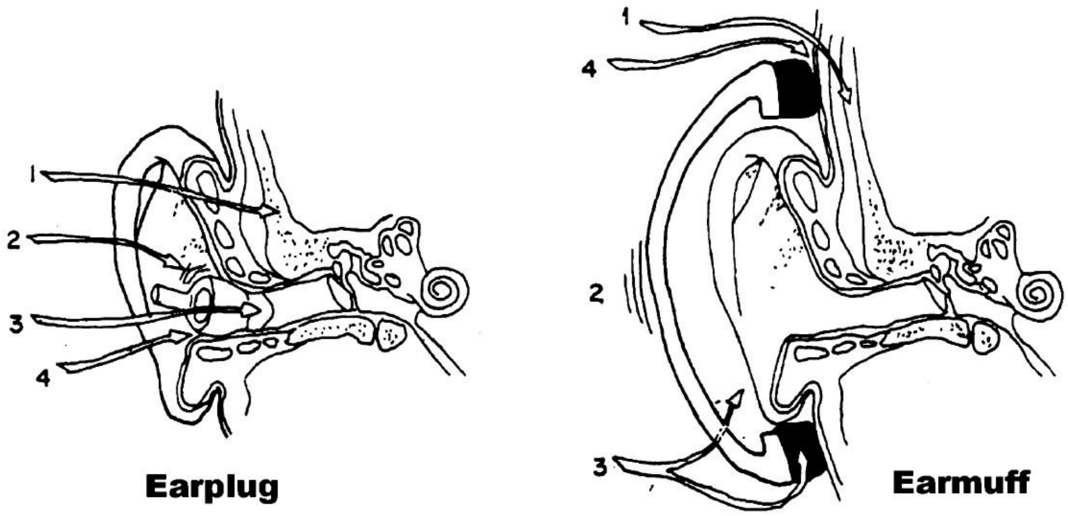


Figure 1-1: Noise transmission pathways for an earplug and an earmuff.[11]

Bone conduction is generally classified as sound transmitted to the inner ear by any path other than air conduction. The term bone conduction is misleading as in reality, skin, flesh, tissue and air transmission through the Eustachian tubes which can excite the cochlea or ossicles, are all encompassed by the bone conduction transmission path [32-34]. Body conduction has been suggested to be a more appropriate description [35], but bone conduction is common in the literature. There are three main bone conduction paths: (1) ear canal wall vibration, which induces an air borne noise near the ear drum (outer ear component); (2) inertial vibrations of the ossicles (middle ear component); and (3) mechanical distortion of the cochlea (inner ear component) [36]. The bone conduction transmission path limits the maximum attenuation able to be achieved by HPDs [33]. HPD vibration occurs because an HPD cannot be rigidly attached to the head, due to flexibility in the HPD material and flesh around the ear, or in the ear canal depending on the type of the HPD [29]. HPD vibration can limit the low frequency attenuation of HPDs [29, 37]. Transmission through the material of the HPD is generally insignificant, unless the HPD provides very poor attenuation. The significance of the transmission path through the material increases with increased HPD surface area [29]. Air leaks encompass any air transmission path by which sound can reach the ear canal or ear drum. Air leaks can form for a number of reasons such as a break in the cushion, and/or poor or incorrect fit, and can reduce attenuation by up to 15 dB [29, 30, 37]. Each of the four identified sound transmission paths should be considered by HPDs.

[11] Adapted from Fig 10.5 in Berger, et al. [31].

1.1.5 Assessing HPD attenuation[12]

Attenuation is often used to describe HPD performance but the more appropriate terms are insertion loss (IL) and noise reduction (NR) [25]. IL and NR are defined by Eq. 1.1 and Eq. 1.2 in reference to Figure 1-2. If NR measurements are compared to IL without taking into account the transfer function of the open-ear (TFOE see Eq. 1.3) corrections, then 5 to 10 dB errors can result [25]. The three most common measurement methods used to assess the attenuation of HPDs are real-ear attenuation at threshold (REAT), microphone in real-ear (MIRE) and acoustical test fixture (ATF).

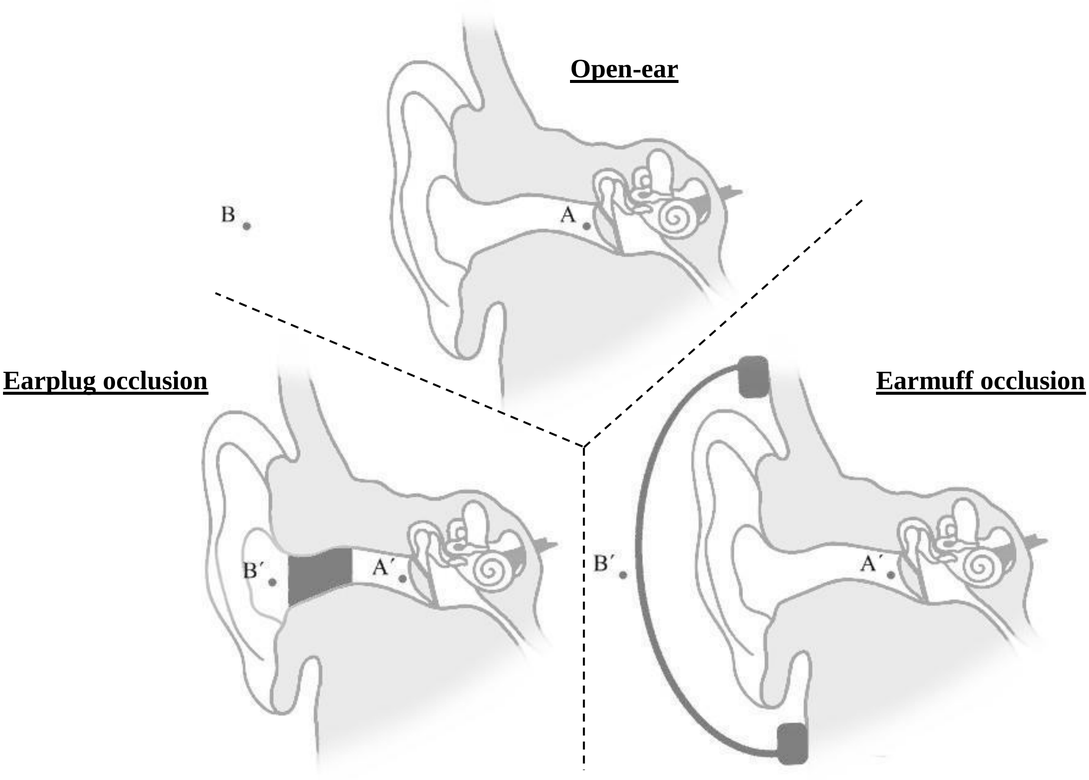


Figure 1-2: Measurement locations used for assessing HPD attenuation.[13]

$$\mathrm{IL} \triangleq \mathrm{A} - \mathrm{A}' \cong \mathrm{REAT} \qquad \text{Eq. 1.1}$$

$$\mathrm{NR} \triangleq \mathrm{B}' - \mathrm{A}' \qquad \text{Eq. 1.2}$$

$$\mathrm{TFOE} \triangleq \mathrm{A} - \mathrm{B} \qquad \text{Eq. 1.3}$$

Where:

Where:	A	≜	Open-ear sound pressure level at the tympanic membrane.
	B	≜	Sound pressure level at the centre of the subject’s head if the subject were absent
	A′	≜	Occluded-ear sound pressure level at the tympanic membrane.
	B′	≜	Sound pressure level at a reference measurement point outside the HPD.

[12] Publications by Berger [25, 38] and Casali [26] were used to compile this section.
[13] Adapted from Fig 1 in a paper by Berger [25].

1.1.5.1 Real-ear Attenuation at Threshold (REAT)

The REAT method is the benchmark HPD assessment method in the literature [25] and is commonly used for publishing the attenuation of HPDs. The REAT method is based upon the difference between participants' binaural hearing threshold in the occluded (HPD fitted) and open-ear conditions. The test must be conducted in a room with low background noise levels to avoid masking of the test signals. The test is typically carried out in a room with a diffuse sound field. Test signals of one-third octave bands of pink noise centred on octave band centre frequencies from 125 to 8000 Hz are typical. HPD attenuation is typically determined for a test population. Participants experience is an important consideration for the REAT method as experienced users are more likely to achieve a better fit and thus improved HPD attenuation. Furthermore, the involvement of the experimenter can also lead to the participant achieving higher IL than if they fitted HPDs without the involvement of the experimenter [39]. Some characteristics of the REAT method are:

- All sound transmission paths are accounted for, including bone conduction.
- No wires, microphones or other instrumentation need to be attached to the HPD.
- Safe for subjective testing due to sound pressure levels being at or close to the participants' threshold of hearing.
- The REAT method is not suitable for some augmented HPDs such as passive amplitude-sensitive, EMST and ANR type HPDs [26, 40], as the HPD may not provide any attenuation at or near threshold sound pressure levels or the internal noise of electronic HPDs can mask the occluded threshold (see Section 1.1.6).
- The occlusion effect can lead to an over-estimation of HPD attenuation by up to 6 dB below 500 Hz [25, 41]. Physiological noise is transmitted more efficiently due to the occlusion effect, effectively masking the occluded ear hearing threshold, thus leading to an overestimate of HPD attenuation [41]. Physiological noise can be any head, ear canal or ear vibrations due to breathing, blood flow or muscle tremor [41].
- Variance amongst the test population is captured. This is important to capture subjective effects, such as how the HPD fits a range of head and ear, shapes and sizes, and behavioural aspects such as how the wearer interprets fitting instructions, and fits the HPD [25].

The REAT test method has been standardised with the most common examples being: ANSI S12.6: 1997[14] [42], ISO 4869-1: 1990 [43], ISO/TS 4869-5: 2006 [44] and AS/NZS 1270: 2002[15]. ISO 4869-1: 1990 is designed to measure the maximum attenuation possible for an HPD, as the experimenter is allowed to assist the participant to achieve an optimum fit. ISO/TS 4869-5: 2006

[14] ANSI S12.6: 2008 supersedes this version but it was understood there were no revisions to the room or equipment specifications and so the latest standard was not obtained in place of the 1997 version which was available to the author.

[15] AS/NZS 1270: 2002 also defines general and physical requirements for HPDs.

has near identical specifications to ISO 4869-1: 1990; however ISO/TS 4869-5: 2006 defines a test method to assess the attenuation of HPDs, representative of a group of inexperienced users (subject-fit method). ANSI S12.6: 1997 defines two methods, A and B. Method A is an experimenter-supervised fit method and Method B is a subject-fit method. ISO 4869-1: 1990 and ANSI S12.6: 1997 Method A are roughly equivalent, whereas ISO/TS 4869-5: 2006, ANSI S12.6: 1997 Method B and AS/NZS 1270: 2002 are similar [25]. AS/NZS 1270: 2002 is the main standard of interest for this work; however, ANSI and ISO standards are also relevant as they have similar specifications and test methods.

1.1.5.2 Microphone in real ear (MIRE)

The MIRE method uses a microphone to measure the sound pressure level beneath an HPD whilst being worn by a person. MIRE methods can be implemented as either NR or IL assessments. NR requires a microphone either side of an HPD, whereas IL requires a single microphone to measure the sound pressure level beneath the HPD, but the HPD must be removed. MIRE can be implemented as a monaural or binaural measurement. Some characteristics of the MIRE method are:

- Suited to field measurement of HPDs, referred to as f-MIRE [25].
- Does not measure the bone conduction transmission path. This can lead to an overestimation of HPD attenuation relative to REAT, mainly above 1 kHz in high attenuation devices [25, 26].
- Can be used over a wide range of sound pressure levels, which makes MIRE suited for testing of augmented HPDs not suited to REAT (see Section 1.1.6).
- The presence of the microphone and wiring can reduce HPD attenuation due to air leaks if there is a break in or beneath the cushion [25, 26].

Ideally the sound pressure level beneath the HPD is measured as close as possible to the ear drum. A typical approach to measure the sound pressure level near the ear drum is to insert a soft probe tube microphone into the ear canal, with the probe tip located near the ear drum. Such measurements by probe tube microphone require specialist equipment, trained personnel and careful experimentation. Probe tube microphone type measurements are typically required to assess earplugs due to limited space beneath the plug. An alternative and less intrusive implementation for earmuffs is the use of small microphones beneath the HPD, sometimes mounted to earplugs or taped to the participant near the ear canal entrance [26]. A MIRE method has been standardised in ANSI S12.42: 2010 [45]. The MIRE method will be discussed further in Section 1.1.7.

1.1.5.3 Acoustical test fixture (ATF)

ATF methods use an artificial fixture (or dummy head) to test HPDs and are typically based on IL measurements [25, 26]. ATFs typically have dimensions representative of a human head, with microphone/s (monaural or binaural) located at the approximate ear location. There are a range of commercial ATFs available, and custom ATFs have also been used in the literature. ATFs range in complexity and can include approximations of the auditory system. Some characteristics of the ATF method [25, 26] are:

- Ideally suited to HPD testing in moderate to loud noise exposures or loud impulsive noises, which may be unsuitable or dangerous for human participants [25, 26].
- Especially useful for product quality control, where a large number of tests are required or for fast comparative testing.
- ATFs do not account for the anatomical variations of end users. Anatomical variations can lead to varying levels of attenuation due to how the HPD fits an individual [25, 26].
- ATFs do not account for behavioural aspects with fitting HPDs such as an individual's experience with fitting HPDs or their interpretation of the fitting instructions [25, 26].
- ATFs typically exclude the bone conduction sound transmission pathway which can lead to unrealistic levels of attenuation. Some ATFs do approximate the bone conduction pathway, but do not account for anatomical variations as mentioned above.

Some examples of standardised ATF methods are ISO 4869-3: 2007 [46] and ANSI S12.42: 2010, which will also be discussed further in Section 1.1.7.

1.1.6 REAT test facilities

There are currently no facilities in Australasia which are accredited to test HPDs in accordance with AS/NZS 1270: 2002 to the author's knowledge. A facility which once held NATA accreditation was visited by the author at the former Chatswood site of the National Acoustic Laboratories in Sydney, Australia. The original use of the room was understood to be high-intensity sonic testing and had thick concrete walls and heavy double doors which provided sufficiently low background noise levels. The approximate dimensions of the room were 6 x 5 x 3 m. The room had a carpeted floor and two absorption and diffuser panels, hung on the walls to improve the diffusivity of the sound field. The sound field was generated by one large speaker placed in and facing into a corner on the floor. A number of papers in the literature have described facilities setup in accordance with ANSI S12.6, which has similar specifications to AS/NZS 1270: 2002. Giguère and Abel [47] developed a facility to meet the requirements of ANSI S12.6: 1984 using a 21 m^3 room with dimensions of 3.5 x 2.7 x 2.3 m. Three speakers were placed near the corners of the room and absorbent and reflecting panels were distributed around the room. Varying the room absorption gave a range of reverberation times and from this the highest allowable reverberation time (less than 1.6 s) was selected. It was not clear how the position of absorbent or reflective panels were selected, but they appeared to be distributed randomly around the room. The room was surveyed for uniformity measurements in a 150 x 150 mm horizontal grid to identify a suitable reference point. Duncan, et al. [48] designed a room to meet the requirements of ANSI S12.6: 1997 with adjustable reverberation time by varying the room lining. Maximum background noise levels were exceeded at times due to occasional extraneous noise, but were avoided by management of testing times. The sound field qualification was carried out by rotating an ATF and recording binaural sound pressure level variation, but this was not in accordance with REAT standards. Schmitt, et al. [49] developed a multi-purpose facility with a main purpose to conduct REAT testing in accordance with ANSI S12.6: 2008. The location of the room had low background noise levels such that a single walled, custom-built reverberant test chamber could be used; however the ventilation flow rate had to be reduced to achieve the required background noise levels. The room was designed to achieve good modal distribution and overlap and three sound diffusing panels were mounted in the room to ensure oblique and tangential modes were excited. The room lining was also variable with removable absorptive panels. Three speakers were used to generate the sound field with a fixed 30 dB attenuator between the amplifier outputs and speaker inputs. The attenuator could be removed for producing high sound pressure levels. de Almeida-Agurto, et al. [50] described a room that met the requirements of ANSI S12.6: 1997 and ANSI S12.42: 1995. The room measured 5.4 x 3.4 m (the room height was not stated) with a reference point height of 1.1 m. Three speaker sets, each consisting of a mid-range and woofer driver, were used to generate the sound field. It appears that suitable sound fields for REAT testing are able to be achieved in relatively small size rooms. Reverberant rooms are a common starting point and diffusers can be used to improve the diffusivity. Absorption treatments can be applied to reduce the reverberation time. Multiple sound sources are also useful to achieve the required diffuse sound field.

1.1.7 Testing specialist HPDs

Non-conventional HPDs will be referred to as specialist, referring to a group of HPDs defined by AS/NZS 1270: 2002, whereas augmented has been used in the literature [26, 40]. Specialist will be used for consistency with AS/NZS 1270: 2002, but there is significant overlap between specialist and augmented HPDs. AS/NZS 1270: 2002 defines specialist HPDs to include: level-dependent earmuffs and earplugs, ANR earmuffs, earmuffs with audio communications, acoustic helmets and any other devices that by design or incidentally affects the sound pressure level that would otherwise reach the inner ear. ANR earplugs should also be included on the list in AS/NZS 1270: 2002. It is possible that they were omitted as they may not have been common at the time. At the time of writing AS/NZS 1270: 2002 there were no clearly defined test methods for specialist HPDs, but once they became available the standard was to be revised. Guidance in AS/NZS 1270: 2002 for testing specialist devices is to test using standard REAT procedures with any electronics turned off but batteries fitted. The REAT test method is typically suited to conventional HPDs, but is also applicable to other passive augmented HPDs, such as passive uniform attenuation, passive wave resonance ducted and passive dynamically adjusted-fit HPDs [40]. The REAT method is not typically suited to passive amplitude-sensitive, EMST or ANR type HPDs as the HPD provides little to no attenuation at low sound pressure levels, or the internal noise of electronic HPDs can mask the occluded threshold [26, 40]. Such HPDs provide the most attenuation at high sound pressure levels, which can be much higher than that assessed by the REAT method. The main advantages of passive amplitude-sensitive and EMST HPDs are improved communication and safety in loud noise environments [26, 40]. Assessment methods other than REAT are required to assess passive amplitude-sensitive, EMST or ANR type HPDs. ANSI S12.42: 2010 specifies MIRE and ATF methods for testing HPDs in moderate to loud continuous noise (up to 105 dB overall), and impulse noise (peak of 130 to 170 dB) which are suited to those HPDs which are not suited to the REAT method. The MIRE method in ANSI S12.42: 2010 is applicable to earmuffs using a small earplug mounted microphone and for deep-fit custom-moulded ANR earplugs, using the in-canal microphone of the ANR earplug. The use of instrumented participants is preferred for continuous noise measurements, but the method cannot be used for impulsive noise, due to risk to the participant. The ATF method in ANSI S12.42: 2010 is preferred for impulse noise, however can be used for all types of earmuff and earplug (except deep-fit custom-moulded ANR earplugs) in continuous noise. ANSI S12.42: 2010 also provides guidance for calculating the expected noise exposure in accordance with ANSI S12.68: 2007. General assessment methods for level-dependent, ANR HPDs and helmets are of interest as they are available for use in industrial settings and the current REAT method (AS/NZS 1270: 2002) is unsuitable for assessing them. Relevant assessment methods will be described in the following paragraphs.

Level-dependent HPD is introduced here to collectively refer to passive amplitude-sensitive and EMST type HPDs. ANSI S12.42:2010 specifies continuous noise and impulsive noise methods for the assessment of level-dependent HPDs. Continuous noise assessments use MIRE or ATF methods in broadband pink noise (± 3 dB in one-third octave bands from 100 to 10000 Hz) at four overall sound pressure levels of 75, 85, 95 and 105 dB to characterise the HPD’s level dependent behaviour. Smaller increments can be used if the four specified steps are not sufficient. Level-dependent HPDs most often finds use in infrequent loud impulsive noises. As such, testing methods have sought to assess the IL of HPDs at high impulse sound levels ($L_{C,peak}$ greater than 130 dB). Equipment for impulse noise assessments must have a sufficiently fast response and be able to handle high sound pressure levels [40]. HPD assessments in impulsive noise are typically carried out using ATFs as it can be dangerous to involve participants. Impulse noise assessments are beyond the scope of this work and are addressed in the literature [26, 40, 45][16]. The current recommendations in AS/NZS 1269-3: 2005 [52] for loud impulse noise are a minimum of class 5 HPDs for noises from impacts, small-calibre weapons or tools and a minimum of well-fitted earplugs (at least class 3) worn in combination with earmuffs (any class) for noise from large-calibre weapons and blasting noises. It is important to note that if an HPD is intended to be used in loud impulse noises, it should be assessed in such incident noise, which is a current limitation of AS/NZS 1270: 2002.

ANR HPDs offer potential attenuation gains over conventional HPDs, primarily in the frequencies at and below 500 Hz. MIRE and ATF methods are more appropriate and are typically used to measure the active component of IL. The active component of IL can be determined by measuring the total IL with the ANR system on and subtracting the passive IL measured with the ANR system off [45, 53]. The active component of IL is then added to the real-ear attenuation measured with all electronics turned off, to determine the overall IL of the device. Addressing the active and passive component of IL individually is specified by ANSI S12.42: 2010 and is typically carried out at a moderate[17] broadband sound pressure level. The active component of IL has been found to be limited at high sound pressure levels in some[18] ANR devices [54]. A comparison of objective (MIRE) and subjective[19] methods for ANR HPDs found no clear preference based on attenuation results, but the objective method was easier procedurally [55]. In addition, large spatial variations (up to 20 dB) were identified for the beneath earmuff cup microphone [55]. A more recent study identified no significant differences between microphone locations in the concha, at a shallow depth in the ear canal and near the ear drum [56]. One method in ANSI S12.42: 2010 specifies a small

[16] ISO 4869-4: 1998 [51] specifies methods for testing level-dependent type earmuffs but has since been withdrawn.

[17] The moderate occluded level is determined to be at least 10 dB higher than the occluded level with the test signal turned off.

[18] ANR devices tested were grouped as industrial (HPDs or commercial communication headsets) or domestic (music listening headphones). The ANR component of IL for some domestic devices was reduced at high sound pressure levels compared to that determined in moderate sound pressure levels.

[19] Masked threshold and a loudness balance test were used for subjective procedures Refer to papers by Berger [38] and Żera, et al. [55] for further discussion of these subjective assessment methods.

microphone attached to an earplug to locate a microphone in each ear to be approximately flush with the plane of the ear canal opening.

The primary use of a helmet is typically for safety or protection of the wearer; however, helmets can act as HPDs if they fully cover the head and ears. Helmets are referred to in REAT standards (AS/NZS, ISO and ANSI standards) but the assessment of helmets is not common in the literature. A KEMAR manikin[20] has been used to assess the sound attenuation of flight helmets, finding the ATF method gave comparable attenuations and lower standard deviations compared to a REAT method [57]. Miniature microphones have been used to measure the attenuation (IL) of flight helmets[21], finding helmet attenuation to be much less than standard earmuffs below 1000 Hz, attributed to little to no spring force on the earmuff cups and helmet shell [58]. Above 1000 Hz the helmet outperformed earmuffs which was attributed to reduction of the bone conduction transmission path [58], however the design incorporated helmet cups which is typical for reports of helmet attenuation exceeding that of earmuffs. Overall there seems to be no obvious reason to discount helmets as serviceable HPDs, but care is required in their assessment.

1.1.8 HPD ratings

AS/NZS 1269-3: 2005 specifies the classification method[22] and the octave band method to determine the noise exposure of a wearer of HPDs. Both methods are based on reducing the maximum noise exposure ($L_{Aeq,8hr}$) to below 85 dB but lower limits (such as $L_{Aeq,8hr}$ = 80 dB) may also be used. The classification method is a simplification of single number ratings which are employed in various forms around the world. Examples of single number ratings include the noise reduction rating (NRR) and noise reduction level statistics (NRS), used in North America; the single number rating (NRS), used in Europe; and the sound level conversion (SLC), used in Australasia. The SLC is based on an observation that the difference between C-weighted incident noise and the A-weighted noise beneath an HPD was approximately independent of the incident noise spectrum [59]. SLC is the only single number rating considered in this work[23]. A single number rating allows various models of HPD to be compared by calculating the likely attenuation achieved for an example spectrum of noise. The classification method reduces the complexity of single number ratings by

[20] The KEMAR manikin is a common ATF originally designed for hearing aid development, but has been used for HPD type measurements.

[21] Helmets had an earmuff cup within the helmet to cover the ear.

[22] Commonly referred to as class and was previously known as the grade system.

[23] See other papers [60-62] for further discussion of single number ratings.

assigning a single number (1 to 5) to a range of SLC values to ensure an easily understandable metric is available to end users for HPD selection and comparison as in Table 1-2.

Table 1-2: Classification of HPDs from AS/NZS 1269-3: 2005.[24]

SLC80	Class	$L_{Aeq,8hr}$ (dB)
10 to 13	1	< 90
14 to 17	2	90 to < 95
18 to 21	3	95 to < 100
22 to 25	4	100 to < 105
26 or greater	5	105 to < 110

The classification method and the octave band method rely on a measurement of the attenuation of the HPD and a measurement of the incident noise (or noise exposure). The attenuation of the HPD is determined by the REAT method (AS/NZS 1270: 2002) with a minimum number of participants of 16 for earmuffs, or 20 for earplugs. A standard deviation is subtracted from the mean to allow for a protection factor in attenuation used in subsequent calculations. The classification method is based on an overall sound pressure level, whereas the octave-band method requires measurement of the incident noise in octave bands from 125 to 8000 Hz. The octave band method is preferred over the classification method if $L_{Aeq,8hr}$ is greater than 110 dB or the noise is narrow band in character, has significant tones and/or has significant high or low frequency components. The classification method uses an assumed average noise spectrum with a typical overall noise level of $L_{Ceq,8hr} = 100$ dB. The assumed noise spectrum and attenuation (mean – 1 SD) is used to calculate SLC80. The noise exposure ($L_{Aeq,8hr}$) for the chosen HPD should be less than 85 dB for 84 % (mean – 1 SD) of end users (hence the 80 in SLC80).

The octave band method also first requires that a standard deviation be subtracted from the mean real-ear attenuation. The attenuation (mean – 1 SD) is then subtracted from the octave band incident noise levels. The resulting octave band noise exposure levels are then summed logarithmically to calculate the overall noise exposure level. The overall exposure level ($L_{Aeq,8hr}$) must be less than 85 dB for the HPD to be a suitable selection. The octave-band method is slightly more complex than the classification method as it relies on measuring the incident noise level in octave bands and a calculation to determine the overall noise exposure for an HPD. The classification method is simple to implement but can be unsuitable for noise exposures with non-typical characteristics.

[24] Adapted from Table A4 (p31) in AS/NZS 1270: 2002.

1.1.9 Field measurement of HPDs

Assessing the attenuation of HPDs worn by participants outside of a laboratory setting is often referred to as a field measurement. The attenuation determined in the field has been estimated to be only 25 % for earplugs, or 64 % for earmuffs, of the attenuation assessed in a laboratory setting [63]. Reasons for the discrepancy have been attributed to the variability in human physiology, lack of education regarding the fitting of HPDs, lack of management involvement to ensure employees have HPDs readily available and know how to use them, and low employee motivation to wear HPDs correctly [64]. Most standard REAT test methods have incorporated a subject-fit method (ISO/TS 4869-5: 2006, Method B of ANSI S12.6:1997 and AS/NZS 1270: 2002), with minimal instruction from and interaction with the experimenter, to better approximate the real-world attenuation [25, 65]. Perhaps more important than the correct use of HPDs is whether they are being used at all as no attenuation (not wearing HPDs) has the potential to be much more damaging than poor attenuation due to incorrect fit or use, but this is not a focus of this thesis.

Recent publications have focused on individual fit-testing of HPDs as a more direct approach to address the discrepancy between laboratory and field. Fit-testing involves assessing the attenuation of an HPD fitted to a participant [66-69]. Individual fit-testing is understood to be used to assess roll-down foam earplugs, pre-moulded earplugs and custom-moulded earplugs. Individual fit-testing uses an MIRE method, termed f-MIRE to represent the field application, where a dual-element probe-tube microphone (or similar) is used to measure the difference in sound pressure level beneath and outside the HPD. Authors have developed corrections to estimate the equivalent real-ear attenuation from f-MIRE measurements [68, 69]. Commercial fit-testing systems are available such as the 3M™ E·A·Rfit™ Validation System [68]. Although individual fit-testing systems are promising they were not considered in this work.

Studies which were of more interest to this work involved the field assessment of HPD attenuation using instrumented participants. Some of these field studies share common features with the fit-testing systems referred to above. The dual-element microphone used by Voix and Laville [69] was implemented to assess the attenuation of custom-fit earplugs and earmuffs over the course of a full working day by Nélisse, et al. [70]. The sound pressure level beneath earmuffs was measured by drilling a small hole and passing the probe through the earmuff shell and foam lining to avoid breaking the cushion’s seal. A digital recorder was used to measure the time history of two microphones (outside and beneath the HPD) for each ear, attenuation was highly variable for both earplugs and earmuffs, with earmuffs offering the better protection [70]. The f-MIRE to REAT corrections referred to previously were also used for the custom-moulded earplug, but corrections were yet to be developed for earmuffs. A similar implementation to Nélisse, et al. [70] assessed a custom-moulded earplug using electret microphones inside and outside the plug in Kusy, and Châtillon [71]. Both microphone signals were recorded with hardware worn by the participant so as to not impede their regular activities. A standard dosimeter was worn by the participant to help validate the recorded levels. The field method measured protection values up to 10 dB less than laboratory based measurements below 1000 Hz, whereas above 1000 Hz, the field and laboratory measurements agreed reasonably well [71]. Corrections similar to those in Voix and Laville [69] were applied between MIRE and REAT measurements in a laboratory setting using an IL paradigm by de Almeida-Agurto, et al. [50]. A microphone was located near the ear-entrance point using a behind-the-ear clip. All measurements were conducted in a laboratory environment and correction factors between MIRE and REAT measurements were determined for each octave band centre frequency and averaged over four different earmuff models. Good agreement was obtained between measured MIRE IL and an empirical REAT estimation model[25] and REAT [50]. Field assessments of HPDs should attempt to estimate real-ear attenuation and the use of correction factors shows promise.

1.1.10 Summary

There is a lack of publications on NIHL and the effectiveness of HPDs in New Zealand. Extensive literature is available on the poor attenuation of HPDs in the field and this remains a current concern in the literature. Recent publications have assessed the field attenuation of earplugs and earmuffs using an f-MIRE method to quantify the HPD attenuation over time and corrections have also been developed to estimate the real-ear attenuation based on the f-MIRE method. Implementing a field based assessment method for HPD attenuation was identified as an objective of this work and has not been carried out in New Zealand to the author’s knowledge. Ideally the measured field implementation will compare to current workplace noise standards which rely on a REAT assessment of HPD attenuation. There is no REAT facility currently available in New Zealand and with interest from SAI Global (NZ) Ltd., developing a REAT facility in accordance with AS/NZS 1270: 2002 became the first objective. Assessing the laboratory effectiveness of HPDs was identified as the second project objective for three reasons: the widely reported lower field attenuation compared to

[25] The model was developed by Schroeter and Poesselt [72].

laboratory measurements, the lack of such publications in New Zealand and the identified unsuitability of the current REAT method for some currently available specialist[26] HPDs.

1.2 Thesis objectives

The general goal of this work is to add to the understanding of HPD effectiveness in New Zealand, with the following objectives:

1. Develop equipment, facilities and test procedures to assess the attenuation of HPDs in accordance with AS/NZS 1270: 2002.[27]
2. Evaluate laboratory-based HPD assessment methods for both conventional and non-conventional HPDs.
3. Develop and demonstrate a prototype device to assess the field attenuation of HPDs.

[26] AS/NZS 1270: 2002 uses specialist as defined in Section 1.1.7.

[27] The HPD test facility was developed to be run commercially, operated in partnership between the University of Canterbury and SAI Global (NZ) Ltd.

1.3 Thesis overview

Chapter 1 presented a literature review and outlined the motivation and objectives. Chapter 2 describes the development of a facility to conduct HPD testing in accordance with AS/NZS 1270: 2002 to meet the first objective. Chapter 3 reviews AS/NZS 1270: 2002 relative to the literature, with consideration of Chapter 2. Chapter 4 presents a demonstration and overview of various test methods for a selection of conventional and specialist (or non-conventional) HPDs. Chapter 5 presents the development of a prototype field testing device. Conclusions are presented in Chapter 6.

2. Development of a REAT test facility

This chapter describes the room, equipment, test method and procedures developed to meet the requirements of AS/NZS 1270: 2002.

2.1 Test site

An IAC audiology booth was found to be the most suitable test room available at the University of Canterbury[28]. The booth had a low background noise level, a clean and professional appearance for subjective testing and was accessible. The booth is rectangular with double walled side walls and roof with double acoustic doors. The floor has rubber vibration isolation mounts. The booth is fitted with air vents, fluorescent lighting, a fire alarm, a sprinkler system and a patch panel for cable connections. The original configuration of the booth did not meet the sound field requirements of AS/NZS 1270: 2002 and modifications were subsequently made. The development of similar rooms in the literature [47-50] appeared to follow no set method to achieve the required sound field. A trial and error approach was considered a practical approach to improve the sound field in the booth[29]. The booth modifications are summarised in Table 2-1.

[28] Potential test rooms at the University of Canterbury were surveyed for their suitability as a new construction was not possible for various reasons.

[29] ISO 354: 2003 was considered for design guidance. ISO 354: 2003 is intended for design of reverberation rooms and recommends a room volume of 150 m^3 which was much larger than the 18 m^3 volume of the booth.

Table 2-1: Modifications to an audiology booth carried out to meet the requirements of AS/NZS 1270: 2002.

	Modification	Description
1	Sound sources	Four speakers were used as four was a convenient number for the signal generation equipment and multiple speakers have been used in other REAT facilities (see Section 1.1.6).
2	Room lining	The original wall and roof lining in the REAT booth was an absorptive material with a perforated metal facing sheet. All interior surfaces were relined with medium density fibreboard (MDF) to increase the surface reflectivity to improve the diffuseness of the sound field. 18 mm thick MDF was used on all the walls and floor and 12 mm thick MDF was used on the roof.
3	Emergency light	The background noise levels in the 1000 Hz and adjacent one-third octave bands were equivalent to or exceeded the maximum allowable background noise levels. The relatively high background noise levels were attributed to the power supply of an emergency light in the booth. Replacing the emergency light with a modern version eliminated the problem.
4	Fluorescent light covers	The fluorescent light covers were found to be producing faintly audible clicking noises. The clicking was attributed to the light covers expanding or contracting in their mounts. Removing the covers eliminated the problem.
5	Fire alarm buzzing	A faulty fire alarm system produced a faint buzzing noise from the in-booth fire alarm and all nearby fire alarms. It was unclear what caused the buzzing but was fixed by a person with knowledge of the fire alarm system.
6	Air conditioning equipment	Air conditioning equipment on the floor above the booth was found to contribute to the background noise levels in the 125 Hz one-third octave band. The sound transmission path was considered to be structural vibration but was not quantified. A timed 30 minute cut-off switch was installed and used to turn off the air conditioning equipment when carrying out REAT assessments and consequently background noise measurements. Noise levels were up to 10 dB lower in the 125 Hz one-third octave band with the unit off.

Participants were seated in the booth with their head at the reference point, 1.1 m above the floor (see Section 2.3.3.7). Speakers were placed upright on the floor facing into the centre of the booth on the horizontal plane. A schematic of the test setup is shown in Figure 2-1. The floor to roof height was 2.05 m. The outer wall and door are not shown.

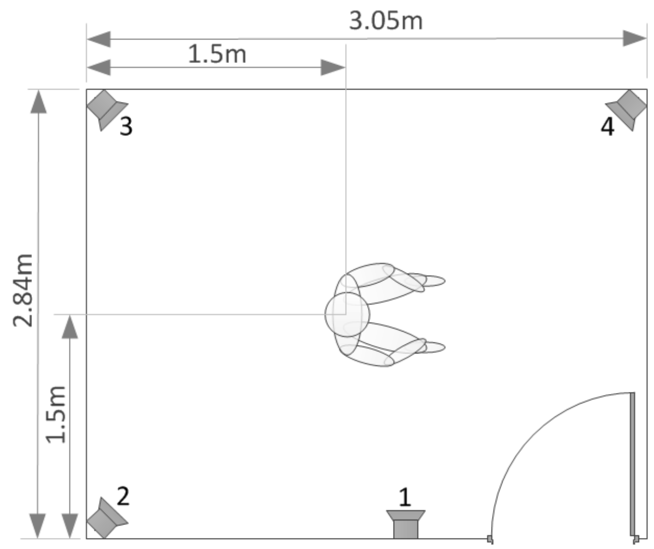


Figure 2-1: Room setup for HPD assessments.

2.2 Equipment

National Instruments hardware and software (LabVIEW) were used to carry out REAT assessments[30]. All equipment used for HPD testing is illustrated in Figure 2-2. All equipment other than the speakers and the participant push button (used to detect positive response to stimulus) was located outside the booth. Connections were made via a patch panel.

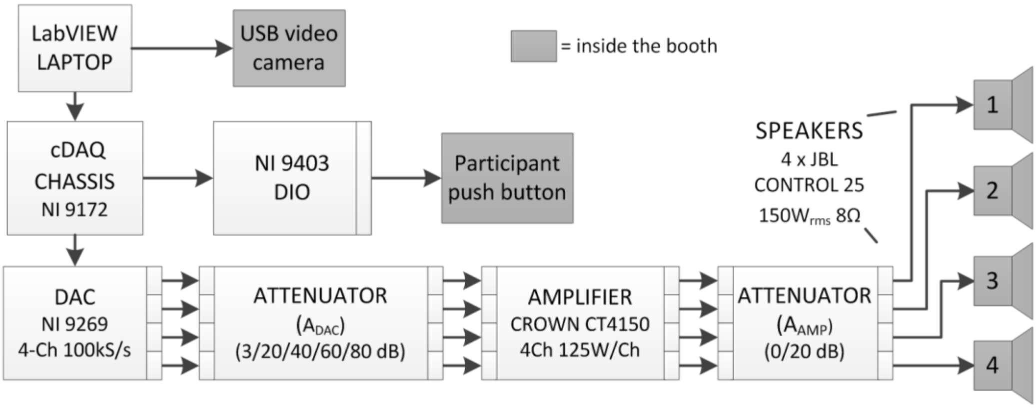


Figure 2-2: Equipment used for HPD testing.

Four speakers were used to generate the sound field in the booth, each with their own independent channel throughout the equipment chain. Signal processing was carried out within the LabVIEW test program and signals were generated with the NI-9269 analogue output module, hereafter referred to as the digital-to-analogue converter (DAC). The DAC had a fixed voltage range of ± 10 V with 16-bit resolution, corresponding to a dynamic range of 96 dB. The lower 40 dB of the dynamic range was used to satisfy distortion requirements (see Section 2.3.3.3), leaving only 56 dB of usable range, much less than the required dynamic range of 110 dB. Two in-house built attenuators were consequently used to extend the dynamic range of the DAC. The attenuators were positioned after the DAC (A_{DAC}), to scale the DAC output, and after the amplifier (A_{AMP}), to reduce the inherent noise of the amplifier. A_{DAC} was a passive H-pad type attenuator designed to match the input and output impedances of the DAC and amplifier inputs. A_{DAC} had fixed steps of 3, 20, 40, 60 and 80 dB selected by a rotary switch[31]. A_{AMP} had settings of 0 and 20 dB, selectable via a toggle switch for each

[30] National Instruments hardware and LabVIEW software were used as they are in common use at the University of Canterbury and others had successfully implemented National Instruments hardware and software in REAT test facilities, such as, the REAT test facility at the former Chatswood, Sydney site of the National Acoustics Laboratories and the NASA Auditory Demonstration Laboratory [49], see Section 1.1.6.

[31] A_{DAC} = 3 dB was chosen to provide minimal signal attenuation while matching the impedances of the DAC and amplifier. A_{DAC} = 80 dB was chosen to attenuate the minimum test signal level produced by the DAC below the measurable sound pressure level in the booth, with the amplifier running.

channel[32]. A_{AMP} was a passive L-pad type attenuator designed to match the speaker impedance (8 Ω). With A_{AMP} = 20 dB, sound pressure levels up to 65 dB were able to be generated. A_{AMP} = 0 dB was used to generate levels of 65 dB and above. The test program indicated the range of sound pressure levels that could be achieved for various attenuator combinations.

2.3 Physical requirements of the test facility

This section describes the test site and test equipment used for REAT testing. Measurements carried out to qualify the test facility in accordance with AS/NZS 1270: 2002 are presented and discussed.

2.3.1 Test signals

Each test signal was a one-third octave band of pink noise with centre frequencies of 125, 250, 500, 1000, 2000, 4000 and 8000 Hz. Signal processing was carried out within the LabVIEW test program using in-built function blocks. There were no audible clicks or pops while changing between test signal centre frequencies and changes between test signals were made in a single step. Third order Butterworth filters were used for test signal filters which were evaluated in accordance with AS/NZS 4476: 1997 [73] and were found to meet the Class 1 relative attenuation requirements (see Appendix A.2.1).

2.3.2 Test site

2.3.2.1 Uniformity

AS/NZS 1270: 2002 requires sound pressure levels at each of six measurement position (indicated in Figure 2-3) to be within ± 2.5 dB of the sound pressure measured at the reference point. The difference between the left and right positions must be no greater than 3 dB.

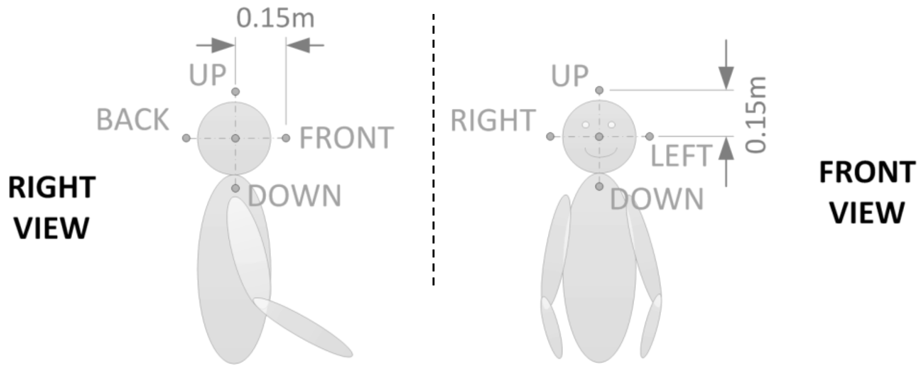


Figure 2-3: Uniformity measurement positions.

[32] A_{AMP} = 20 dB was used to attenuate the noise output from the amplifier so that there was no measurable difference in sound pressure level with the amplifier on or off.

Continuous noise was generated for each one-third octave band test signal at an approximate in-band level of 40 to 50 dB to assess the uniformity. Sound pressure levels were measured in one-third octave bands using a diffuse-field microphone (Brüel & Kjær Type 4942) and an averaging time of 30 s ($L_{eq,30s}$) to account for small fluctuations in sound pressure level. Measurements were repeated five times at each position and test signal. Table 2-2 summarises the uniformity measurements for the various uniformity positions as sound pressure level relative to the sound pressure level at the reference point (ΔL_p). Worst-case 95 % confidence intervals are indicated in brackets for those positions closest to limits for a single position and three repetitions.

Table 2-2: Summary of uniformity measurements.

		One-third octave band centre frequency (Hz)						
		125	250	500	1000	2000	4000	8000
ΔL_p (dB)	Front	-0.2	0.0	-0.3	0.1	-0.1	0.1	-0.2
	Back	0.0	-0.4	0.6	0.8	-0.3	0.0	-0.1
	Up	0.3	-1.9 (-2.4)	-1.2	-0.9	-0.3	-0.4	-0.5
	Down	-0.4	0.9	0.1	-0.1	0.6	0.1	0.2
	Left	-0.3	0.4	1.5	-0.1	0.0	0.2	-0.4
	Right	-0.2	0.0	-1.1	0.2	-0.2	0.5	-0.2
	Left / Right	-0.1	0.4	2.6 (2.9)	-0.3	0.1	-0.3	-0.2

The largest difference in sound pressure level was measured in the up position in the 250 Hz one-third octave band, which was 1.9 dB less than the reference point. There was also a difference of 2.6 dB in the 500 Hz one-third octave band between the left and right positions where a maximum difference of 3 dB is allowed. Results indicate that the sound field meets the uniformity requirements of AS/NZS 1270: 2002.

2.3.2.2 Directionality

A cardioid response microphone (OKTAVA 012) was used to assess the directionality of the sound field in the booth. The microphone was rotated using a rotating assembly shown in Figure 2-4. Sound field effects due to the rotating head and tripod were not accounted for.

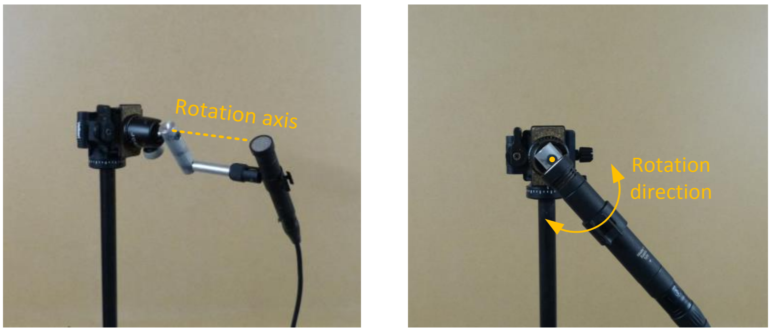


Figure 2-4: Rotating arm assembly used to rotate the directional microphone in a single plane.

The directional response of the microphone, and thus the allowable in-plane variation, was determined by rotating the microphone in an anechoic room. The directional response was determined in the horizontal plane and assumed to be symmetrical about the longitudinal axis of the microphone (see Appendix A.1.2). Continuous broadband pink noise was generated at an approximate one-third octave band sound pressure level of 55 to 60 dB. The use of broadband noise instead of assessing each test signal individually was deemed to be appropriate for two reasons:

1. The in-plane variation was found to be much less than the maximum allowed variation.
2. The sound pressure levels in adjacent bands were found to not exceed ± 3 dB for all microphone orientations in each of the three planes.

Sound pressure levels were measured in each of the three orthogonal room planes centred on the reference point. The maximum in-plane sound pressure level variation for each measurement plane (in dB) is summarised in Table 2-3. Results indicate that the sound field meets the directionality requirements of AS/NZS 1270: 2002. Detailed results can be found in Appendix A.2.2.2.

Table 2-3: Measured in-plane variation for the three orthogonal planes of the room.

		One-third octave band centre frequency (Hz)				
		500	1000	2000	4000	8000
Plane	1	1.5	0.6	0.8	0.5	0.8
	2	1.4	1.3	0.8	1.1	1.8
	3	1.7	1.6	1.1	1.0	2.0
Max. allowed		3.8	3.8	4.4	5.1	3.6

2.3.2.3 Reverberation time

The reverberation time (T60) was measured by the interrupt method described in ISO 354: 2003 [74]. A low-noise microphone (G.R.A.S. 40HF) was used to measure the sound pressure level at the reference point, with the participant and chair absent. The low-noise microphone was used without frequency or directionality corrections as the change in level was of interest rather than absolute sound pressure levels. The reverberation time for the 125 Hz one-third octave band was assessed individually while all other bands were tested using broadband pink noise. The difference in one-third octave bands was not less than 6 dB for the 125 Hz band as specified in ISO 354: 2003. Sound field build up time was at least 5 s in all cases. Sound pressure levels were measured using exponential averaging settings of $\tau = 1/128\ \mathrm{s}$ and $\mathrm{dt} = 70\ \mathrm{ms}$. Measurement settings were considered to be appropriate for the assessment of reverberation times less than 1 s (see Appendix A.2.2.3). The reverberation time for each recorded decay curve was calculated by linear interpolation of the curve in accordance with ISO 354: 2003[33]. Five decays were recorded and used to determine reverberation times for each test signal. The five determined reverberation times were then arithmetically averaged. Reverberation times were found to meet the requirements of AS/NZS 1270: 2002 of less than 1.6 s, as in Table 2-4. More detailed results from reverberation time measurements can be found in Appendix A.2.2.3.

Table 2-4: Measured reverberation time at the reference point.

		One-third octave band centre frequency (Hz)						
		125	250	500	1000	2000	4000	8000
T60 (s)	μ	0.3	0.5	0.5	1.0	1.1	1.0	0.8
	σ	0.0	0.1	0.1	0.1	0.0	0.0	0.0

2.3.2.4 Background noise

AS/NZS 1270: 2002 specifies maximum allowable sound pressure levels in one-third octave bands from 63 Hz to 10 kHz to ensure test signals will not be masked. The sound pressure level was measured at the reference point using a low noise microphone (G.R.A.S. 40HF) with the microphone diaphragm centred at the reference point. The microphone level was checked prior to measurements using a 94 dB microphone calibrator (Brüel & Kjær Type 4231). Corrections were applied in post-processing to account for the microphone frequency response and diffuse sound field[34] (see Appendix A.1.1). Loud intermittent noises attributed to uncontrollable events, such as doors being closed loudly elsewhere in the building, contaminated some measurements of background noise. If the measurement was contaminated the test was stopped and restarted. This was considered acceptable as threshold testing can be stopped and repeated if the participant hears any other noises during hearing threshold testing. Sound pressure levels were measured in one-third octave bands with a slow time weighting ($\tau = 1$ s) and sampled at discrete time intervals ($\mathrm{dt} = 0.1$ s) over a 120 s time period. Measurements were carried out with all test equipment on and running for various settings of A_{AMP} and A_{DAC} but with no test signal present. Sound pressure levels in the 125 Hz one-third octave band varied with time so an arithmetic average of the peaks was calculated. All other one-third octave bands were arithmetically averaged over the 120 s time period. Background noise levels in the REAT booth with all equipment on and running but no test signal present are summarised in Figure 2-5.

[33] Start interpolation 5 dB below initial sound pressure level with a 20 dB evaluation range and the bottom of the evaluation range at least 10 dB above the background noise of the measuring equipment.

[34] It was assumed that a diffuse sound field correction was appropriate as the sound field met the diffusivity and uniformity requirements of AS/NZS 1270: 2002.

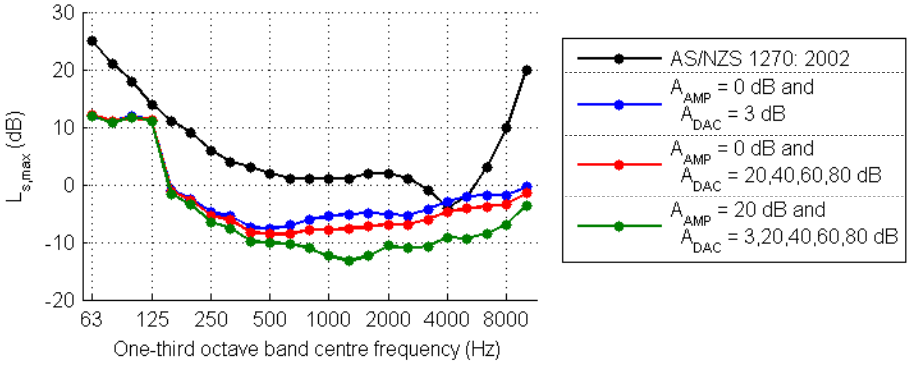


Figure 2-5: Typical background noise levels in the REAT booth.

Settings of A_{AMP} = 0 dB and A_{DAC} = 3 dB did not meet the requirements of AS/NZS 1270: 2002 for the 4000 and 6300 Hz one-third octave bands. Settings of A_{AMP} = 0 dB and A_{DAC} = 20, 40, 60 and 80 dB met the requirements of AS/NZS 1270: 2002 with the 4000 Hz one-third octave band being close to the maximum allowable background noise levels. With A_{AMP} = 20 dB, the background noise levels were much lower than maximum allowable background noise levels for all one-third octave bands except the 125 Hz band. A_{AMP} = 0 dB was only used for sound pressure levels higher than 65 dB, thus the slightly higher background noise levels at this setting were not of concern for HPD assessments by the REAT method. Background noise levels after hours were lower than daytime (0700 to 1800 hrs) noise levels (particularly below 1000 Hz) as shown in Figure 2-6, due to air conditioning equipment and other building services not operating after hours. Dynamic range, attenuator characteristics and distortion measurements were carried out after hours (1800 to 0700 hrs), also with all equipment on and running but no test signal present and A_{AMP} set to 20 dB.

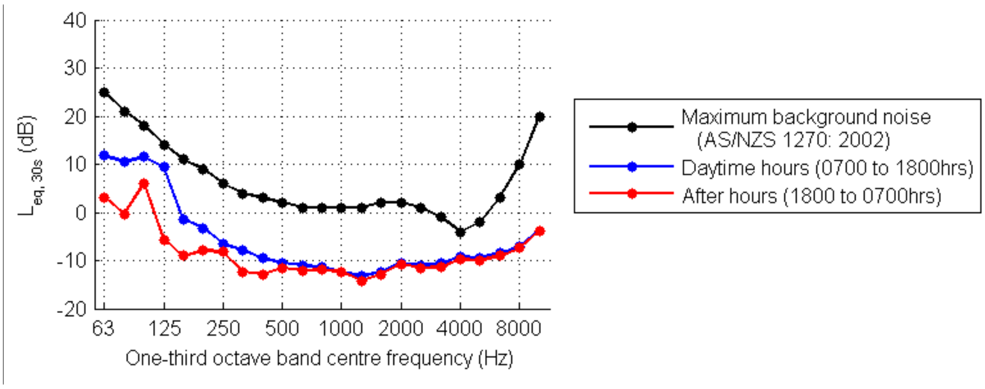


Figure 2-6: Typical background noise levels in the REAT booth during daytime and after hours.

2.3.3 Test equipment

2.3.3.1 Signal source

AS/NZS 1270: 2002 requires that signals be uncorrelated if using multiple sources. Each signal had a separate channel throughout the generation equipment. Cross correlation of each sound source signal with the other three signals was carried out in LabVIEW using a nominal signal level for signal correlation calculations. Normalised cross correlation (ρ_{xy}) was calculated by Eq. 2.1.

$$\rho_{xy}[n] = \frac{r_{xy}[n]}{\sqrt{r_x[0]r_y[0]}} \qquad \text{Eq. 2.1}$$

Where: r_{xy} = Cross correlation of signal x and y

r_x = Auto correlation of signal x

r_y = Auto correlation of signal y

Each 0.5 s test signal (see Section 2.3.3.5) was cross correlated with the other three test signals, to give six cross correlation pairs in total. The maximum normalised cross correlation ($\rho_{xy,max}$) amongst the six pairs was recorded and averaged over ten 0.5 s samples to account for fluctuations in correlation as signals were filtered from individual random noise sources. Results from signal correlation measurements are summarised in Table 2-5.

Table 2-5: Maximum normalised cross correlation for four test signals.

		One-third octave band centre frequency (Hz)						
		125	250	500	1000	2000	4000	8000
$\rho_{xy,max}$ (no unit)	μ	0.5	0.4	0.3	0.2	0.2	0.1	0.1
	σ	0.2	0.1	0.1	0.1	0.1	0.1	0.0

The largest maximum normalised correlation was 0.5 for the 125 Hz test signal. Examples of the typical test signals and the six normalised cross correlation pairs are shown in Figure 2-7.

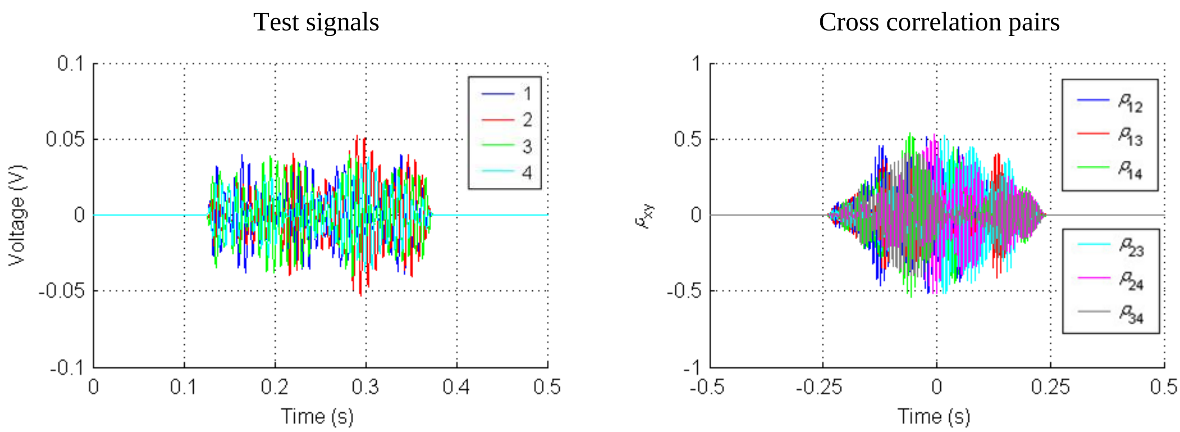


Figure 2-7: Test signals and normalised cross correlation pairs for the 125 Hz test signal.

Two independent random signals can only be uncorrelated (ρ_{xy} = 0) if they each contain infinite energy, thus there will always be some degree of correlation between two band-limited signals. The dependence of correlation on test signal energy is supported by results in Table 2-5 which show cross correlation reducing at higher centre frequencies (larger bandwidth). Results indicate that there was correlation amongst test signals, but ρ_{xy} was typically less than 0.6. Considering each signal had an independent channel throughout the signal generation equipment, results shown here were considered sufficient to meet the signal correlation requirements of AS/NZS 1270: 2002[35].

2.3.3.2 Dynamic range

AS/NZS 1270: 2002 specifies test signals must be able to be produced over the range of sound pressure levels defined in Table 2-6.

Table 2-6: Test signal dynamic range required by AS/NZS 1270: 2002.

		One-third octave band centre frequency (Hz)						
		125	250	500	1000	2000	4000	8000
L_p (dB)	Min.	0	-10	-15	-20	-20	-25	-10
	Max.	80	75	70	70	70	85	95

Measurements of sound pressure level at the reference point (L_p) and voltage across the speaker terminals (V_{ST}) were used to determine the maximum and minimum sound pressure level produced for each test signal frequency. Sound pressure level measurements were made using a diffuse-field microphone (Brüel & Kjær Type 4942) and the voltage across the speaker terminals (V_{ST}) was measured using a signal analyser (Brüel & Kjær PULSE 3560-C). Determination of the lower sound pressure levels (below 0 dB) encountered the inherent noise of the measurement system for acoustic measurements and the inherent noise of the amplifier and/or the inherent noise of the signal analyser for electrical measurements. Unwanted noise levels were logarithmically subtracted from measurements for sound pressure level and the speaker terminal voltage (see Appendix A.3). The lower limit of dynamic range was determined to be at least 3 dB above the limiting acoustic or electrical noise (after noise subtraction). Measurement of the voltage across the speaker terminals (or electrical calibration) was used to determine sound pressure levels below the background noise of the room ($L_{p,V}$) by extrapolating the linear relationship between sound pressure level (L_p) and speaker

[35] A rule of thumb is that uncorrelated signals will have a correlation coefficient of less than 0.7 but no references for this could be found. Other REAT standards (ISO 4869 and ANSI S12.6: 1997) suggest using uncorrelated signals rather than include it as a requirement. de Almeida-Agurto, et al. [50] used three speakers connected in parallel to a single noise source to produce a sound field in accordance with ANSI S12.6: 1997 in a similar size room to that used here.

terminal voltage (V_{ST}) (see Appendix A.2.3.1). The dynamic range of the system is summarised in Table 2-7 for both sound pressure level (L_p) and speaker terminal voltage ($L_{p,V}$) measurements.

Table 2-7: Test signal dynamic range determined by measurement of sound pressure level and speaker terminal voltage.

		One-third octave band centre frequency (Hz)						
		125	250	500	1000	2000	4000	8000
L_p (dB)	Max.	80	75	70	70	70	85	85
	Min.	5	5	5	5	10	10	15
$L_{p,V}$ (dB)	Min.	0	-10	-15	-20	-20	-25	-10

The required maximum level of 95 dB for the 8000 Hz test signal could not be met due to encountering speaker distortion at 85 dB. This was not considered to be a problem as only very high attenuation HPDs were likely to be affected.

2.3.3.3 Distortion

Table 2-8 summarises the distortion requirements in AS/NZS 1270: 2002, which must be met for one-third octave bands from 31.5 Hz to 16 kHz over the dynamic range of the system (Table 2-6). Results are tabulated as the difference in sound pressure level relative to the in-band sound pressure level ($\Delta L_{p,x_r}$) where the band relative to the test signal band is represented by x_r.

Table 2-8: Test signal distortion limits.

	x_r				
	0	-1 / 1	-2 / 2	-3 / 3	≤-6 / 6≤
$\Delta L_{p,x_r}$ (dB)	0	-6	-15	-30	-40

Considering distortion limits for the 4000 Hz test signal and the lower in-band level of -25 dB, sound pressure levels in bands centred two octaves or more away must be less than -65 dB. Measurements of L_p and $L_{p,V}$ (described in Section 2.3.3.2 above and further in Appendix A.2.3.1) were made in 5 dB increments over the required dynamic range with each test signal tested individually using various combinations of A_{DAC} and A_{AMP}. Both L_p and $L_{p,V}$ were measured using a 30 s time averaging and no frequency weighting. An example of measurements obtained for the 1000 Hz test signal is shown in Figure 2-8. Sound pressure level is coloured with low to high represented by dark to light. Measurements of L_p and $L_{p,V}$ were limited by the background noise in the REAT booth and the inherent noise of the amplifier as noted in Section 2.3.3.2 above.

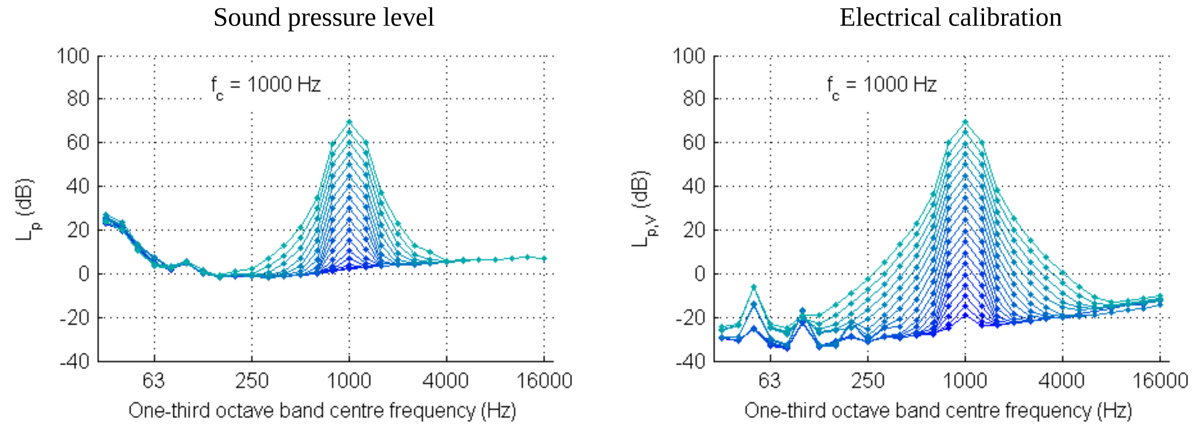


Figure 2-8: Sound pressure levels and speaker terminal voltages for the 1000 Hz test signal.

Sound pressure level determined from speaker terminal voltage ($L_{p,V}$) shows small peaks in one-third octave bands with centre frequencies of 50, 100 and 200 Hz, considered to be due to electrical noise contamination of low voltage levels. As an alternative view, results for sound pressure level and speaker terminal voltage were re-plotted as $\Delta L_{p,x_r}$ and $\Delta L_{p,V,x_r}$ in Figure 2-9, where the in-band level was subtracted from L_p and $L_{p,V}$ to normalise the results to the test signal sound pressure level at the reference point, where colour (indicating sound pressure level) has been kept consistent between Figure 2-8 and Figure 2-9. Results are plotted $\Delta L_{P,x_r}$ and $\Delta L_{P,V,x_r}$ from measurements based on sound pressure level (L_p) and speaker terminal voltages ($L_{p,V}$) in one-third octave bands. Distortion limits from AS/NZS 1270: 2002 are indicated by the thick black line and sound pressure levels produced for each test signal which meet the distortion requirements should be below the limit.

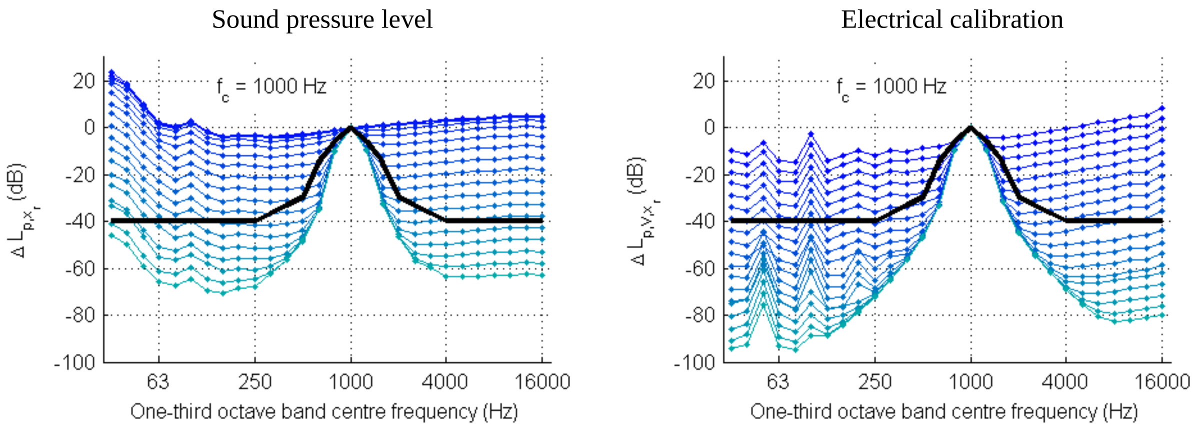


Figure 2-9: Distortion measurements for the 1000 Hz test signal.

Figure 2-9 indicates that the distortion specifications for all one-third octave bands are not met for the 1000 Hz test signal. Distortion specifications are mostly not achieved at low sound pressure levels and only the immediately adjacent bands meet the distortion requirements for speaker terminal voltage measurements. These results were typical for other test signals (see Appendix A.2.3.1). Not meeting the distortion specifications is considered to have a negligible effect on REAT assessments as the levels which do not meet the distortion specifications are at least 10 dB lower than the maximum allowable background noise levels, such that there will be negligible masking for participants with normal hearing thresholds. Meeting distortion specifications in AS/NZS 1270: 2002 at low test signal sound pressure levels is further discussed in Appendix A.2.3.1.

2.3.3.4 Attenuator characteristics

AS/NZS 1270: 2002 requires attenuator steps to be 2.5 dB or smaller, and errors of no more than 1 dB over any 80 dB range or 2 dB over the entire generation range. Attenuator steps were set at 1.25 dB. Sound pressure levels from acoustic ($\mathrm{L_p}$) and speaker terminal voltage ($\mathrm{L_{p,V}}$) were determined at each 5 dB step using a 30 s time averaging with no frequency weighting (as in Section 2.3.3.2 above[36] and Appendix A.2.3.1). Results from attenuator characteristic measurements were plotted as $\Delta\mathrm{L_p}$ vs. $\mathrm{L_{CL}}$ and $\Delta\mathrm{L_{p,V}}$ vs. $\mathrm{L_{CL}}$ defined by Eq. 2.2 and Eq. 2.3 below.

$$\Delta\mathrm{L_p} = \mathrm{L_p} - \mathrm{L_{CL}} \qquad \text{Eq. 2.2}$$

$$\Delta\mathrm{L_{p,V}} = (\mathrm{V_{ST}} - \mathrm{L_{CL}}) \qquad \text{Eq. 2.3}$$

Where: $\mathrm{L_P}$ = Measured sound pressure level at the reference point (dB)

$\mathrm{L_{CL}}$ = Calibrated sound pressure level stored in the test program (dB)

$\mathrm{V_{ST}}$ = Measured speaker terminal electrical voltage (dB re 1 V)

Measurements of $\mathrm{L_p}$ and $\mathrm{L_{p,V}}$ at low levels were influenced by the background noise of the REAT booth and inherent noise of the amplifier. The unwanted noise was subtracted logarithmically (see Appendix A.3). Results of $\Delta\mathrm{L_p}$ and $\Delta\mathrm{L_{p,V}}$ for the 1000 Hz test signal are shown in Figure 2-10 for acoustic ($\mathrm{L_p}$) and electrical ($\mathrm{L_{p,V}}$) measurements. Results show the maximum level variation is less than 1 dB over the required dynamic range with consideration for the background (ambient) sound levels or inherent electrical noise. Results shown here were similar for all test signals and other test signal results can be found in Appendix A.2.3.3.

[36] Experimental setup and results obtained in the previous section for distortion measurements were also used to assess the attenuator characteristics. The attenuator characteristics were assessed at every 5 dB step rather than each 1.25 dB step of the attenuator, assumed to be a reasonable assumption to reduce the number of measurement points.

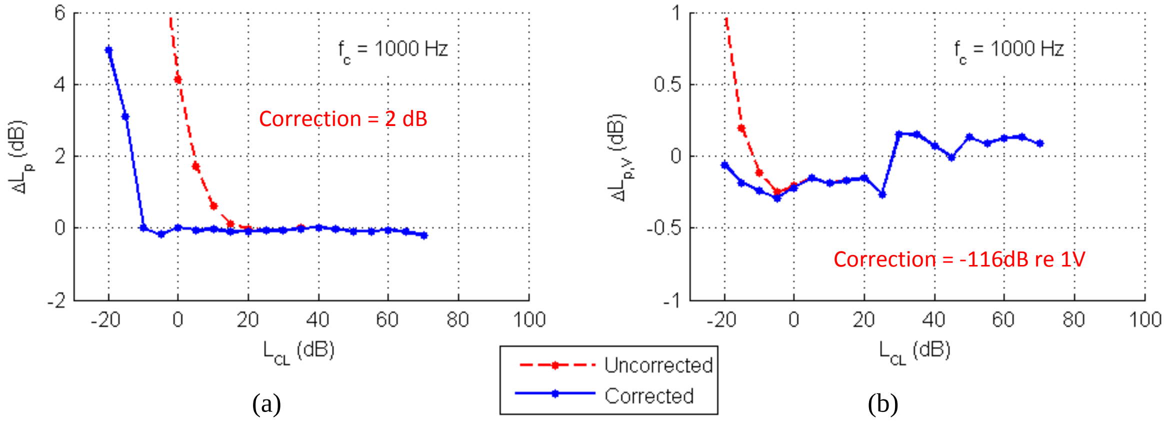


Figure 2-10: Attenuator characteristics for the 1000 Hz test signal.

2.3.3.5 Signal pulsing

Test signals must be pulsed between two and two-and-one-half times per second with a 50 % duty cycle and with no audible clicks, pops, or other transients according to AS/NZS 1270: 2002. An example of the signal processing steps carried out on the original broadband pink noise signal to produce a pulsed one-third octave band test signal are shown in Figure 2-11 for a single channel.

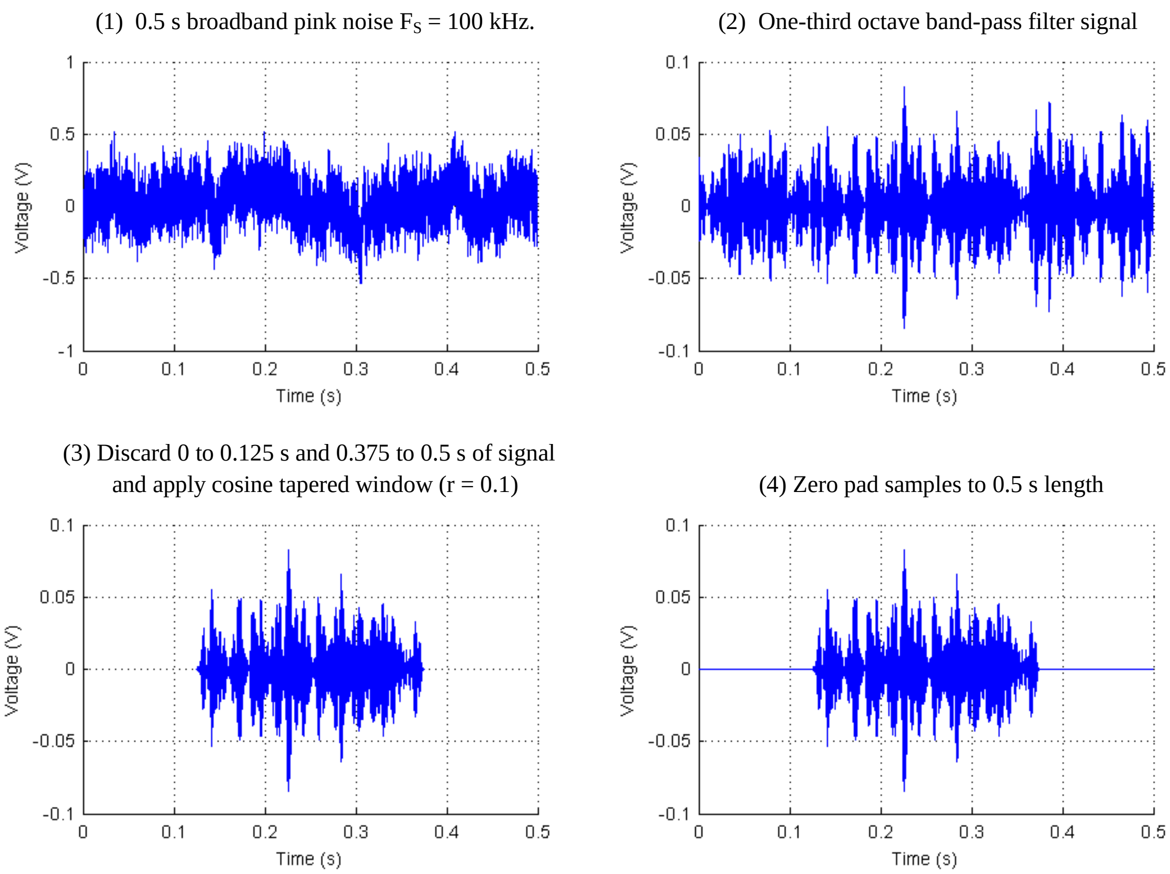


Figure 2-11: Example of signal processing steps for the 1000 Hz test signal.

AS/NZS 1270: 2002 specifies when exciting the system with pure tones at the test signal centre frequencies, the on-phase (the time the signal remains within 1 dB of its maximum level) shall be greater than $150\ \mathrm{ms}$ and the output during the off-phase shall be at least 20 dB below the maximum levels. Assessments of the on-phase and output of the off phase carried out by assessment of the speaker terminal voltage (V_{ST} as in Section 2.3.3.2) for a single speaker. A pure-tone was produced for each test signal centre frequency with a 50 % duty cycle and 2 Hz pulse-rate. Speaker terminal voltage (V_{ST}) was acquired by a signal analyser (Brüel & Kjær PULSE 3560-C) in one-third octave bands using measurement settings of $\tau = 1/2048$ s and $\mathrm{dt} = 0.001$ s over a 10 s period. Results are tabulated in Table 2-9 and were found to meet the requirements of AS/NZS 1270: 2002. Examples of the speaker terminal voltage (V_{ST}) vs. time recordings for each test signal can be found in Appendix A.2.3.4.

Table 2-9: Results from pure-tone signal pulsing measurements.

	One-third octave band centre frequency (Hz)						
	125	250	500	1000	2000	4000	8000
f_m (Hz)	125.9	251.2	501.2	1000	1995	3981	7943
On-phase time (s)	0.2	0.2	0.2	0.2	0.2	0.2	0.2
On-phase − off-phase (dB re 1V)	> 60	> 60	> 60	> 60	> 60	> 60	> 60

2.3.3.6 Fitting noise

A broadband pink noise was used as a fitting noise to assist the participant with adjusting the HPD to achieve the best fit. The sound level at the reference point was set to 70 dBA to meet the requirement of 70 ± 5 dBA in AS/NZS 1270: 2002.

2.3.3.7 Head positioning device

Participants were seated on an adjustable height chair to assist with locating their head in the correct position for REAT assessments. A plum bob was used to assist participants to locate their head at the reference point, by touching their nose on the plum bob as shown in Figure 2-12. The plum bob was removed once the participant was seated comfortably and ready to begin testing. Two LED lights (also shown in Figure 2-12) were used to line up their reflection in the crosshairs of the lights to assist with maintaining their head at the reference point.

Figure 2-12: Demonstration of the plum bob head positioning device.

2.3.3.8 Participant observation

A video camera was used during REAT assessments to view participants. No video or still images of any kind were recorded or stored.

2.4 Participants

HPD testing by the REAT method was approved by the University of Canterbury Human Ethics Committee low risk process (Ref. HEC 2013/36/LR-PS see Appendix A.4). Participants were screened prior to participating in REAT assessments. The screening consisted of an otoscopic inspection, a pure-tone hearing threshold test and determination of participants' experience with HPDs. The otoscopic inspection was carried out to check ear canals were free from any obstruction, excessive cerumen or infection. Participants' experience with HPDs was determined by questions from AS/NZS 1270: 2002. Hearing thresholds were determined by a manual ascending method in accordance with ISO 8253-1: 2010 with supra-aural headphones and sound pressure level increments of 5 dB. Audiometric screening was carried out in a single walled audiology booth next door to the REAT booth. Background noise levels met the requirements of ISO 8253-1: 2010 for typical supra-aural headphones as shown in Figure 2-13.

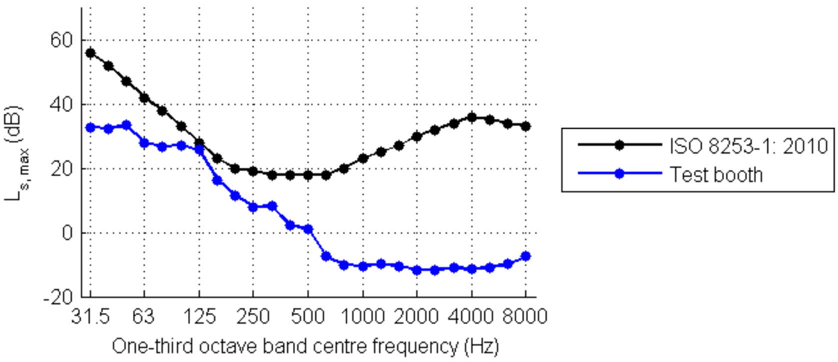


Figure 2-13: Background noise levels in the booth used for audiometric screening.

A clinical audiometer (GSI 61) was used for determining pure-tone thresholds[37]. Participants' hearing thresholds were in the normal range of -10 to 20 dB HL for pure tones of 125, 250, 500, 1000, 2000, 4000 and 8000 Hz measured separately in each ear. Participants with hearing thresholds outside the normal range were excluded from participation.

2.5 Test program

A REAT assessment requires participants' hearing thresholds to be determined for open-ear and occluded conditions. A LabVIEW program was developed to implement the REAT assessment of HPDs. The LabVIEW program was used to generate suitable test signals and control the threshold determination method. The specific procedural requirements such as participant instructions, allowable variation in practice thresholds and quiet periods prior to open-ear and occluded hearing thresholds were taken directly from AS/NZS 1270: 2002, with an exception that no practice sessions were conducted to reduce the time required to conduct an assessment as participants were volunteers. It is possible that the choice to not carry out practice sessions led to a measurement artefact with higher than actual hearing thresholds in the 1000 Hz test signal as it was the first signal tested.

Hearing thresholds were determined using an automated bracketing method (fixed frequency Békésy tracking) guided by requirements in ISO 8253-1: 2010 [75] and overseen by the author. The test program ran on a 0.5 s loop where each 0.25 s noise pulse was centred in a 0.5 s sample length resulting in a 50 % duty cycle and 2 Hz pulse rate (see Section 2.3.3.5). Each noise pulse was generated in discrete steps of 1.25 dB with an attenuation rate of $2.5\ \mathrm{dB/s}$ (recommended by ISO 8253-1: 2010). The procedure for each threshold determination method was:

1. Starting below the participant's hearing threshold, raise the level of the pulsed test signal ($2.5\ \mathrm{dB/s}$ in 1.25 dB steps). When participant could hear the noise, they pushed and held a button.
2. With the button held the noise level lowers ($2.5\ \mathrm{dB/s}$ in 1.25 dB steps). When the participant could no longer hear the noise they released the button, triggering the level to rise again.

Each reversal was recorded and the level overshot the recorded sound pressure level by one 1.25 dB step, prior to reversing up or down in level. The first reversal was ignored and the rising and falling was repeated until three peaks and four valleys were recorded. The threshold was determined by averaging the peaks' average and the valleys' average. The test program indicated the threshold

[37] The audiometer had a current calibration to IEC 60645: 2001. AS/NZS 1270: 2002 specifies a Type 1 or Type 2 audiometer complying with AS 2586 which is equivalent to IEC 645-1; however, AS 2586 and IEC 645-1 have both been superseded by AS IEC 60645-1.

determination was compromised if peaks deviated by more than 10 dB or valleys deviated by more than 10 dB from each other, in which case the threshold needed to be re-determined. Test signals were one-third octave bands of pink noise with octave band centre frequencies from 125 to 8000 Hz (see Section 2.3.1. The order of the test signals was 1000, 2000, 4000, 8000, 500, 250, 125 and a repeat of the 1000 Hz test signal.

ISO 8253-1: 2010 requires any automatic threshold determination method generate equivalent results to a manual method. The implemented automatic bracketing method was compared to a manual ascending method. A manual bracketing method was also trialled but was found to be difficult to implement and was subsequently abandoned[38]. A step size of 5 dB was used for the manual ascending method. The test stimulus was three pulses over 1.5 s. Three pulses were used to compare to the continuously generated pulses in the automatic method. Participants were screened by pure-tone audiometry with supra-aural headphones using the ascending method in accordance with ISO 8253-1: 2010. All participants had normal hearing thresholds (-10 to 20 dB HL) as shown in Figure 2-14. The solid line indicates the mean threshold and shaded areas indicate 95 % confidence intervals for five participants and a single repetition.

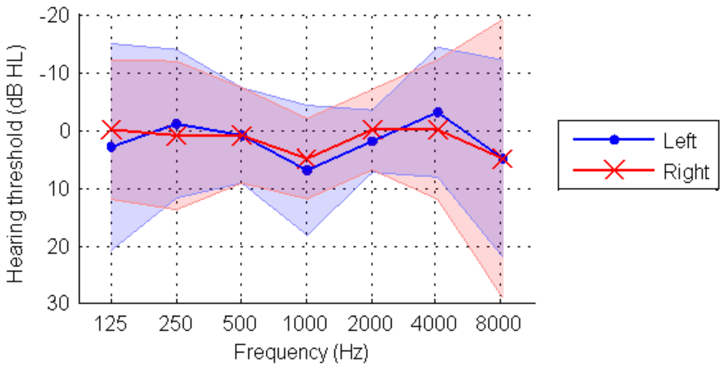


Figure 2-14: Hearing thresholds (n = 5) determined by pure-tone audiometry.

Participants' thresholds were assessed by the automatic and manual methods in the REAT booth. Tests were conducted in one session and were counterbalanced. A one minute quiet period was implemented prior to each threshold determination. Results from hearing threshold testing are shown in Figure 2-15. The solid line indicates the mean threshold and shaded areas indicate 95 % confidence intervals for five participants and a single repetition.

[38] Participants were not able to consistently resolve to a single threshold.

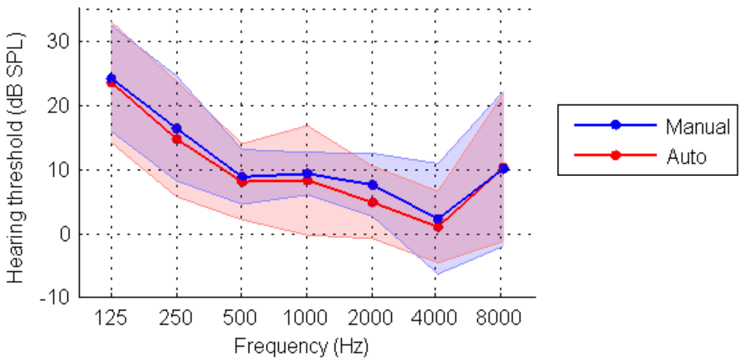


Figure 2-15: Hearing thresholds (n = 5) determined by an automatic bracketing and manual ascending methods.

The automatic method determined hearing thresholds the same or lower compared to the ascending method. The maximum difference in hearing thresholds was 3 dB for the 2000 Hz test signal. There is a large variation in both threshold determination methods; however, the variation is comparable or less than that determined by pure-tone testing. Note 2 in Section 6.3.5 of ISO 8253-1: 2010 states automatic threshold determination methods are on average 3 dB less than manual methods. The same or less difference was observed in the above comparison between manual and automatic methods. The presented comparison was considered suitable evidence to validate the automatic threshold determination method.

2.6 Qualification measurements

Real-ear attenuation measurements of an earmuff (3M™ PELTOR H7F) were carried out to qualify the facility. The earmuff was chosen as earmuffs typically achieve consistent fit for an untrained group of participants. The published attenuation (in accordance with AS/NZS 1270: 2002) was assumed to be a suitable reference. Three participants (1 female and 2 male) were assessed before the test was abandoned. Results are shown in Figure 2-16. Shaded areas indicate 95 % confidence intervals for three participants and a single repetition.

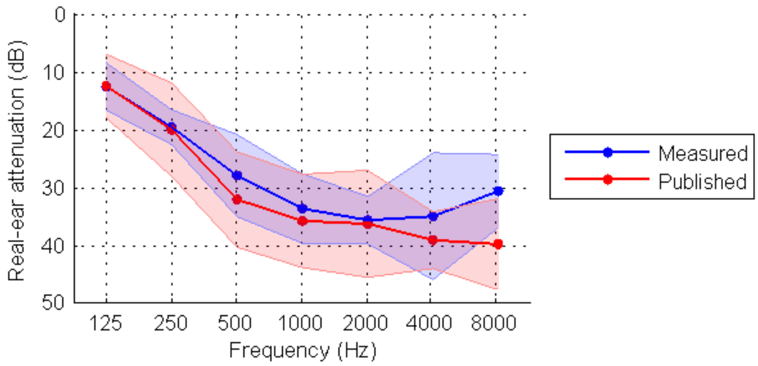


Figure 2-16: Comparison of the measured (n = 3) and published real-ear attenuation of an earmuff.

The test was abandoned because of lower than expected attenuation at higher frequencies which warranted further investigation. Measured IL was either comparable to or lower than the published attenuation. The biggest differences were 8 dB and 4 dB for the 8000 Hz and 4000 Hz test signals respectively. Reasonable agreement was obtained at low frequencies. Measured standard deviations were comparable although there was a small sample size in the measured IL. Test signal levels were found to be correct when rechecked by microphone. A possible explanation for the reduced attenuation was the age of the earmuff. The earmuff was 1 to 2 years old and had not been carefully stored. The cushion had some minor distortion possibly due to being stored with its arms folded but this was not explored further[39].

Berger [76] qualified a REAT test facility by measuring participants' binaural open-ear threshold of hearing in a diffuse-field. Binaural open-ear hearing thresholds were assessed in this work in the earmuff assessment and the qualification of the threshold determination method. The median of open-ear thresholds are plotted in Figure 2-17 relative to open-ear thresholds reported by Berger [76][40] and tabulated data in ISO 389-7: 2005.

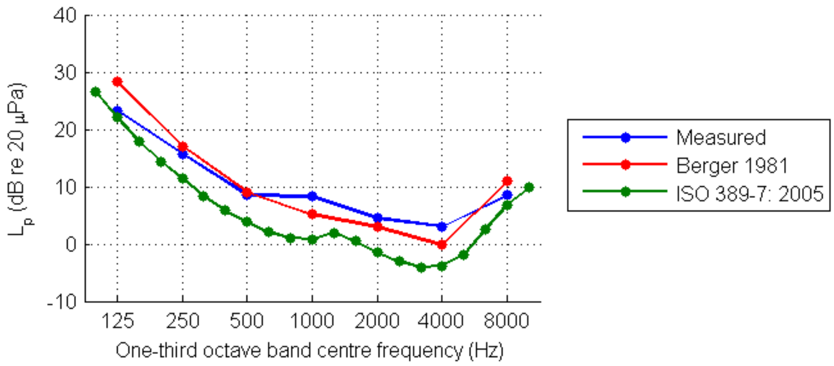


Figure 2-17: A comparison of median open-ear thresholds measured in the developed facility (n = 8) and reported by Berger [76] and ISO 389-7: 2005.

Measured open-ear thresholds showed reasonable agreement with those reported by Berger; however, there is poor agreement with ISO 389-7: 2005 diffuse-field thresholds. Re-plotting the open-ear thresholds determined for each participant gives an indication as to the spread of determined hearing thresholds as shown in in Figure 2-18.

[39] The earmuff was tested later using ATF methods and also measured reduced attenuation at high frequencies. Further REAT testing with additional participants showed improved agreement with the published attenuation (see Section 4.4.2).

[40] Values of diffuse-field open-ear hearing thresholds were from Figure 3 in [76].

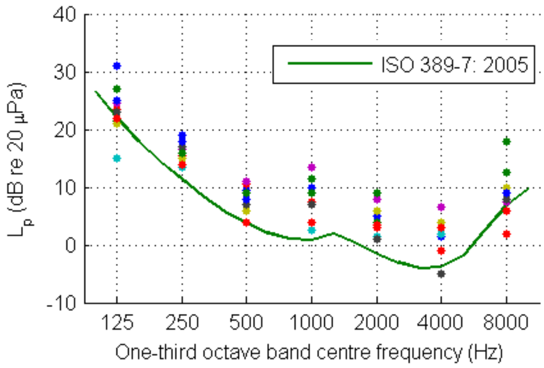


Figure 2-18: Individual binaural open-ear thresholds (n = 8) measured in the developed facility compared to reference thresholds for diffuse-field listening in ISO 389-7: 2005.

Results from REAT measurements and open-ear diffuse-field hearing thresholds do not conclusively validate the test setup and equipment. Differences amongst diffuse-field hearing thresholds have previously been attributed to inadequate determination of stimulus levels, physiological noise, transducer distortion or mechanical vibration coupled to the subject [77]. Berger [76] also identified participant instructions for test stimulus response, gender, race and otological rejection criteria, but the effects of the last three were mostly ignored. The three immediately apparent sources of error in the presented open-ear thresholds are the test procedure, test signal stimulus level and participant instructions. The test procedure used minimal or no practice sessions which may explain the elevated measured thresholds at 1000 Hz, as this signal was the first assessed. Practice sessions were carried out for participants who required them[41] but were not part of the procedure for all participants. The test stimulus level was set by producing a one-third octave band test signal continuously and measuring sound pressure level with an averaging time of 30 s ($L_{eq,30s}$), which may have led to two additional sources of error. One was not allowing suitable warm up time for the sound generation equipment. Typically the amplifier was allowed time to warm up, but there was no sound being produced by the speakers. It was possible that the sound pressure levels altered over time and were further compromised as the calibration and qualifying measurements were carried out using continuous noise at a range of levels, whereas the speaker load was very light during REAT testing due to the low sound pressure levels and pulsed test signal. This may also contribute to the 1000 Hz test signal showing spuriously high levels due to the test signal order and minimal to no practice sessions as noted. In addition sound pressure levels varied due to the use of random noise and relatively short time averaging. Berger [76] noted differences of 5 to 10 dB for participants' response to test stimulus between when they were sure they could hear it or when they thought they could hear it, which was not explicitly defined in this study. Participants were instructed to respond when they

[41] Practice sessions were carried out with some participants to familiarise them with the test procedure.

could hear the noise and if they required further clarification they were instructed to respond only when they were sure. For the purposes of this work the facility was considered to be qualified for carrying out REAT measurements. Inter-laboratory comparisons should be considered for further qualification of the REAT method or determination of open-ear thresholds. Future experiments should seek to quantify the effect of minimal to no practice sessions, calibrating the signals correctly (warming up the speakers) and ensure procedures and instructions are consistent and explicit.

2.7 Summary

A double-walled audiology booth was modified to meet the requirements of AS/NZS 1270: 2002 so as to carry out REAT assessments of HPDs. A test program was developed to produce suitable test signals and control and organise the threshold determination method. The booth and signal generation equipment were evaluated in accordance with AS/NZS 1270: 2002 and were found to satisfy most of the requirements in the standard with the exception of distortion requirements at low sound pressure levels. Background room noise and inherent noise of the measuring equipment were problematic for determining sound pressure levels below -20 dB SPL; however, this was not considered to be a problem for the assessment of open-ear hearing thresholds and consequently should not affect REAT assessments. Thresholds were determined using an automatic bracketing method in accordance with ISO 8253-1: 2010 and validated by comparison with a manual ascending method (n = 5). Thresholds determined by the automatic method were equivalent to or lower than those determined by the manual ascending method with a maximum difference of 3 dB in the 2000 Hz one-third octave band test signal. REAT assessments of an earmuff (3M™ PELTOR H7F) were found to be comparable to, or less than the published attenuation and standard deviations were comparable. Open-ear thresholds did not exactly agree with published data but showed similar trends. Differences were attributed to measurement error and inconsistent participant instructions. The facility was considered qualified for REAT assessments for the purposes of this work. Further experiments to explore the calibration and procedural artefacts identified as possible sources of error should be carried out. Further measurements of open-ear thresholds and the real-ear attenuation of HPDs should be carried out in future and include inter-laboratory comparisons.

3. Review of AS/NZS 1270: 2002

This chapter addresses the REAT specifications in AS/NZS 1270: 2002 by review of the specifications in comparable standards and the literature, with consideration of the test facility development in Chapter 2. REAT standards used for comparison were ISO 4869-1: 1990, ISO/TS 4869-5: 2006 and ANSI S12.6: 1997[42]. ISO 8253-1: 2010 [75] and ISO 8253-2: 2009 [78] were also considered in this review as the threshold determination procedures and diffuse-field audiometric specifications were relevant to the REAT method.

3.1 Test signals

All reviewed REAT standards (and ISO 8253-2: 2009) specify test signals of one-third octave bands of noise, centred on octave band frequencies from 125 to 8000 Hz. ISO 4869-1: 1990 specifies an additional optional test signal centred on 63 Hz. Each test signal is filtered from a broadband noise source where pink noise is specified by all standards but white noise can also be used in ANSI S12.6: 1997. Real-ear attenuation below 125 Hz has been found to be similar to that determined at 125 Hz but physiological noise becomes a significant measurement artefact at low frequencies [38]. Each REAT standard defines filter specifications in accordance with various versions of IEC 61260, either directly or indirectly, thus the test signal specifications in various REAT standards are considered equivalent. The absence of any literature on the differences in HPD attenuation between pink and white noise suggest they may be equivalent. Pink noise was the most common broadband noise source used for REAT assessments in the literature.

3.2 Test site

3.2.1 Uniformity

Uniformity specifications are consistent across all reviewed standards and ISO 8253-2: 2009 for diffuse-field audiometry.

[42] ANSI S12.6: 2008 supersedes ANSI S12.6: 1997.

3.2.2 Directionality

All standards require a directional microphone to be rotated through 360° in three planes, centred about the reference point so as to assess the variation in sound pressure level in each plane. In-plane variation of the sound pressure level at 500 Hz and above must be less than a maximum allowable variation depending on the directionality characteristics of the microphone. The maximum allowable variation in AS/NZS 1270: 2002 and ANSI S12.6: 1997 is based on the free-field rejection of the microphone, where free-field rejection is the front-to-side rejection for cosine microphones, or front-to-rear rejection for cardioid microphones, as summarised in Table 3-1.

Table 3-1: Allowable in-plane variation for directionality assessments in AS/NZS 1270: 2002 and ANSI S12.6: 1997.

Microphone free-field rejection (dB)	Allowable in-plane variation (dB)
> 25	6
20	5
15	4
10	3
< 10	Unsuitable

Maximum allowable variation in ISO 4869 standards is based on the front-to-random sensitivity index of the microphone, as summarised in Table 3-2. ISO 4869 is used to collectively refer to ISO 4869-1: 1990 and ISO/TS 4869-5: 2006. Directionality specifications in ISO 4869 are also defined in ISO 8253-2: 2009 for diffuse-field audiometry.

Table 3-2: Allowable in-plane variation for directionality assessments in ISO 4869.

Front-to-random sensitivity index (dB)	Allowable variation (dB)
≥ 5	5
4.5	4.5
4	4
< 4	Unsuitable

The sensitivity index (SI) is analogous to the directivity index (DI) of a sound source [79]. The experimental setup and results from determining the free field rejection of the microphone (see Appendix A.1.2) can also be used to determine the sensitivity index. By assuming the directional characteristics of the microphone are symmetrical about its longitudinal axis, the sensitivity index can be determined in a free-field using Eq. 3.1 and Eq. 3.2.

$$\mathrm{SI} = 10\log_{10}(S_\theta) \qquad \text{Eq. 3.1}$$

$$S_\theta = \frac{2\pi P(0)}{\int_0^{2\pi} P(\theta)\, d\theta} \qquad \text{Eq. 3.2}$$

Where: $P(0)$ = Magnitude of the mean-square sound pressure level with microphone pointing directly at the incident sound.

$P(\theta)$ = Magnitude of the mean-square sound presure level arriving at the microphone microphone at angle θ with the incident sound.

The maximum allowable variations determined from the free-field rejection and the sensitivity index for the OKTAVA 012 microphone used in this work are summarised in Table 3-3.

Table 3-3: Allowable in-plane variation (dB) for the free-field rejection and the sensitivity index of the OKTAVA 012 cardioid microphone.

	One-third octave band centre frequency (Hz)				
	500	1000	2000	4000	8000
Free-field rejection	3.8	3.8	4.4	5.1	3.6
Sensitivity index	4.3	4.9	4.7	4.4	4.5

The microphone type has been shown to influence whether ISO 4869 directionality specifications can be met [80]; however, no relation was found between HPD attenuation and variations in the sound field which still met REAT specifications assessed by various types of directional microphone [81]. The ISO and ANSI specifications appear to be essentially equivalent. In the author's opinion, the ISO specifications use of sensitivity index is preferred as the ISO specification aligns with the maximum permissible background noise levels and threshold assessment methods in AS/NZS 1270: 2002. Determination of the sensitivity index does involve an additional calculation rather than the simple front-to-side or front-to-rear rejection but it is straightforward.

AS/NZS 1270: 2002 and ANSI S12.6: 1997 specify that the three orthogonal planes of the test room should be used to assess directionality, whereas ISO 4869 specifies that directionality is assessed as the difference between expected maximum and minimum directions of incident sound energy. Guidance in ISO 4869 is to carry out the test in a sufficient number of directions where the expected maximum and minimum sound pressure levels may occur. This can be problematic if there is no clear direction at which the maximum and minimum may occur or it is difficult to repeatedly orientate the microphone at the desired locations. It is proposed that using the orthogonal planes of the room is a sufficient assessment of directionality.

3.2.3 Reverberation time

The reverberation time specification (less than 1.6 s) is the same in the standards reviewed.

3.2.4 Background noise

Background noise levels must be sufficiently low to ensure open-ear thresholds are not spuriously high due to masking [38]. Maximum background noise levels are specified in AS/NZS 1270: 2002, ISO 4869-1: 1990 and ISO/TS 4869-5: 2006 in one-third octave bands, whereas ANSI S12.6: 1997 specifies maximum background noise levels in octave bands, summarised in Figure 3-1. The limits of ISO 4869-1: 1990 below 63 Hz must be met if the optional 63 Hz test signal is used. ANSI S12.6: 1997 octave band levels were corrected to one-third octave bands by subtracting 4.8 dB from octave band values[43].

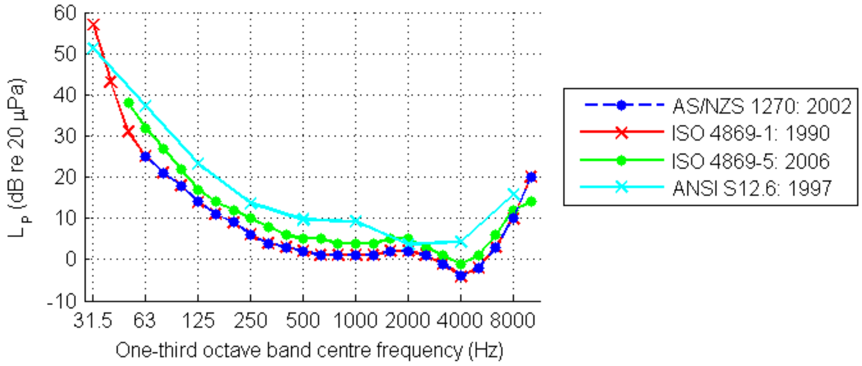


Figure 3-1: Maximum background noise levels in REAT standards.

Measurement of maximum permissible background noise levels must be carried out with all equipment on and running but with the test signal absent. ANSI S12.6: 1997 and AS/NZS 1270: 2002 allow any hearing threshold tests to be repeated if extraneous noise becomes audible in the test room. Experience with setting up the test room (see Chapter 2) found extraneous noise to be nearly unavoidable in shared building spaces. In which case repeating the threshold determination was a reasonable allowance. Maximum background noise levels in ISO/TS 4869-5: 2006 are stated to be low enough to conduct threshold testing for participants with a maximum sensitivity of 0 dB HL. Levels are equivalent to ISO 8253-2: 2009 which also allows measurement of hearing thresholds down to 0 dB HL, with a maximum uncertainty of + 2 dB due to ambient noise masking. Participants with hearing thresholds in the range of -10 to 20 dB HL are permitted by AS/NZS 1270: 2002, suggesting test signals may be masked if maximum background noise levels are present and participants have sensitive hearing (-10 to 0 dB HL). Berger [38] demonstrated a method to calculate maximum background noise levels and this method has been used and adapted to one-third octave bands. Eq. 3.3 describes the calculation for each one-third octave band (i). Results are summarised in

[43] Conversion from one-third octaves to octaves has been done by addition of 4.9 dB to one-third octave band levels [38]. 4.8 dB was used here as $10\log_{10}(10^0 + 10^0 + 10^0) = 4.771$ dB.

Figure 3-2. The maximum daytime noise levels in the developed facility are also shown for comparison.

$$\mathrm{MBNL}_i = \mathrm{MAF}_i + \mathrm{CF}_i - \mathrm{SDC}_i \qquad \text{Eq. 3.3}$$

Where:	MBNL	=	Calculated maximum background noise level for open-ear threshold testing.
	MAF	=	Minimum audible diffuse-field from ISO 389-7: 2005.
	CF	=	Critical band conversion factor where $\mathrm{CF} = \log_{10}(\mathrm{OB}_{1/3}/\mathrm{CB})$. Where $\mathrm{OB}_{1/3}$ is the one-third octave band bandwidth $\cong 0.232 * \mathrm{f_m}$, and CB is the critical bandwidth, and $\mathrm{CB} = 10^{\mathrm{CR}/10}$, where CR is the critical ratio[44] from Table I in [83].
	SDC	=	Signal detectablility correction = 6 dB for < 1 dB of masking from ambient noise from [38].

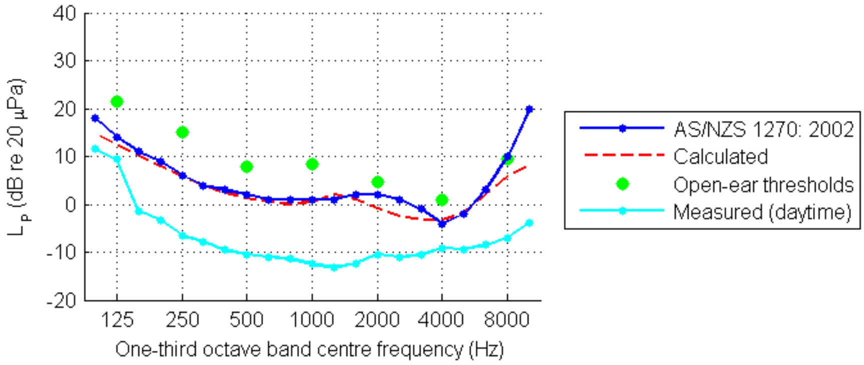


Figure 3-2: Maximum background noise levels from AS/NZS 1270: 2002 and proposed new levels compared to measured open-ear threshold levels (n = 8) in the developed facility.

The measured open-ear thresholds shown in Figure 3-2 approach the maximum permissible noise levels in AS/NZS 1270: 2002 and higher than the measured thresholds in this work. Further testing with artificial generation of maximum background noise levels in AS/NZS 1270: 2002 with sensitive hearing participants (-10 to 0 dB HL) should be carried out to confirm the proposed levels are appropriate.

The specified measurement settings in AS/NZS 1270: 2002 (slow time weighting over a time period of at least 120 s) were found to be helpful. This was in contrast to ISO 4869-1: 1990, ISO/TS 4869-5: 2006 and ANSI S12.6: 1997 which did not specify how measurements were to be made.

[44] The critical ratio (CR) is the power ratio of signal-to-noise (dB) for a signal masked by broadband noise and can be used to estimate the critical bandwidth [82].

3.3 Test equipment

3.3.1 Signal source

AS/NZS 1270: 2002 specifies test signals must be uncorrelated if using two or more signal sources. All other standards suggest uncorrelated signals may be necessary if sound field specifications are unable to be met. There is no further information on how to establish whether signals are uncorrelated, most likely because quantifying the correlation is difficult with a band-limited random signal (see Section 2.3.3.1). Suitably uncorrelated signals should be able to be achieved if each signal source has its own signal generator and channel throughout the signal generation equipment chain.

3.3.2 Dynamic range

Dynamic range specifications ensure the system is able to generate a suitable range of sound pressure levels for REAT testing. A wide range is required as the difference between open-ear and occluded hearing thresholds can be up to 60 dB for high attenuation HPDs[45] [33]. Additional dynamic range of 10 dB above the maximum occluded threshold and 10 dB below the open-ear threshold is typically required for the threshold determination method. Dynamic range specifications are summarised in Table 3-4. The 63 Hz test signal is optional in ISO 4869-1: 1990 as indicated by an asterisk (*).

Table 3-4: Required dynamic range in REAT standards.[46]

	One-third octave band centre frequency (Hz)							
	63*	125	250	500	1000	2000	4000	8000
AS/NZS 1270: 2002	-	0 / 80	-10 / 75	-15 / 70	-20 / 70	-20 / 70	-25 / 85	-10 / 95
ISO 4869-1: 1990[47]	10 / 80	-5 / 70	-10 / 70	-15 / 80	-20 / 80	-20 / 90	-20 / 90	-20 / 90
ISO/TS 4869-5: 2006	-	10 / 70	0 / 70	-5 / 80	-10 / 80	-15 / 90	-15 / 90	-15 / 90

All standards allow sound pressure levels below 0 dB to be determined on the basis of electrical calibration. The specification to allow electrical calibration below 0 dB conflicts with the maximum allowable background noise limits in AS/NZS 1270: 2002 as maximum allowable background noise limits are most often above 0 dB (see Section 2.3.2.4). Electrical calibration could reasonably be used up to the background noise limits in the room or the inherent noise of the microphone. Electrical calibration is further discussed in Appendix A.2.3.1.

[45] ILs of approximately 70 and 80 dB for the 4000 and 8000 Hz test signals for a full-face helmet worn with earplugs were measured in Section 4.4.5. ILs with the helmet and earplugs in combination encountered the dynamic range limits of the test facility limits but this is considered an extreme case.

[46] Dynamic range limits are shown as (min. / max.) sound pressure level (dB re 20μPa).

[47] Distortion limits shall be met up to at least a 70 dB sound pressure level.

ANSI S12.6: 1997 specifies that the test equipment must be able to generate signals from at least 10 dB above the participants' occluded hearing thresholds to 10 dB below their open-ear hearing thresholds, but the lack of tabulated hearing thresholds makes qualification measurements difficult. Using the ANSI S12.6: 1997 specifications of 10 dB below the lowest open-ear hearing threshold and ISO 389-7: 2005 open-ear diffuse-field thresholds (rounded to the next lowest 5 dB) gives an estimate of the lowest test signal level, tabulated in Table 3-4.

Table 3-5: Current and proposed dynamic range requirements.

	One-third octave band centre frequency (Hz)						
	125	250	500	1000	2000	4000	8000
Current minimum AS/NZS 1270: 2002	0	-10	-15	-20	-20	-25	-10
Proposed minimum dynamic range limit	10	0	-10	-10	-15	-15	-5

The upper limit of dynamic range appears to be appropriate for all but the highest IL HPDs.

3.3.3 Distortion

Distortion specifications ensure a suitable signal quality is maintained over the dynamic range of the system. All three standards specify that the equipment shall be capable of generating each test signal without any hum, buzzing, crackle or rattle being audible over the full dynamic range of the system. The distortion specification is relevant at higher noise levels due to speaker and amplifier distortion and low sound pressure levels where the inherent noise of the sound generation equipment and inherent noise of the microphone are encountered. The distortion specifications in reviewed standards are summarised in Figure 3-3, where ΔL_p is the sound pressure level relative to the in-band level and x_r is the relative band number.

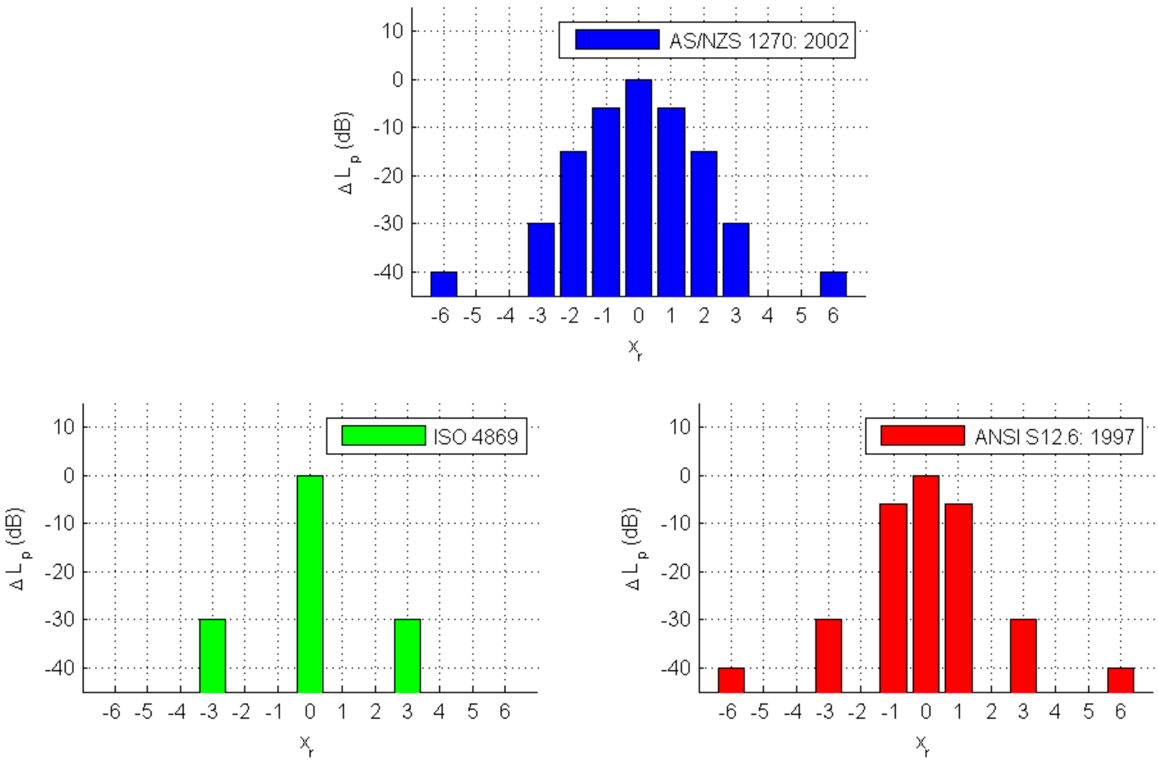


Figure 3-3: Distortion specifications in reviewed REAT standards.

Distortion specifications are assessed by measuring sound pressure levels with a microphone at the reference point or by electrical calibration below 0 dB, as in the dynamic range requirements above. The distortion specifications in the standards reviewed give approximately equivalent test signals, assuming interpolation can be used between missing data points, and the distortion specifications must be met over the specified dynamic range for each test signal. For AS/NZS 1270: 2002, sound pressure levels must be determined down to -65 dB in the case of the 4000 Hz test signal for one-third octave bands two octaves or more removed from the test signal centre frequency, over a one-third octave band frequency range of 31.5 Hz to 16 kHz. Measurement of such low sound pressure levels by acoustic or electrical calibration was found to be impractical as discussed in Section 2.3.3.3. It is proposed that the regular distortion requirements should only be met to 20 dB below the minimum audible diffuse-field threshold, similar to the 10 dB below the lower limit proposed for the dynamic range specifications in the previous section.

3.3.4 Attenuator characteristics

All reviewed standards specify attenuator steps to be 2.5 dB or smaller. Attenuator linearity is a crucial specification for hearing threshold determination and REAT testing. Linearity specifications in ISO 4869 and AS/NZS 1270: 2002 are identical in that any two positions of the attenuator must not exceed 2 dB over the total dynamic range, or 1 dB over any 80 dB range. Linearity specifications in ANSI S12.6: 1997 are required to be assessed by measuring the difference in output between any two attenuator settings with a pure-tone test signal and shall not differ by more than 3/10 (0.3) of the indicated increment, or by 1 dB, whichever is smaller. It is unclear whether the ISO 4869 and AS/NZS 1270: 2002 attenuator specifications or the specifications in ANSI S12.6: 1997 are the preferred option. A single set of measurements was able to be used to assess the dynamic range, distortion and attenuator linearity requirements in AS/NZS 1270: 2002 using the test signal which was advantageous from a practical point of view.

3.3.5 Signal pulsing

Signal pulsing specifications are consistent across all reviewed standards.

3.3.6 Fitting noise

A fitting noise is required to assist participants with fitting the HPDs under test. All standards specify pink noise with some variations in level (60 to 75 dBA). The variation in level is unlikely to affect how participants adjust the HPD. The use of a fitting noise is believed to be unnecessary for slow recovery foam earplugs or similar types of HPD as the fit cannot be quickly adjusted and re-trialled.

3.3.7 Head positioning device

A device is required to assist the participant to maintain their head at the reference point for the duration of the test for all REAT standards reviewed.

3.4 Participants

Participants' physiology and behaviour and their interaction with the person conducting the test can have a large influence on REAT testing [38]. All participant requirements are essentially equivalent amongst the reviewed standards and can be summarised by:

- Normal hearing thresholds determined by pure-tone audiometry.
- Ear canals free of impacted cerumen and infection.
- Participants with head, pinnae or ear features which might adversely affect the fitting of HPDs are excluded.
- No jewellery or glasses which might adversely affect the attenuation of HPDs are to be worn during testing.

There is an onus on the person conducting the test to determine whether participants are suitable or not, with consideration for the guidelines above. Determining how much soft cerumen is allowed (common with participants, especially those who do not regularly wear earplugs) or what type of head features should be restricted is difficult. There is a notable absence of work reported in the literature in regards to soft cerumen or head and ear features, most likely due to difficulties in providing a suitable definition.

An experienced HPD user is considered to be proficient at fitting HPDs and thus likely to achieve a higher IL than an inexperienced user. The ISO and ANSI REAT standards incorporate a trained-subject (can be referred to as experimenter-assisted) method and an inexperienced-subject (sometimes referred to as naïve subject) REAT method to approximate HPD attenuation for either experienced or inexperienced users of HPDs. A trained-subject method allows the person conducting the test to assist with or supervise the fitting of HPDs and approximates the attenuation likely to be achieved by a proficient user of HPDs. ISO 4869-1: 1990, Method B in ANSI S12.6: 1997 and AS/NZS 1270: 2002 are considered subject-fit methods [25], due to minimal interaction between the person conducting the test and participants and a requirement to use participants who are inexperienced with HPDs, determined by a questionnaire. Comparison between different subject-fit methods was not found in the literature; however, the literature does report lower attenuation for subject-fit methods relative to trained-subject methods, where subject-fit methods provide a better approximation to real-world conditions [64, 65]. The subject-fit methods stated above are considered to be essentially equivalent.

3.5 Threshold determination method

AS/NZS 1270: 2002 specifies that any threshold determination method in ISO 8253 will be suitable for HPD testing. ISO 8253-1: 2010 specifies two manual methods: the ascending method and the bracketing method. Any automated method is allowed to be used as long as it generates equivalent results. An automated bracketing method (fixed frequency Békésy tracking) appears to be a common method used for threshold determination [42, 47, 49]. AS/NZS 1270: 2002 specifies an attenuator step size less than or equal to 2.5 dB which is believed to favour automatic methods due to increased test times for step sizes smaller than 5 dB [84]. A manual ascending method and bracketing method have been shown to determine equivalent hearing thresholds [85] and automatic methods generally have lower standard deviations [86]. Automatically determined thresholds are typically up to 3 dB less than thresholds determined by manual techniques using 5 dB steps[48]. An experiment was carried out comparing an automatic bracketing method to a manual ascending method (see Section 2.4) and found automatic thresholds were the same or lower than those determined by manual methods with a maximum difference of 3 dB. Based on the measurements and the literature there are no significant

[48] According to Note 2 of Section 6.3.5 in ISO 8253-1: 2010 [78].

differences between hearing threshold determination methods defined in ISO 8253-1: 2010, suggesting any method which meets the standard will be suitable for HPD testing.

3.6 Summary

REAT specifications in AS/NZS 1270: 2002 have been reviewed in comparison to ISO 4869-1: 1990, ISO/TS 4869-5: 2006 and ANSI S12.6: 1997. The specifications in AS/NZS 1270: 2002 are considered to be appropriate and were essentially equivalent (or identical) to the reviewed standards. Some minor points have been identified in this review for future consideration. The maximum background noise levels in AS/NZS 1270: 2002 are potentially too high. New maximum allowable background noise levels are proposed. Further work is required to make a valid recommendation for maximum allowable background noise levels and should include masking experiments. The distortion requirement of at least 40 dB below the in-band level for bands two octaves or more removed was found to be impractical to meet at low sound pressure levels. It is proposed that the lower limit of dynamic range be 10 dB below the open-ear threshold of hearing and the lower limit of distortion requirements be 20 dB below the open-ear threshold of hearing. Diffuse-field hearing thresholds in ISO 389-7 may be a suitable reference for open-ear thresholds. The use of electrical calibration for sound pressure levels should also be allowed below the room ambient noise or the inherent noise of the microphone. A suggested replacement wording for when electrical calibration may be used is: *Electrical calibration may be used for any sound pressure levels below the background noise levels of the room or the inherent noise of the microphone.* Overall, the suggested corrections are considered minor and should be followed up further and include inter-laboratory comparisons.

4. Laboratory-based assessment methods

The REAT method is unsuitable for the assessment of some non-conventional HPDs (see Section 1.1.7). Types of non-conventional HPDs which are not suited to being assessed by the REAT method include: level-dependent, as the HPD can provide little to no attenuation at the low sound pressure levels used for REAT assessments; and ANR (active noise reduction) HPDs, as occluded thresholds can be masked by the internal noise of the HPD. Level-dependent and ANR HPDs are generally referred to as non-conventional HPDs, whereas AS/NZS 1270: 2002 uses specialist (see Section 1.1.7). Specialist will be used in this section. When AS/NZS 1270: 2002 was prepared there were no available methods for assessing specialist HPDs (Section 5 of AS/NZS 1270: 2002). The goal of this chapter was to demonstrate and evaluate HPD assessment methods for conventional and specialist HPDs, to provide information and recommendations for any future revision of AS/NZS 1270: 2002.

4.1 Approach

The assessment of HPD attenuation by the REAT method, an adapted MIRE method and the ATF methods were considered in this chapter. The test procedure for the REAT method was not in accordance with AS/NZS 1270: 2002 because practice sessions were not conducted and participant numbers were below the required number (see Chapter 2); however, the REAT method was considered adequate for the work described here. The MIRE and ATF methods used ANSI S12.42: 2010 for general guidance. HPD IL determined by the MIRE and ATF methods in this chapter used continuous broadband noise. The assessment of HPD attenuation in impulse noise was not considered.

A selection of HPDs was used to evaluate HPD assessment methods. The selected HPDs included two conventional earplugs, three conventional earmuffs, an EMST (electronically-modulated sound transmission) earmuff, an ANR headphone and an abrasive blasting helmet. An EMST earmuff was chosen to be representative of level-dependent HPDs. An ANR headphone was chosen to be representative of ANR type HPDs. An abrasive blasting helmet was also included as helmets are considered specialist HPDs in AS/NZS 1270: 2002. Furthermore, ATF assessments of helmets are of interest in other projects at the University of Canterbury and assessments of helmets used as HPDs were found to be uncommon in the literature.

4.2 Test sites

Two test sites were used for the HPD assessments reported in this chapter. The REAT method was carried out in a modified audiology booth (Chapter 2), which will be referred to as the REAT booth. The sound field in the REAT booth met the approximate diffuse-field requirements of AS/NZS 1270: 2002 (see Chapter 2). MIRE and ATF assessments were also carried out in the REAT booth and additional ATF assessments were carried out in a reverberation room. Broadband pink noise was used for all MIRE and ATF assessments in the REAT booth and reverberation room. The frequency response of the generated broadband noise was adjusted in software so as to be approximately flat (± 2 dB in one-third octave bands from 100 to 10000 Hz) in the REAT booth. The reverberation room was used to achieve higher sound pressure levels than the REAT booth for the assessment of the level-dependent and ANR HPDs. The frequency response in the reverberation room was not adjusted so as to be approximately flat due to equipment limitations. An omni-directional sound source (Brüel & Kjær Type 4296) was used to generate the sound field in the reverberation room and the sound field was considered to meet the requirements of AS/NZS 1270: 2002, ISO 4869 and ANSI S12.42: 2010, but was not assessed for uniformity and directionality. The assessment of conventional HPD IL by the MIRE and ATF methods was carried out in the REAT booth at an overall sound pressure level of 90 dB. The assessment of the IL of level-dependent and ANR HPDs in the REAT booth and reverberation room was carried out over a range of sound pressure levels. The range of sound pressure levels was from an overall level of 70 dB, to an upper limit of 90 dB in the REAT booth and an upper limit of 105 dB in the reverberation room in 5 dB increments (see Figure 4-1). Sound pressure levels were determined by a diffuse-field microphone (Brüel & Kjær Type 4942) located at the reference point. The inherent noise consists of the ambient noise of the room and/or the inherent noise of the microphone.

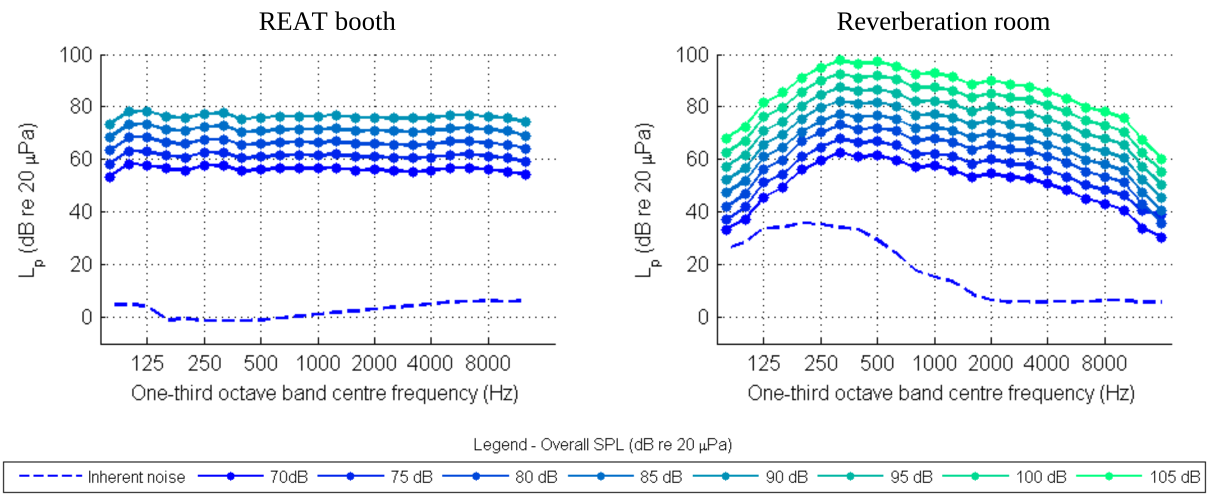


Figure 4-1: Sound pressure levels for the MIRE and ATF methods.

4.3 Method

The test method and equipment used for the MIRE and ATF methods are described below. See Chapter 2 for description of the REAT method.

4.3.1 MIRE

The MIRE method implemented in this work relied on participants wearing small microphones mounted to earplugs[49]. The earplug mounted microphone, hereafter referred to as the MIRE earplug, was used to measure the sound pressure level for the open-ear and occluded cases. The difference in sound pressure level between the open-ear and occluded case was used to determine the HPD IL. Participants' involvement with the MIRE method was approved by the University of Canterbury Human Ethics Committee's low risk process (Ref. HEC 2014/18/LR-PS, see Appendix A.4). The sound pressure level was measured with no frequency weighting and an averaging time of 10 s ($L_{eq,10s}$). Each occluded measurement was repeated three times, where the participant removed and refitted the HPD for each repetition. MIRE measurements were conducted in the REAT booth with participants seated with their head at the reference point as they would for the REAT method (see Section 2.3.3.7). Earplugs were not assessed by the MIRE method. Electret microphones were used to measure sound pressure levels for the MIRE method. The electret microphones had an omni-directional response and a diameter and depth of 6 mm and 7 mm respectively. The microphone and mounting post were heat shrunk together and glued to a pre-moulded earplug (MOLDEX® JETZ®)[50] as shown in Figure 4-2. The microphone was located on the outer face of the earplug. The instrumented earplugs were fitted to participants' ear canals for MIRE assessments with new earplugs used for each participant.

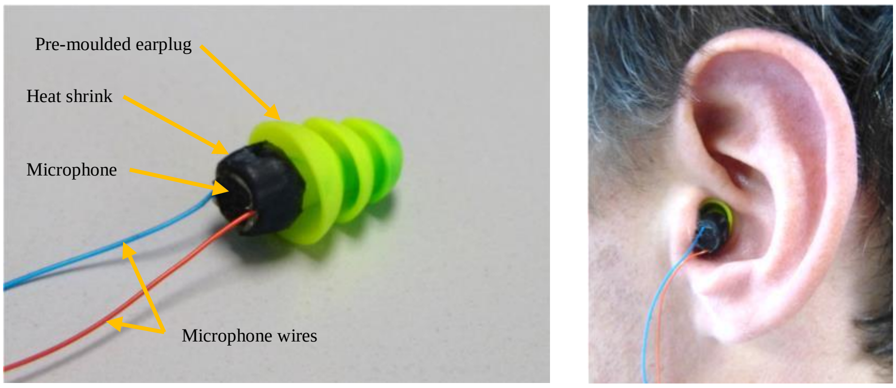


Figure 4-2: Electret microphone and earplug used for MIRE assessments.

[49] The MIRE method typically implements measurements using a probe-tube microphone located as close as possible to the tympanic membrane, but this was not carried out in this work.

[50] A MOLDEX® JETZ® pre-moulded earplug was used.

Signals were acquired by a signal analyser (Brüel & Kjær PULSE 3560-C) operating on battery power to reduce the influence of electrical noise. The electret microphones were also run on battery power (1.5 V) and a common ground was established between the microphone power supply and the signal analyser to reduce any influence of electrical noise. The maximum IL able to be determined in this implementation is shown in see Figure 4-3. The maximum IL was determined from the difference between the maximum noise level used for the MIRE method[51] and the inherent noise of the microphones for each participant. Shaded areas indicate 95 % confidence intervals for five participants and a single repetition. The relatively low maximum IL for the 100 Hz one-third octave band was attributed to electrical noise as indicated below.

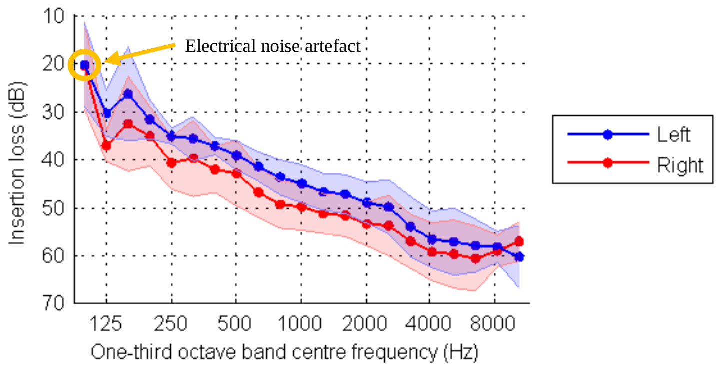


Figure 4-3: Maximum IL (n = 5) of the implemented MIRE method.

The maximum IL in Figure 4-3 was subtracted from the measured HPD IL by logarithmic subtraction (see Appendix A.3) for each participant, microphone (left and right) and one-third octave band. The maximum IL exceeded that of the measured IL in a single one-third octave band (100 Hz) for the left side microphone of one participant for the M4 earmuff (see Table 4-3) and logarithmic subtraction was not carried out in this case.

The electret microphone wires passed beneath the earmuff cushion. Each wire had an individual diameter of 0.45 mm and the wires were joined to a standard coaxial cable (diameter = 2.0 mm) outside the earmuff. The coaxial cable passed through the neck opening of the helmet assessed in this work. This was assumed to have a negligible effect on IL in this case as there was essentially no seal around the neck, but this was not quantified. The effect of a break in the earmuff cushion was assessed using the G.R.A.S. 45CA (IEC 60711) and a single earmuff (3M™ PELTOR™ H7F 290). Short lengths of wire were used to represent a break in the cushion. A range of different wire

[51] The maximum noise level used for the MIRE method was an approximate in-band level of 80 dB in one-third octave bands from 100 to 10000 Hz. A maximum limit of 85 dB was determined in Chapter 2 but this was for an individual one-third octave band centred on 8000 Hz.

materials were used as it was assumed the material would have a negligible effect. Photos of the setup to assess the effect of wire diameter on IL are shown in Figure 4-4 below.

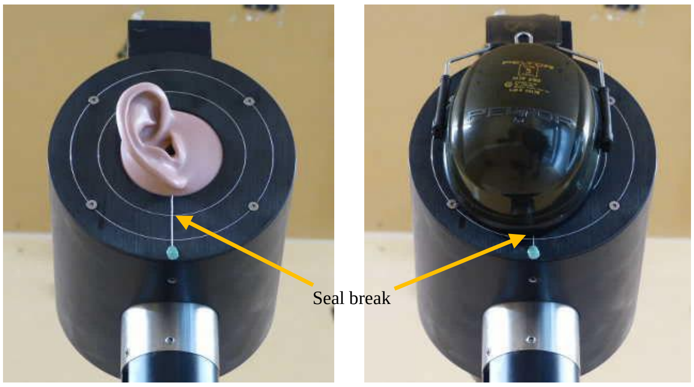


Figure 4-4: Experimental setup for assessing a break in the earmuff cushion.

Sound pressure levels were measured in one-third octave bands (100 to 10000 Hz) for both occluded and open-ear cases with no frequency weighting and an averaging time of 10 s ($L_{eq,10s}$). Five lengths of wire with various diameters (Ø) from 0.5 to 3.2 mm were used to represent a break in the earmuff cushion. Occluded sound pressure levels with the break in place were measured five times, the earmuff being removed and refitted each time. The change in IL (ΔIL) with various breaks in the earmuff cushion, normalised to the IL with no break in the cushion, is shown in Figure 4-5. Shaded areas indicate 95 % confidence intervals for three repetitions. A negative change in IL indicates a reduction in IL (less attenuation).

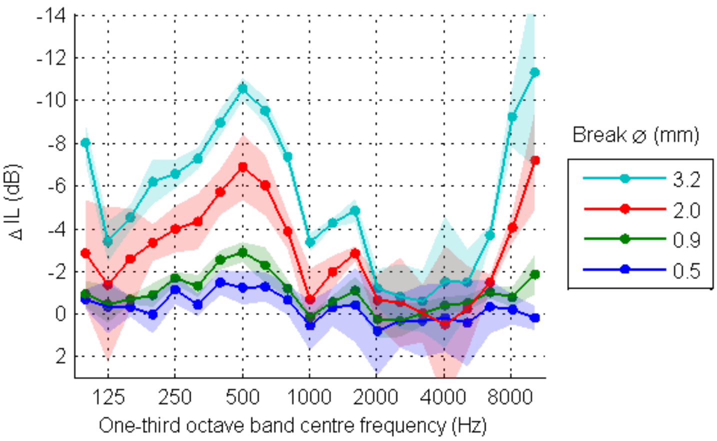


Figure 4-5: Change in insertion loss with various diameter breaks beneath the earmuff cushion.

The wire diameter of 0.5 mm reduced the attenuation by less than 2 dB. It is possible the effect of a break beneath the earmuff cushion on IL would be less if repeated on participants due to the flexibility of human flesh and skin, but this was not quantified. ANSI S12.42: 2010 specifies individual microphone wire diameter must be less than or equal to 0.5 mm including insulation. A wire diameter of 1.5 mm has been reported to reduce attenuation by less than 2 dB with participants

[58]. In another assessment of earmuff attenuation by Henrique Trombetta Zannin and Gerges [30], petroleum jelly was applied to the contact surface of the earmuff cushion to reduce air leaks. Attenuation (IL) improved by less than 5 dB between 100 and 200 Hz. An individual wire diameter of 0.45 mm used in this implementation of the MIRE method was considered appropriate.

A maximum overall noise level of 90 dBA was used for the MIRE method. The maximum noise level corresponded to a maximum exposure time of approximately 2.5 hours without HPDs according to OSH [22] and AS/NZS 1269-1: 2005 requirements [87]. The participant was in high noise levels intermittently for a maximum time of 15 minutes and always had earplugs fitted. Earplug IL was determined by the REAT method prior to participating in any MIRE assessment to ensure each participant was suitably protected. A minimum real-ear attenuation of 10 dB in each one-third octave band test signal was met before carrying out MIRE assessments. The general procedure for the REAT method, followed by the MIRE method was as below.

<u>REAT</u>

1. Participant seated in the room with head located at the reference point.
2. Determine open-ear threshold.
3. Fit MIRE earplugs to left and right ears.
4. Determine occluded-ear threshold with MIRE earplugs in place.
5. If the MIRE earplug IL is less than 10 dB at any test signal, refit and go back to step (3). Participants did not participate if a minimum IL of 10 dB could not be achieved.

<u>MIRE</u>

6. Determine MIRE open-ear sound pressure level.
7. Re-check earplug fit by visual inspection.
8. Participant fits the HPD and the level of broadband pink noise is increased to maximum sound pressure level for MIRE.
9. The occluded sound pressure level is measured with no frequency weighting and an averaging time of 10 s ($L_{eq,10s}$).
10. The broadband noise level is decreased to sound pressure level of approximately 50 dB.
11. Participant removes and refits the HPD. Repeat from Step 8 for three HPD fits in total.
12. Carry out additional occluded assessments if required, checking earplug fit each time.

The changes in broadband noise level were gradually increased or decreased (5 dB/s) for the comfort of participants. The fit of the MIRE earplugs was considered a trained-subject method. The measured real-ear attenuation of the instrumented earplug for participants in the MIRE method is summarised in Figure 4-6. Shaded areas indicate a 95 % confidence interval for five participants and a single repetition.

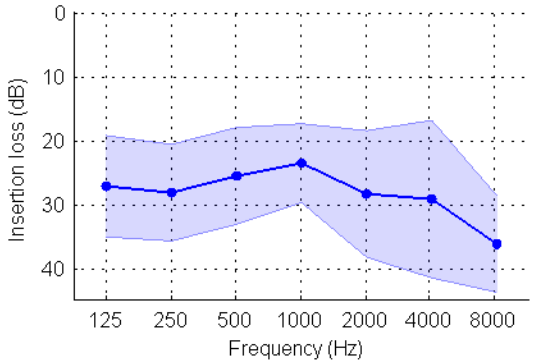
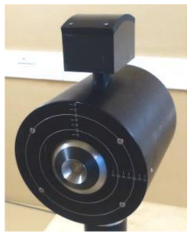


Figure 4-6: Real-ear attenuation of instrumented earplugs used for MIRE assessments.

4.3.2 ATF

The ATFs used in this work are described in Table 4-1.

Table 4-1: Acoustical test fixtures (ATFs) used in this work.

ATF	Configuration	Description	Picture
G.R.A.S. 45CA[52]	ISO 4869-3	The ISO 4869 configuration has been designed to measure the IL of earmuffs for design and quality assurance purposes in accordance with ISO 4869-3: 2007. The configuration can also be used to measure headphones. 1” microphones are located at the approximate ear entry point.	
	IEC 60318 (IEC 60318-1)	The IEC 60318 configuration uses a G.R.A.S. RA0039 ear simulator and is intended for application in supra-aural and circumaural headphone type devices. The ear simulator simulates the sound pressure level at the ear-entrance point. It has been designed in accordance with IEC 60318-1: 2009 [88].	
	IEC 60711 (IEC 60318-4)	The IEC 60711 configuration uses a G.R.A.S. RA0045 ear simulator to measure the approximate sound pressure level at the eardrum. This configuration has artificial pinnae and a hard walled ear canal. Measurements are possible for earplugs, earphones, circumaural or supra-aural devices. This configuration is designed in accordance with IEC 60711 which has since been replaced by IEC 60318-4: 2010 [89].	
Brüel & Kjær HATS Type 4100		The Brüel & Kjær HATS Type 4100 has 1/2” microphones located at the approximate ear-entrance point with rubber pinnae. The primary use of the HATS Type 4100 is for sound quality testing according to the product data [90]. The ATF has been used to assess HPDs in the literature [91].	

[52] The G.R.A.S. 45CA is designed to assess the IL of earmuffs in accordance with ISO 4869-3: 2007. The G.R.A.S. 45CA does not meet the requirements of ANSI S12.42: 2010.

4.3.2.1 Experimental setup

The difference in sound pressure level between the open-ear and occluded condition in continuous broadband noise was used to determine the IL of the HPD. Sound pressure levels were assessed with no frequency weighting and an averaging time of 30 s ($L_{eq,30s}$). Microphone signals were acquired using a signal analyser (Brüel & Kjær PULSE 3560-C). Measurements with the G.R.A.S. 45CA were carried out as monaural (right) measurements. The isolation plug [92] was fitted to the unused side (left). Measurements with the Brüel & Kjær HATS Type 4100 used the average sound pressure level of the left and right side microphones to determine the IL. ATF measurements in the REAT booth were carried out by placing each ATF on a plinth to locate the ATF at the reference point as shown in Figure 4-7.

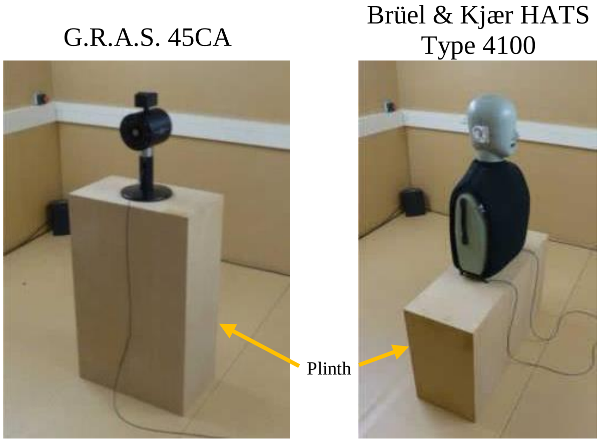


Figure 4-7: Plinth used for ATF assessments in the REAT booth.

ATF assessments in the reverberation room were carried out by placing the ATFs on a tripod so as to locate the ATF head-centre at the reference point. All other equipment was located outside the room.

4.3.2.2 Acoustic isolation

A suitable ATF should have an acoustic isolation at least 10 dB greater than the HPD IL to ensure the measured IL is minimally affected by sound transmitted via flanking paths [45, 46]. Acoustic isolation is typically assessed by occluding the transmission path with a high IL occlusion. Measurements were carried out to determine if the G.R.A.S. 45CA and the Brüel & Kjær HATS Type 4100 met the above acoustic isolation requirement. The acoustic isolation of the G.R.A.S. 45CA was assessed in the REAT booth using the acoustic isolation cup [92]. Petroleum jelly was used to seal the isolation cup against the ATF and around cables. The acoustic isolation was also determined for the case of the ATF on a chair as the plinth was suspected to be contributing unusual results. Results from acoustic isolation measurements for the G.R.A.S. 45CA (ISO 4869-3) are shown in

Figure 4-8. The IL limit is the difference between the maximum sound pressure able to be produced in the REAT booth and the inherent noise of the G.R.A.S. 45CA (ISO 4869). Acoustic isolation at and below 125 Hz was limited by the maximum noise levels able to be generated in the booth and is indicated as a measurement artefact. The minimum acoustic isolation limits from ISO 4869-3: 2007 are also plotted. The acoustic isolation of an ATF must be greater than the indicated limits (below the line in this case) for an ATF to meet the acoustic isolation requirements of ISO 4869-3: 2007.

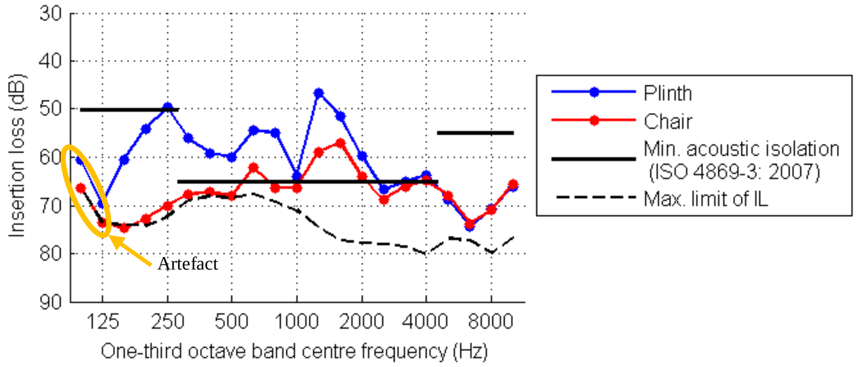


Figure 4-8: Acoustic isolation of the G.R.A.S. 45CA.

Acoustic isolation with the plinth was worse (lower) than without the plinth (chair). This could be due to vibration of the ATF induced by vibration or acoustic resonance of the plinth but this was not quantified[53]. The acoustic isolation was improved without the plinth, but was still not able to meet the requirements of ISO 4869-3: 2007 in all one-third octave bands. The plinth was used for all ATF assessments using the G.R.A.S. 45CA for convenience, as the reference point was too low for conventional tripods and the chair was too unstable. Using the plinth led to a limitation in HPD IL primarily in the one-third octave bands centred on 1250 and 1600 Hz. Acoustic isolation for the IEC 60711 and IEC 60318 configurations of the G.R.A.S. 45CA were not assessed but were assumed to be similar.

Measurements using an earmuff (see Section 4.4.2) showed the Brüel & Kjær HATS Type 4100 exhibited a consistently poor IL below 200 Hz in comparison to the G.R.A.S. 45CA ATF, REAT and MIRE methods. Acoustic isolation measurements of the Brüel & Kjær HATS Type 4100 were consequently undertaken to identify the cause. Initial attempts to achieve a high IL occlusion were unable to surpass the IL of a standard earmuff (3M™ Peltor™ H7F 290). Firstly, the rubber pinnae was removed and the microphone was occluded with a metal block (aluminium and steel were both trialled separately). The metal block was sealed to the Brüel & Kjær HATS Type 4100 with a

[53] Comparable acoustic isolation results without the plinth were obtained when the acoustic isolation measurements were repeated in the reverberation room.

reusable modelling compound. The microphone was in a 15 mm diameter blind hole in the centre of the block with a small amount of absorption material in the surrounding cavity. A photo of the block in place and the measured IL is shown in Figure 4-9. The measured IL for aluminium and steel occlusion blocks is shown in comparison to the IL determined for an earmuff (3M™ Peltor™ H7F 290 earmuff).

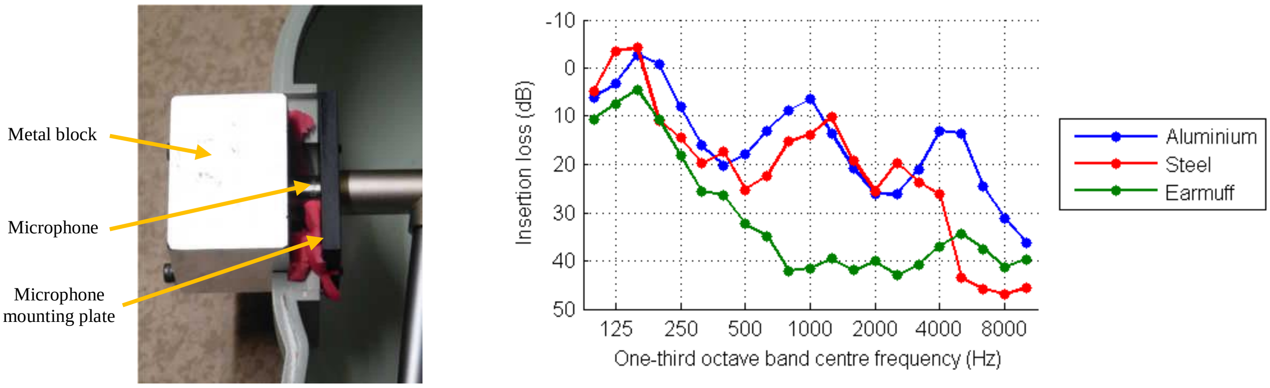


Figure 4-9: Acoustic isolation of the Brüel & Kjær HATS Type 4100 (1).

The metal block occlusions achieved relatively poor IL at most all one-third octave band frequencies, in particular at 100 and 125 Hz and mid frequencies from approximately 315 to 4000 Hz. The relatively poor IL was attributed to rigid attachment of the block to the Brüel & Kjær HATS Type 4100 and a low occluded volume which limited the amount of absorption in the cavity. Next, a larger steel cup was trialled as a high IL occlusion as it provided an increased cavity volume for absorption and thicker walls for higher sound transmission loss and increased seal width. The steel cup could also be assessed using the G.R.A.S. 45CA, whereas the original metal blocks could not due to their dimensions. The cup was made from a piece of solid round steel with an approximate diameter of 120 mm and length of 80 mm. The cup had a cavity with a diameter of 60 mm and depth of 50 mm. The foam insert of an earmuff was used for absorption in the cavity[54]. The steel cup IL was assessed using the G.R.A.S. 45CA (IEC 60711) and achieved reasonable IL, especially below 200 Hz. Next, the sealing face of the steel cup was shaped to fit the Brüel & Kjær HATS Type 4100. The fitted steel cup was sealed to the head with modelling compound and supported by a rubber band, but the clamping force was not measured. The occluded volume of the fitted steel cup was smaller than the flat cup but the differences were not quantified. The other unused ear and microphone was occluded with an earmuff but its presence did not influence the measured IL of the steel cup. A photo of the steel cup fitted to the Brüel & Kjær HATS Type 4100 and the resulting IL is shown in Figure

[54] The foam liner improved IL above 2000 Hz.

4-10. The measured IL results are shown in comparison to the IL determined for an earmuff (3M™ Peltor™ H7F 290) with the Brüel & Kjær HATS Type 4100.

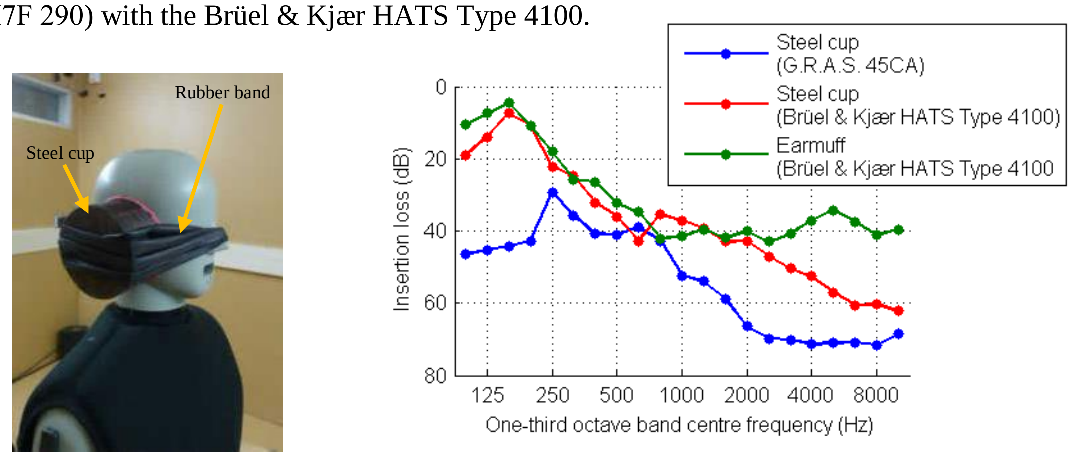


Figure 4-10: Acoustic isolation of the Brüel & Kjær HATS Type 4100 (2).

The steel cup fitted to the Brüel & Kjær HATS Type 4100 showed a similar IL to that of an earmuff (3M™ Peltor™ H7F 290) at frequencies below 2000 Hz. Upon removal there was no obvious weakness in the seal but it was difficult to tell how well the steel cup was fitted to the ATF. Results suggest that the Brüel & Kjær HATS Type 4100 ATF has an IL limit especially at low frequencies. The lightweight and relatively thin head material and poor sealing and isolation of the microphones are considered to contribute to the poor acoustic isolation. A more suitable high IL occlusion is required to better assess the acoustic isolation. A potentially suitable high IL device with damped lead cups and a high spring force headband has been described by Berger [33]. It must be noted that the Brüel & Kjær HATS Type 4100 is neither designed for HPD assessments, nor claims to be in accordance with ATF standards. HPD assessments using the Brüel & Kjær HATS Type 4100 were found to be rare in the literature, most likely as more suitable ATFs are available. Żera and Młyński [91] reported poor earmuff IL using a Brüel & Kjær HATS Type 4100 between 100 and 200 Hz, relative to other ATF methods and a MIRE method.

4.4 Results

The selected HPDs were assessed by the REAT method, MIRE and/or ATF methods. The published attenuation of the HPD was sourced from the packaging (if in accordance with AS/NZS 1270: 2002) or from the list of classified hearing protectors produced by WorkSafe NZ [93].

4.4.1 Conventional earplugs

Two conventional earplugs (see Table 4-2) were assessed by the REAT and ATF methods.

Table 4-2: Conventional earplugs assessed by REAT and ATF methods.

Earplug		Picture	Participants (Male / Female)
P1	PROSAFE Torpedo earplugs Roll-down foam type SLC 80 = 23 dB (Class 4)		(4 / 2)
P2	MOLDEX® JETZ® Pre-moulded earplugs SLC 80 = 22 dB (Class 4)		(3 / 1)

The IL determined by the REAT method (n = 6 and 4 for earplugs P1 and P2) is shown in Figure 4-11 and compared to the published attenuation (assumed n = 20). The measured and published real-ear attenuations were also compared for each test signal using Welch's t-test [94], assuming normally distributed data. The calculated p-value that the means are equivalent for each test signal is shown in Figure 4-11 in italics. The shaded areas indicate 95 % confidence intervals for participant numbers in Table 4-2 with a single repetition.

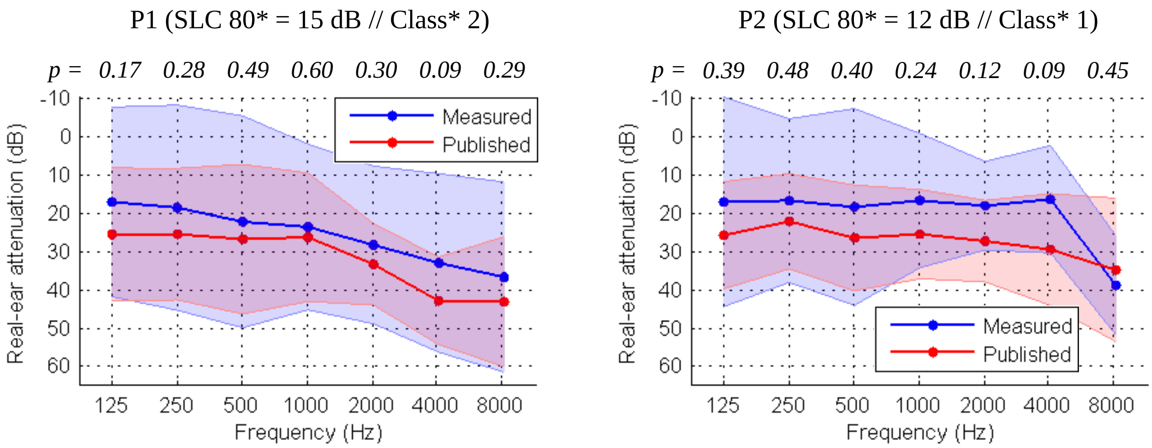


Figure 4-11: Measured and published real-ear attenuation for conventional earplugs.[55]

The measured real-ear attenuation gave a lower mean with higher standard deviations compared to published results. The null hypothesis could not be rejected at the common statistical significance level of 5 %; however, if the statistical significance was relaxed to 9 % the null hypothesis could be rejected for the 4000 Hz test signal. Measured individual real-ear attenuation for each test signal was highly variable with differences of up to 30 dB amongst participants. In some individual cases an IL

[55] SLC 80 and class are marked with a * as the calculation was not in accordance with AS/NZS 1270: 2002 due to limited participant numbers.

close to zero was determined where the fit of the earplug was observed to be very poor. Both earplug types were also assessed by the ATF method using the G.R.A.S. 45CA (IEC 60711). Results are shown in Figure 4-12. The shaded areas indicate 95 % confidence intervals for measurements obtained by the REAT method (as in Figure 4-11 above). ATF measurements had standard deviations of less than 1 dB for three repetitions re-fitted each time and have been omitted. The maximum IL was the difference between the open-ear sound pressure level and the inherent noise of the ATF. The IL of the P1 earplug determined by the ATF method was limited by maximum IL.

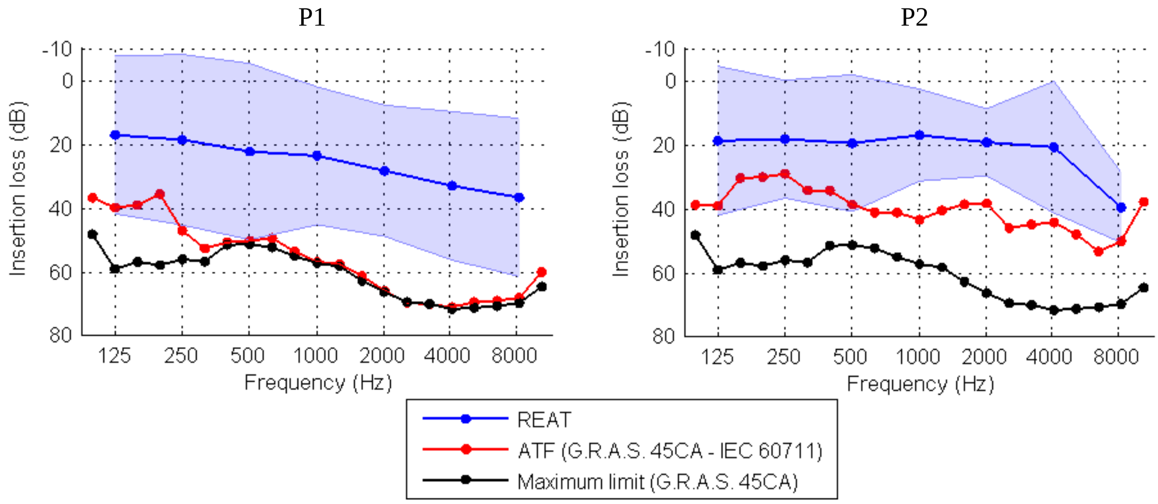


Figure 4-12: IL for conventional earplugs determined by the REAT and ATF methods.

The earplug IL determined by the ATF method significantly exceeded the real-ear attenuation for most one-third octave band test signals. Refer to Section 4.5.1 for further discussion of these results.

4.4.2 Conventional earmuffs

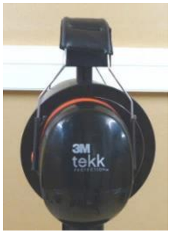
Five earmuffs (see Table 4-3) were assessed by the REAT, MIRE and ATF methods for conventional IL. Earmuffs were purchased locally except for the EMST earmuff which was sourced from the USA[56]. The EMST earmuff and ANR headphone were assessed with batteries fitted but electronics turned off. The ANR headphone was assessed without its chord connected for the purposes of this work[57]. Methods for determining the attenuation of the EMST earmuff and ANR headphone at elevated sound pressure levels are presented in Sections 4.4.3 and Section 4.4.4. The IL determined by the REAT method (n = 5 or 6, see Table 4-3) for the selected earmuffs is shown in Figure 4-13 and compared to the published attenuation (assumed n = 16). No rating in accordance with AS/NZS 1270:

[56] The EMST earmuff was purchased through www.amazon.com.

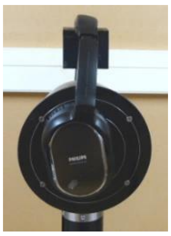
[57] The chord was not connected as the assessment of the ANR function (see Section 4.4.4) was the main goal of assessing this earmuff. The chord should be included for a real-world representation of the earmuffs performance, however this was not considered here.

2002 could be found for earmuff M4. Consequently, the octave band attenuation data provided with the M4 earmuff was used[58]. The measured and published real-ear attenuations were also compared for each test signal using Welch's t-test [94], assuming normally distributed data. The calculated p-value that the means are equivalent for each test signal is shown in Figure 4-13 in italics.

Table 4-3: Earmuffs assessed by the REAT, MIRE and ATF methods.

Earmuff		Photos		Participants (M/F)
M1	3M™ Peltor™ H7F 290 SLC 80 = 31 dB (Class 5)			(3 / 2)
M2[59]	3M™ Peltor™ H10A-290 SLC80 = 33 (Class 5)			(3 / 2)
M3	GARDWELL™ Economy Class 5 Earmuff Model # 550462 SLC80 = 26 dB (Class 5)			(3 / 2)

M4	3M™ Peltor™
	Tactical™ Pro
	Model # MT15H7F
	NRR = 26 dB
				(4 / 1)

M5	Philips™ ANR headphones Model # SHN9500 SLC 80 = N/A[60]			(5 / 1)

[58] It was assumed that the attenuation of the M4 earmuff was carried out using a trained-subject method as the earmuff had an NRR rating. The NRR is understood to be based on a trained-subject method.

[59] This earmuff was sold as a 3M™ TEKK™ Protection™ Professional Earmuff Model # 90561. The SLC80 was calculated from octave band data and the earmuff had a NRR = 30 dB.

[60] The headphone is not a HPD, but has been treated as one for this work.

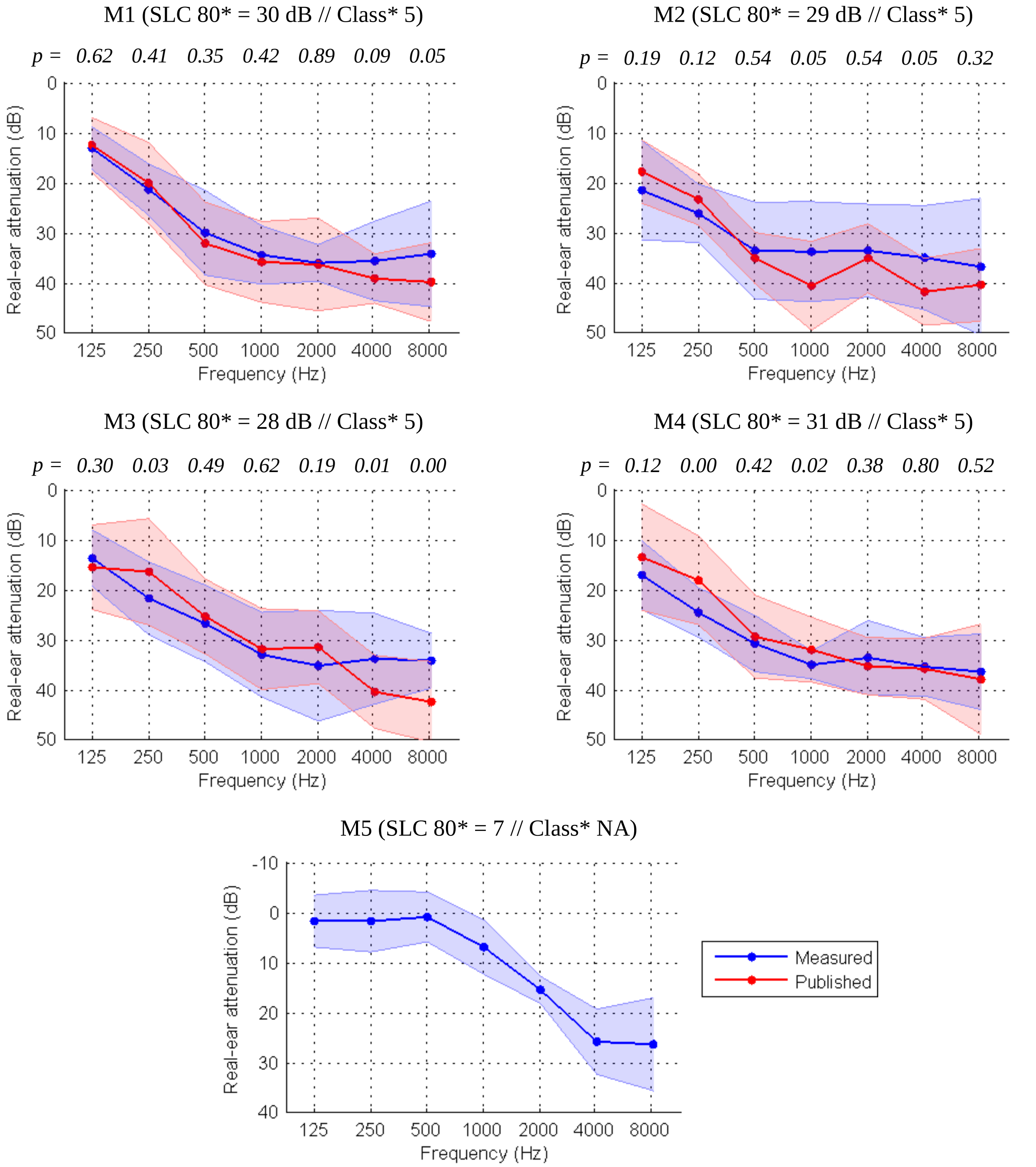


Figure 4-13: Measured and published real-ear attenuation of selected earmuffs.[61]

The measured real-ear attenuation gave generally good agreement with the published attenuation but there were some significant differences for individual test signals. The earmuffs in Table 4-3 were also assessed by the MIRE method and the ATF method using the G.R.A.S. 45CA (all configurations) and Brüel & Kjær HATS Type 4100 with results summarised in Figure 4-14. Shaded areas indicate 95 % confidence intervals for the REAT (see Table 4-3 for n) and MIRE (n = 5)

[61] SLC 80 and Class are marked with an * as the calculation was not in accordance with AS/NZS 1270: 2002.

methods. The standard deviation in the ATF method measurements was found to be less than 1 dB and has been omitted.

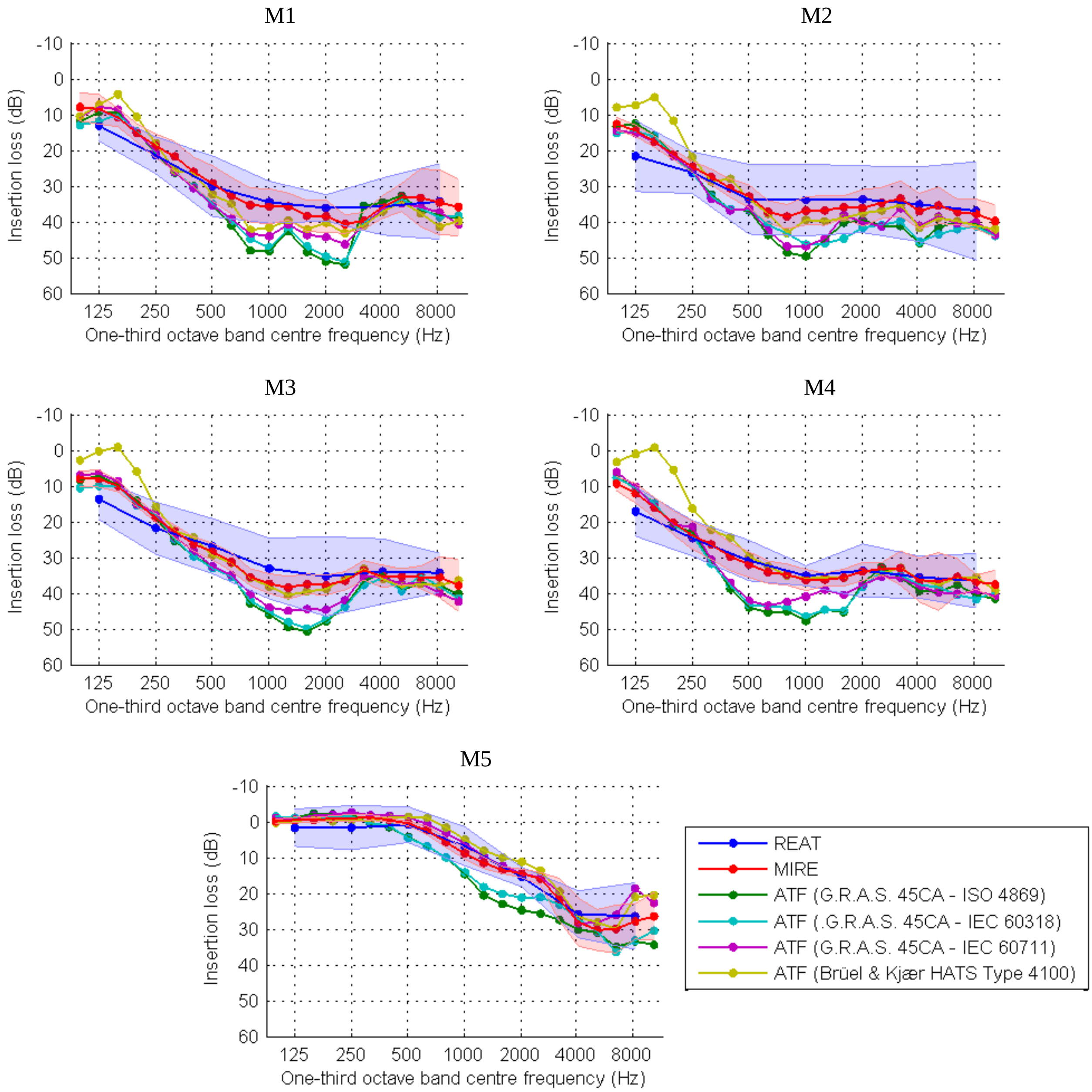


Figure 4-14: IL of earmuffs determined by the REAT, MIRE and ATF methods.

The difference of the MIRE method and each ATF method relative to the REAT method was determined for each earmuff type shown in Figure 4-14. The MIRE method shows the best agreement with the REAT method except for low frequencies (at and below 250 Hz). The Brüel & Kjær HATS Type 4100 has noticeably poor agreement compared to all other methods at low frequencies (below 250 Hz). Refer to Section 4.5.2 for further discussion of these results.

4.4.3 EMST earmuff

Assessment of a single EMST earmuff (3M™ Peltor™ Tactical™ Pro) provided an opportunity to evaluate assessment methods for level-dependent HPDs. The conventional IL of the earmuff was assessed by the REAT, MIRE and ATF methods (see Section 4.4.2). The EMST system was assessed at elevated sound pressure levels using the Brüel & Kjær HATS Type 4100 and G.R.A.S. 45CA (IEC 60711) ATFs in the REAT booth and in the reverberation room. The volume control of the EMST earmuff was set at unity gain. The IL was found to vary by up to 10 dB between left and right cups depending on frequency, but only measurements obtained for the right cup are presented below. IL was assessed in the REAT booth and the reverberation room at a range of overall sound pressure levels from 70 to 105 dB (see Figure 4-1), with the EMST system off and on. Results are summarised in Figure 4-15 and Figure 4-16.

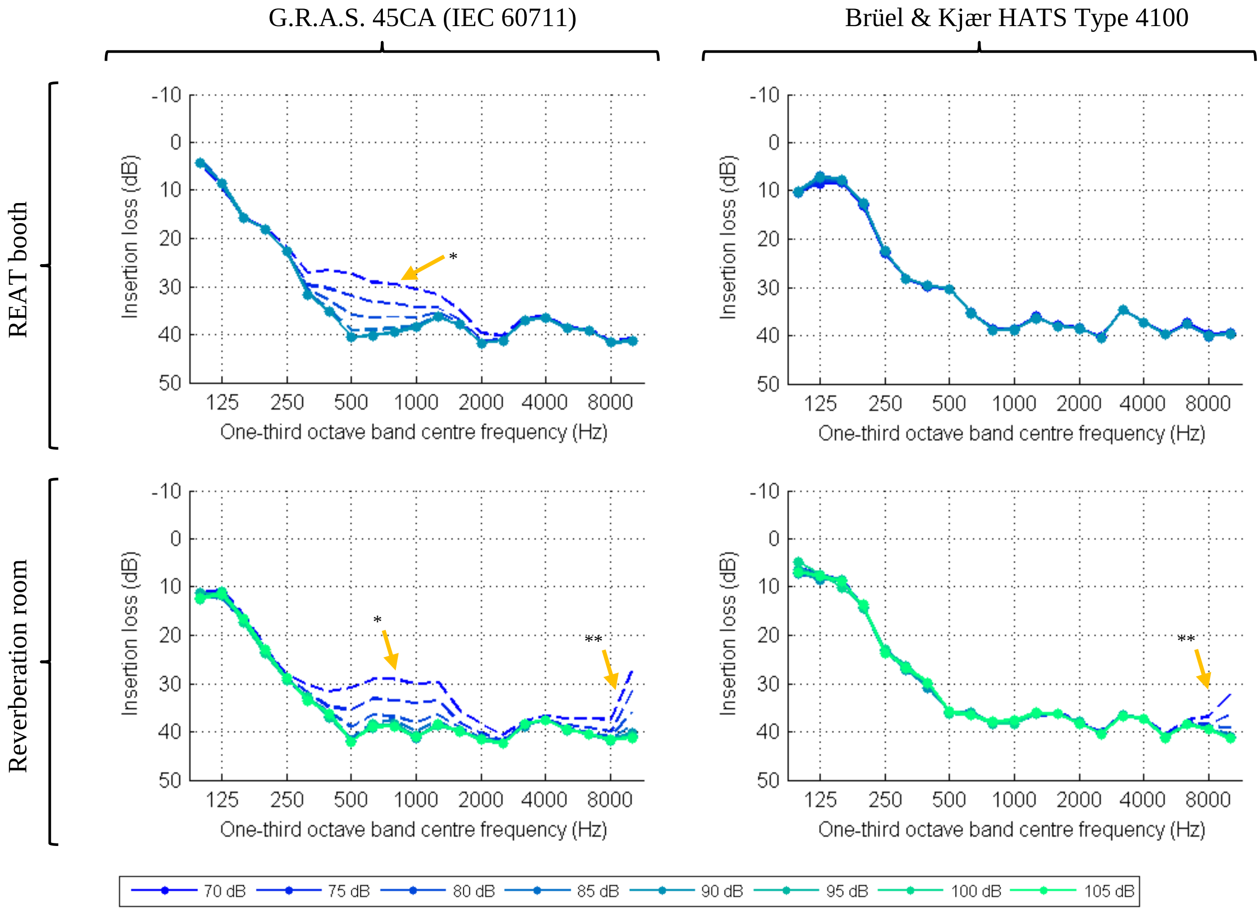


Figure 4-15: IL of EMST earmuff with system off.

The dashed lines indicate a measurement artefact (*) due to the low sound pressure levels not being high enough to determine the IL of the EMST earmuff without influence from the inherent noise of the ATF. The higher frequency levels are limited in the reverberation room (**) due to the relatively low sound levels in the reverberation room (see Figure 4-1). IL results for the EMST earmuff with the system on determined in the reverberation room is shown in Figure 4-16.

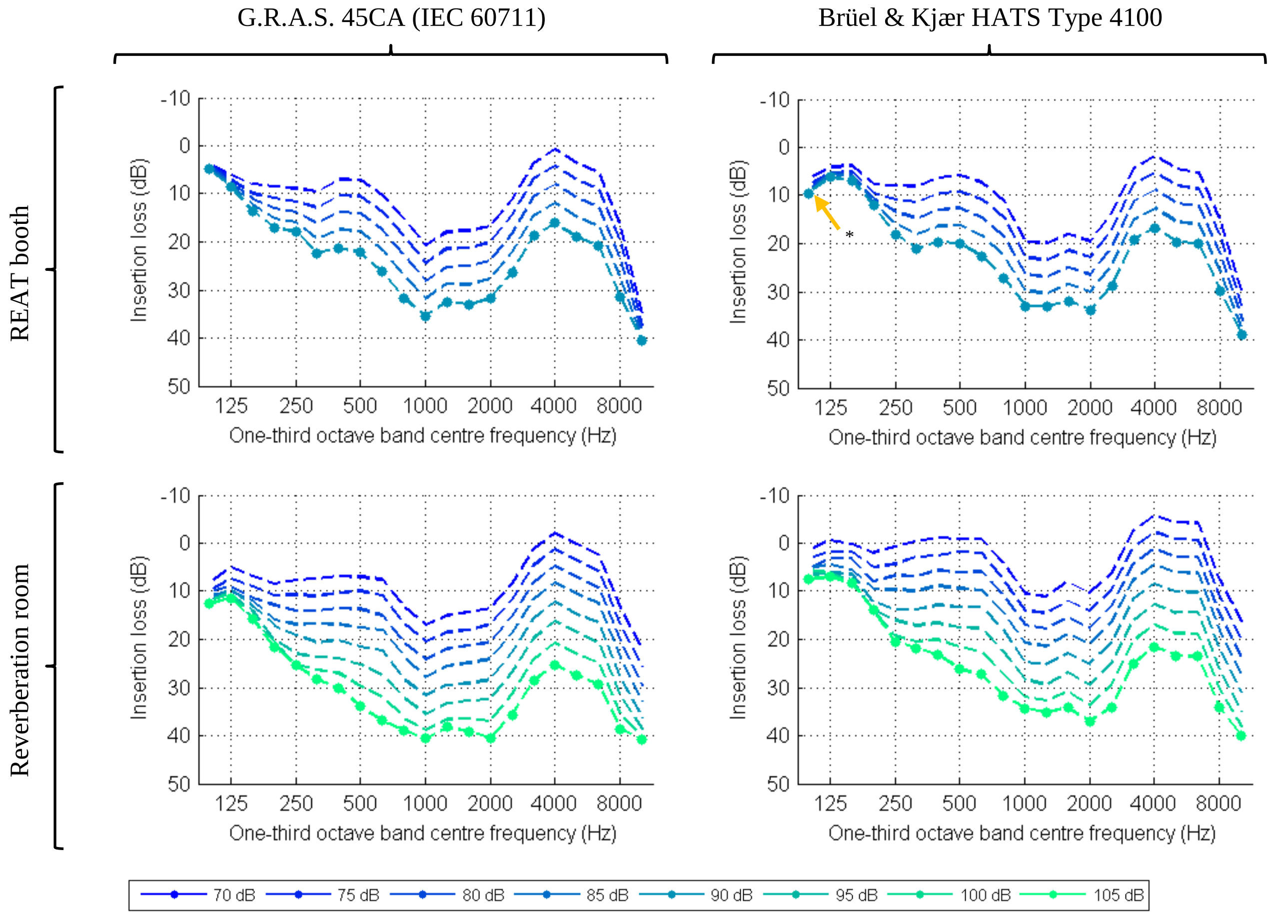


Figure 4-16: IL of EMST earmuff with system on.

Results are shown as dashed lines as the sound pressure levels produced in the reverberation room were not high enough to determine the attenuation of the earmuff with the EMST system on, especially above 250 Hz. The lower than required sound levels are illustrated by the IL results not converging to an IL limit at the higher sound pressure levels. In general, results obtained with both ATFs in the REAT booth and reverberation room displayed similar trends. The IL at a given incident sound pressure level differed between the two assessed ATFs for measurements in the reverberation room which was attributed to a possible error in level calibration but this was not quantified. Measurements obtained with the Brüel & Kjær HATS Type 4100 in the REAT booth showed a slight increase in IL at 100 Hz (* in Figure 4-16) compared to the IL obtained with the G.R.A.S. 45CA (IEC 60711) but this was not able to be explained. Refer to Section 4.5.3 for further discussion of these results.

4.4.4 ANR headphone

Assessment of a single ANR headphone (Philips™ SHN9500) provided an opportunity to evaluate assessment methods for ANR earmuffs. The conventional IL of the ANR headphone (ANR off) was assessed by the REAT, MIRE and ATF methods (see Section 4.4.2). The ANR headphone was assessed in the REAT booth and reverberation room using the Brüel & Kjær HATS Type 4100 and G.R.A.S. 45CA (IEC 60711) to determine the ANR component of IL. Only a single side (right) of the headphone was assessed. The methodology was the same as the EMST earmuff where the IL was assessed in the REAT booth and reverberation room at overall sound pressure levels of 70 to 105 dB (see Figure 4-1) with the ANR system on and off. The ANR component of the IL ($\mathrm{IL_{ANR}}$) was determined in each one-third octave band by Eq. 4.1.

$$\mathrm{IL_{ANR}} = \mathrm{IL_{Total}} - \mathrm{IL_{Conventional}} \qquad \text{Eq. 4.1}$$

Where: $\mathrm{IL_{Total}}$ = Measured IL with ANR system turned on.

$\mathrm{IL_{Conventional}}$ = Measured IL with ANR system turned off.

The ANR component of IL with the two ATFs in the REAT booth and in the reverberation room is summarised in Figure 4-17.

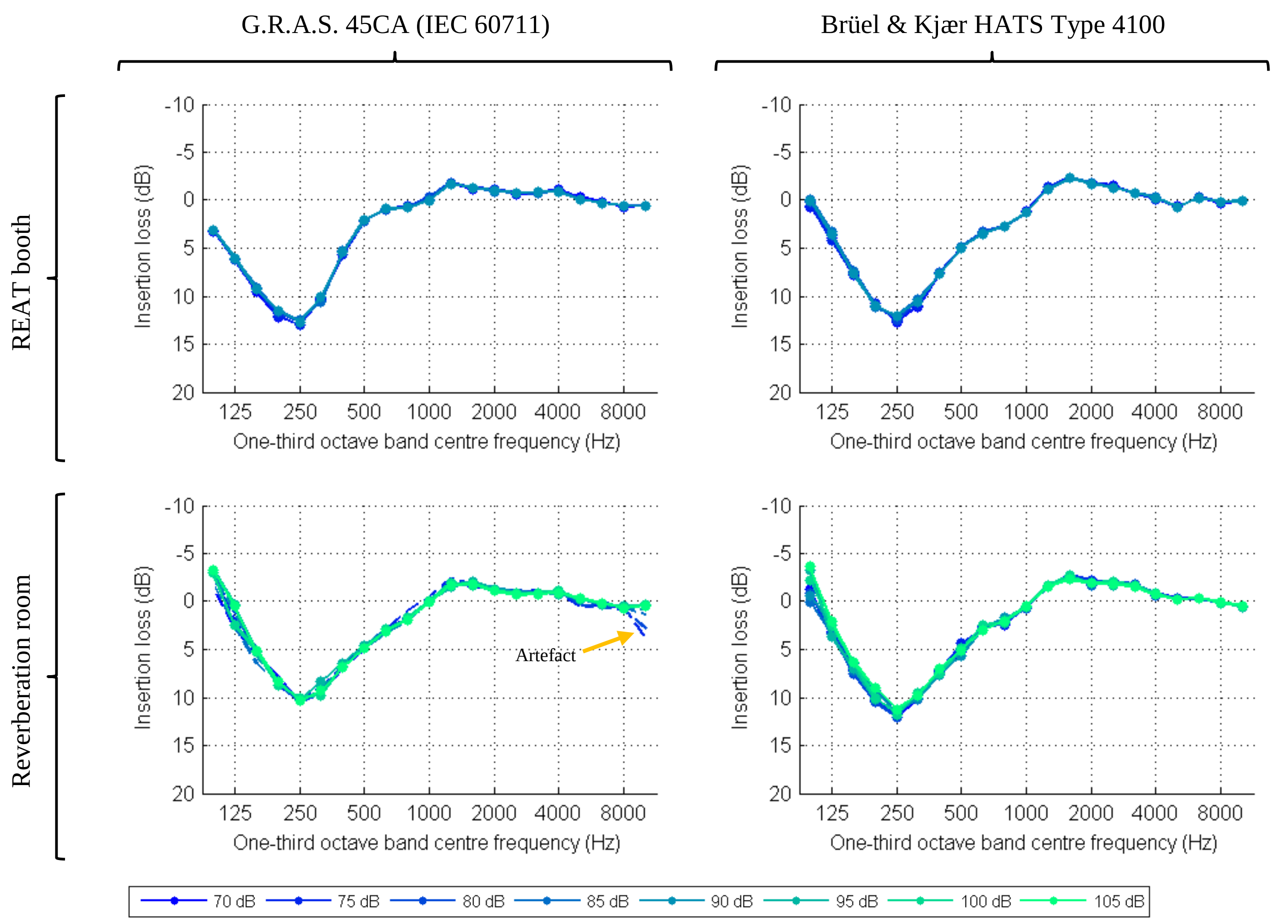


Figure 4-17: ANR component of IL for the ANR headphone.

The inherent noise of the G.R.A.S. 45CA (IEC 60711) was encountered at high frequencies in the reverberation room and is indicated as a measurement artefact in Figure 4-17. Results indicate that the ANR provides a consistent and stable level of attenuation (IL) up to an overall sound pressure level of 105 dB. There are some slight differences for the ANR component of IL between sound field and ATF type, but these were not accounted for. The internal noise of the ANR headphone could also be measured in the REAT booth but was found to be less than an overall sound pressure level of 35 dB. Although the internal noise was audible, the levels are low and of little concern from an HPD perspective. Refer to Section 4.5.4 for further discussion of these results.

4.4.5 Helmet

An abrasive blasting helmet[62] (RPB® NOVA 3™) was assessed by the REAT, MIRE and ATF methods. The helmet is worn to protect the wearer and provides ventilation and cooling when connected to an air supply. The helmet encloses the whole head and attaches to a long sleeved blast jacket as shown in Figure 4-18.

Figure 4-18: Abrasive blasting helmet.

The helmet had a ventilation tube which was fitted, but the ventilation system was not connected for measurements presented here. The presence of the ventilation tube and lack of ventilation system (i.e. no air running) was considered to have a negligible effect on the measured IL of the helmet[63], although it did not represent the real-world use of the abrasive blasting helmet (see Section 4.5.5 for further discussion).

[62] The abrasive blasting helmet can also be referred to as a sand or shot blasting helmet. The manufacturer (RPB®) markets it as a respirator.

[63] The effect of the tube was initially not assessed. To assess if the tube was contributing to the measured IL as a leak, the helmet IL was assessed using the G.R.A.S. 45CA (ISO 4869-3) with the tube connected; with the ventilation tube disconnected but the connection point blocked and sealed; and the ventilation tube disconnected but the connection point left open. The assessment was carried out subsequent to the measurements presented in this chapter and found there was no significant difference in measured IL with or without the ventilation tube connected and with or without the connection point blocked and sealed.

Three participants (two male and one female) were used for REAT assessments of the abrasive blasting helmet. Participants were assessed by the REAT method for the helmet only, earplugs (PROSAFE Torpedo[64]) only and the helmet and earplugs (dual protection). The order of assessment was earplugs, helmet and earplugs (dual protection) and helmet only so that only one earplug fitting was required. The results from REAT assessments (n = 3) are shown in Figure 4-19. Shaded areas indicate 95 % confidence intervals for three participants and a single repetition for each participant. The indicated measurement artefact in Figure 4-19 for the helmet and earplugs (dual protection) was due to encountering speaker distortion at an in-band sound pressure level of approximately 85 dB for the 8000 Hz test signal.

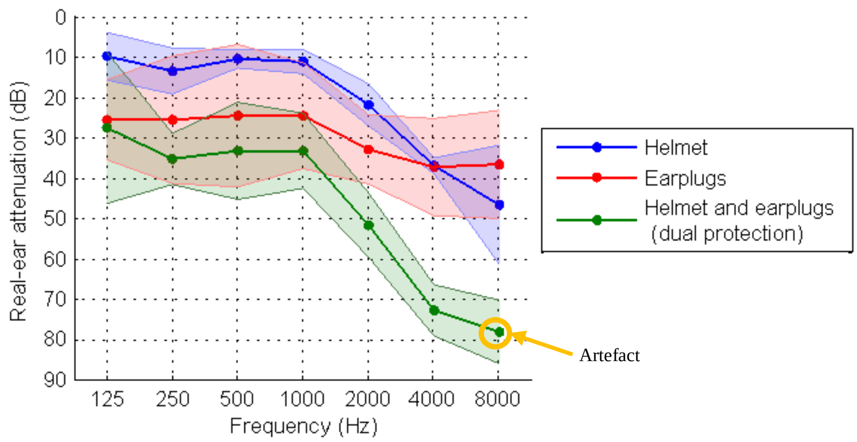


Figure 4-19: Real-ear attenuation of abrasive blasting helmet, roll-down foam earplugs and the helmet and earplugs (dual protection).

The standard deviation for the helmet is low compared to the earplugs and the combination of helmet and earplugs for all but the 8000 Hz test signal. A low standard deviation for the helmet measurements was expected as the helmet fit is less crucial than earmuffs or earplugs, although this is not conclusive due to the low participant numbers. The helmet was also assessed by the ATF and MIRE methods. Results from the REAT (n = 3), MIRE (n = 5) and ATF methods are shown in Figure 4-20. Shaded areas indicate 95 % confidence intervals for the REAT and MIRE methods for three participants and a single repetition. The variation using the ATF test methods was found to be typically less than 1 dB and has been omitted.

[64] This group of participants was separate from those presented in Section 4.4.1.

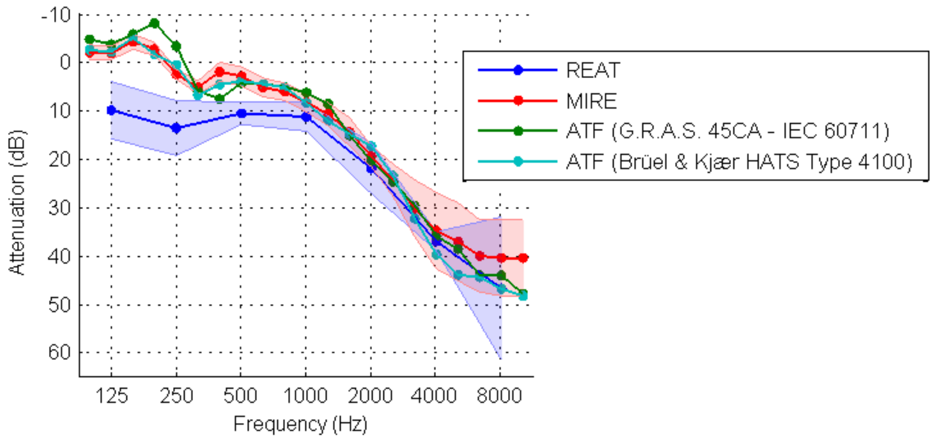


Figure 4-20: IL of the abrasive blasting helmet determined by the REAT, MIRE and ATF methods.

The results obtained by the MIRE and ATF methods show reasonable agreement over the whole frequency range. Results obtained by the MIRE and ATF methods generally agree with the REAT method at 1000 Hz and above. Below 1000 Hz there was less agreement between real-ear attenuation and the IL assessed by the ATF and MIRE methods. A negative IL at and below 250 Hz was measured by the ATF and MIRE methods. Refer to Section 4.5.5 for further discussion of these results.

4.5 Discussion

4.5.1 Conventional earplugs

The measured real-ear attenuation of earplugs was generally less than the published attenuation (see Figure 4-11). The determined SLC 80* of 15 dB and 12 dB corresponded to Class* 2 and Class* 1 for earplug P1 and P2 respectively. The published attenuation was an SLC 80 of 23 dB and 22 dB corresponding to Class 4 and Class 4 for earplug P1 and earplug P2 respectively. SLC 80 and Class are marked with a * as the as the calculation was not in accordance with AS/NZS 1270: 2002 due to the low participant numbers (five and four compared to the required 20 in AS/NZS 1270: 2002). The effect of low participant numbers is discussed further in Section 4.5.6. ISO 4869-1: 1990 offers guidance to compare real-ear attenuation for the same model of earplug between laboratories. The reproducibility for earplugs between laboratories with 95 % confidence is 8 dB at 125 Hz, 6.5 dB for 250 Hz to 4000 Hz and 6.5 dB at 8000 Hz. The differences in real-ear attenuation between the measured and the published attenuation were larger than the between-lab uncertainty in ISO 4869-1: 1990, but it is difficult to identify the reason/s for the larger than expected differences. It is important to note that the uncertainty quoted in ISO 4869-1: 1990 is for comparison between laboratories using a trained-subject method, whereas AS/NZS 1270: 2002 is a subject-fit method and the uncertainty may be larger than trained-subject methods. In addition the uncertainty in

ISO 4869-1: 1990 is based on between laboratories comparison with 16 participants each, whereas five participants were assessed here. Comparisons between different REAT standard methods do not currently exist to the author's knowledge but comparisons of subject-fit vs. trained-subject methods have found subject-fit methods to generally give lower IL [65, 95]. In an inter-laboratory comparison by Murphy, et al. [95], the variance for repeatability (within the same subject) was found to be higher with less experimenter involvement but the variance for reproducibility (between subjects) was more consistent with less experimenter involvement.

Real-ear attenuation for both models of earplug was highly variable amongst participants and was attributed to difficulties in fitting the earplugs. The high variability was exacerbated by only assessing two earplug models and the relatively low participant numbers. Participants' fitting of earplugs was observed to be poor in some cases. The fitting difficulties have been identified to contribute to the relatively high standard deviation for earplugs compared to other HPD types [96-98]. Comparable average attenuations could only be achieved by deeply inserting the earplugs near the limit of comfort (assessed by the author via self-testing) for both earplugs P1 and P2. The material of earplug P1 had variable material consistency (some earplugs had noticeably less formable foam) which may have also contributed to fitting difficulties. Participants in the presented earplug measurements all met the criteria in AS/NZS 1270: 2002, which included normal hearing thresholds and minimal experience with fitting HPDs. Results from the assessment of earplugs are indicative of their attenuation in general; however, further testing should be carried out with additional earplug models and more participants.

IL determined by the ATF method far exceeded real-ear attenuation for both earplug types. Similar earplug ATF results have been published using an ATF with hard-walled ear canals. The agreement between ATF and REAT methods can be improved by using artificial intra-aural skin [99, 100]. ANSI S12.42: 2010 specifies an ATF must have flesh simulation and long ear canals which the G.R.A.S. 45CA (IEC 60711) does not comply with. ATF determined results reported here are unrealistic compared to the IL determined by the REAT method; however, improved agreement may be obtainable with more realistic ATFs.

4.5.2 Conventional earmuffs

Measurements of the real-ear attenuation for earmuffs compared reasonably well with the published attenuation (see Figure 4-13) and showed improved agreement when compared to the comparison between the measured and published attenuation for earplugs (see Figure 4-11). Improved agreement with the published attenuation for earmuffs was expected as earmuffs are much easier to fit than earplugs for untrained participants. ISO 4869-1: 1990 also offers guidance to compare real-ear attenuation for earmuffs between laboratories. The reproducibility between laboratories with 95 % confidence is 4 dB at 125 Hz, 5 dB for 250 to 4000 Hz and 6.5 dB at 8000 Hz. The difference in real-ear attenuation between the published attenuation and that measured in this work varies with the model of HPD, but overall the agreement is considered to be good. The MIRE method had the best agreement with REAT measurements and the MIRE relative to REAT differences are comparable (similar magnitude and trend) to a study of four types of earmuff [50]. The type of HPD also appears to have an influence on the difference between REAT and other assessment methods, but further work is needed to quantify this effect. For ATF methods there are two distinct trends. The Brüel & Kjær HATS Type 4100 shows reasonable agreement with REAT for frequencies 500 Hz and higher. The poor low frequency behaviour is attributed to the poor acoustic isolation of the Brüel & Kjær HATS Type 4100. The G.R.A.S. 45CA has generally poor agreement with REAT results at all frequencies with some slight variations depending on the configuration used. The ISO 4869-1 configuration gave the worst agreement with results obtained by the REAT method. The MIRE and ATF methods measured lower IL compared to REAT at low frequencies (125 and 250 Hz). This low frequency discrepancy has been attributed to physiological noise masking of low frequency test signals in the REAT method [41]. REAT is the only method which captures the variation in participants and their behaviour with HPDs. REAT is also the method used as a reference standard and is the method most frequently used for published HPD attenuation [25].

4.5.3 EMST earmuff

A single EMST earmuff was assessed as an example of level-dependent type HPDs. Other level-dependent HPDs such as passive amplitude-sensitive devices do not enhance sound pressure level beneath the HPD, but the general assessment method implemented here is applicable to other types of level-dependent HPDs. The conventional IL of the HPD (EMST system off) was similar to that of a regular earmuff (see Section 4.4.2). The advantage of EMST HPDs is that low level sounds can be heard normally due to the sound being restored beneath the HPD. The crucial function of such HPDs is that they sufficiently attenuate high level noise. The sound pressure levels were not high enough in the REAT booth or the reverberation room to fully characterise the EMST system. Continuous noise methods in ANSI S12.42: 2010 for level-dependent HPDs require the measurement to be made at overall sound pressure levels of 75, 85, 95 and 105 dB (+/- 1 dB or in smaller steps) to predict the cut-off point. Overall sound pressure levels of 105 dB were achieved in the reverberation room but the frequency response was not sufficiently flat. ANSI S12.42: 2010 specifies a broadband sound pressure level of at least 115 dB with less than 10 dB of variation from 100 to 10000 Hz whereas the sound pressure level in the reverberation room was mostly confined to a low to mid frequency range (250 to 630 Hz). The occluded sound pressure levels measured by the G.R.A.S. 45CA (IEC 60711) and Brüel & Kjær HATS Type 4100 in the reverberation room are shown in Figure 4-21. The EMST off level shows the minimum sound level measured with the earmuff fitted and is attributed to the inherent noise of the measurement system and the background noise in the reverberation room. The inherent noise is used to indicate the sound pressure level determined by the ATF with the EMST system on and no external sound present.

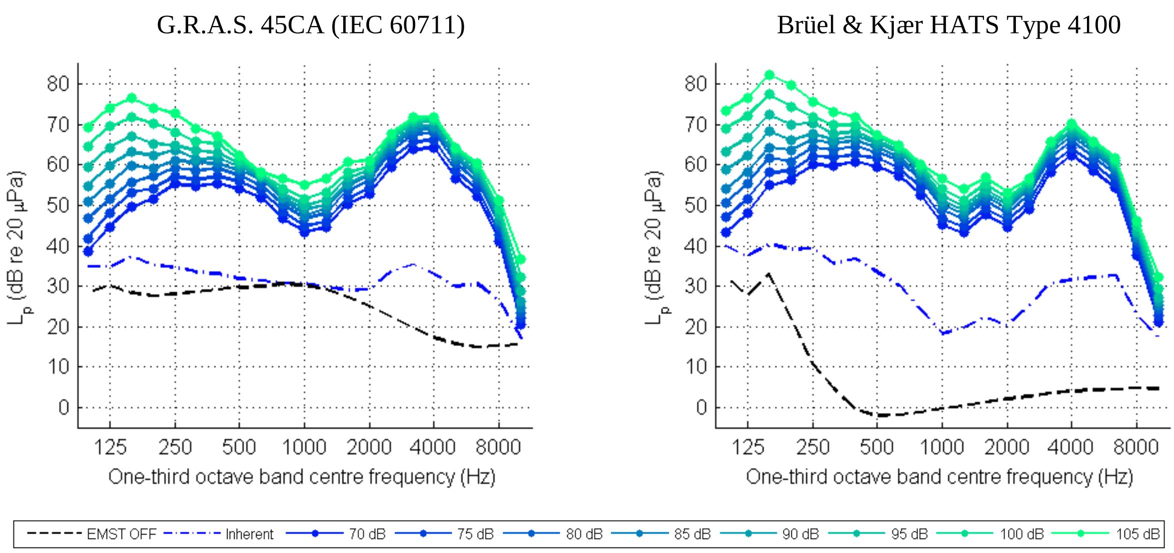


Figure 4-21: Beneath cup sound pressure level for the EMST earmuff with system on.

There is some slight variation between the two ATFs but they each show a similar trend. The overall occluded sound pressure level measured by the G.R.A.S. 45CA (IEC 60711) was 83 dB, thus the noise exposure limit (85 dB) may not have been exceeded[65]. In addition the low frequency (below 500 Hz) sounds were still being restored beneath the HPD, which suggests the EMST system may be frequency dependent or the EMST restoring function has a limited frequency range as the IL measurements at low frequencies did not converge to a maximum limit (see Figure 4-16). The EMST system should be assessed at sound pressure levels exceeding the restoring function of the EMST

[65] This calculation should include a correction for the transfer function of the open-ear to make it relevant to end-users of HPDs.

system for frequencies from 100 to 10000 Hz, but this is a demanding specification due to the high sound pressure levels and wide frequency range required.

Assessing the attenuation of level-dependent HPDs in impulse noise is also an important consideration as level-dependent HPDs are most suited to use in loud intermittent noise environments (e.g. gun shots, hammering). For level-dependent HPDs, a typical assessment in impulse noise is to determine the peak sound reduction in impulse noises with peak levels ranging from 130 dB up to 170 dB [26]. Assessment of HPD attenuation in impulse noise is normally carried out using the ATF method where the instrumentation must be able to measure high level impulse noise up to 180 dB according to ANSI S12.42: 2010. Impulse noise measurements have not been assessed here but have been discussed in the literature review (see Section 1.1.7). Assessing the attenuation of HPDs in impulse noise should be considered in future.

4.5.4 ANR headphone

A single ANR headphone was assessed as an example evaluation of HPD test methods for ANR HPDs. The conventional IL of the ANR headphone (with the ANR system off) was much worse than a regular earmuff and had essentially no attenuation at and below 1000 Hz. The low attenuation at low frequencies made it a near ideal example to demonstrate the attenuation of ANR HPDs as ANR is most effective below 1000 Hz. The REAT and ANR IL for the ANR headphone is summarised in Table 4-4. Overall IL was calculated using Eq. 4.2 for each one-third octave band. The lowest value for the active component of IL ($\mathrm{IL}_{\mathrm{ANR}}$) between the two ATF methods was used for determining the overall IL.

$$\mathrm{IL}_{\mathrm{Overall}} = \mathrm{IL}_{\mathrm{REAT}} + \mathrm{IL}_{\mathrm{ANR}} \qquad \text{Eq. 4.2}$$

Where: $\mathrm{IL}_{\mathrm{Overall}}$ = Estimated overall IL with ANR system turned on.

$\mathrm{IL}_{\mathrm{REAT}}$ = Meausured IL with ANR system turned off.

$\mathrm{IL}_{\mathrm{ANR}}$ = IL measured by the ATF method in each one-third octave band.

Table 4-4: Conventional and ANR component of IL for the ANR headphone.

		One-third octave band centre frequency (Hz)						
		125	250	500	1000	2000	4000	8000
IL_{REAT}	μ	1.8	1.8	1.0	7.0	15.5	25.8	26.3
	σ	2.6	3.1	2.5	2.8	1.4	3.3	4.7
IL_{ANR}	G.R.A.S. 45 CA (IEC 60711)	5.9	12.8	2	0	-1.1	-0.7	0.6
	Brüel & Kjær HATS Type 4100	3.7	12	5.1	1.2	-1.6	-0.1	0.3

The two ATFs gave similar results for the ANR component of IL, with similar trends to those reported in the literature [53, 54]. Rudzyn and Fisher [54] found active IL to be less effective at high sound pressure levels, but this was not observed here for overall sound pressure levels up to 105 dB. ANR HPDs should be assessed at higher continuous sound pressure levels to confirm their attenuation at high sound pressure levels and consider impulse noise if applicable.

The ANR headphone with ANR on had an SLC 80* = 5 dB (Class* N/A[66]), compared to the ANR off SLC 80* = 7 dB (Class* N/A). The HPD rating is worse with ANR on than ANR off using the classification calculation in AS/NZS 1270: 2002 as the noise spectrum used in the classification method calculation places a greater emphasis on the medium frequency components than the low frequencies. The slight negative IL at medium frequencies, referred to as boosting by Rudzyn and Fisher [54], and the poor IL of the ANR headphone led to the decrease in SLC 80 rating with the ANR system on. SLC 80 and Class are marked with a * as the as the calculation was not in accordance with AS/NZS 1270: 2002. ANR HPDs have been shown to be useful in the rare circumstance of high-level noises with significant low-frequency components, typically limited to aviation and military exposures [101, 102]. For most cases it would appear that ANR is unnecessary; however, ANR may be suitable in some low frequency dominated noise environments. The octave band method should be used to calculate the HPDs attenuation in place of the classification method.

[66] SLC 80 must be greater than 10 dB for the classification method to be used.

4.5.5 Helmet

The real-ear attenuation of the helmet and earplugs (dual protection) exceeded 70 dB for the 4000 and 8000 Hz test signals. This is in general agreement with an estimated bone conduction limit with the head covered of 75 dB at 4000 and 8000 Hz [33]. A model for predicting the attenuation of earplugs and earmuffs worn in combination by simple addition of the IL of the individual ILs and logarithmic subtraction of the bone conduction limit has been previously proposed [103, 104], but the simple addition model is only applicable at 2000 Hz and above [104]. Simple addition was used in this case but the discussion is only applicable to the high frequencies (2000 Hz and above). A bone conduction correction was not implemented as it was unclear what limit should be applied as discussed later in this section. The real-ear attenuation (n = 3) for the helmet and earplugs worn together (dual protection) is shown in Figure 4-22 in comparison to the sum of the individual real ear attenuations (n = 3) for the helmet and earplugs (estimated).

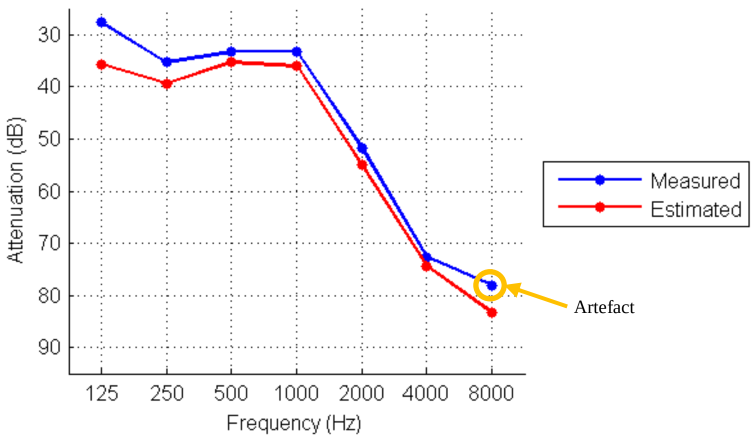


Figure 4-22: Comparison of the measured and estimated real-ear attenuation for the abrasive blasting helmet and earplugs (dual protection).

The measured and the estimated real-ear attenuation had reasonable agreement from 500 to 4000 Hz. Improved agreement between the measured and the estimated IL at 8000 Hz may have been achieved if the speaker distortion artefact was not encountered at higher sound pressure levels. A possible explanation for simple addition providing a reasonable estimate is that the helmet has no seal around the ear and the helmet has minimal contact with the head and no contact with the earplug. The helmet has foam pads which are intended to cover the ear; however, the fit of the pads was poor as shown in Figure 4-23. Similar poor fits were observed for participants in the REAT method.

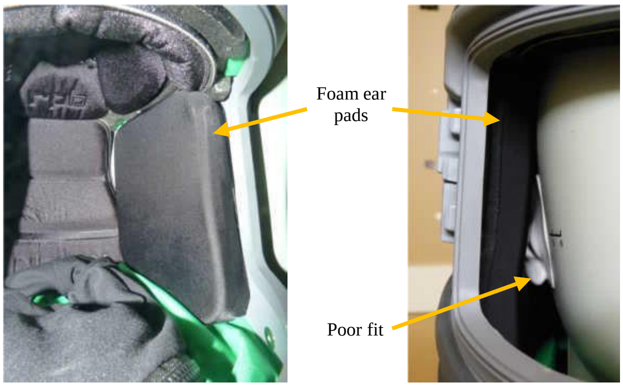


Figure 4-23: Foam ear pads to cover the ear in the abrasive blasting helmet.

Zwislocki [35] identified IL limits of approximately 40 to 65 dB over the frequency range of 100 to 10,000 Hz in one of the original works on the maximum IL able to be achieved by HPDs. More recently, Ravicz and Melcher [32] assessed participants wearing earplugs, earmuffs and a custom made acoustic helmet (fully covering the head) by a MIRE method and a variation of the REAT method. Berger, et al. [33] assessed participants fitted with deeply-inserted foam earplugs and an ANR earmuff, and deeply inserted earplugs worn with a flight helmet which partially covered the face with a visor[67]. Data from Berger, et al. [33] has also been tabulated in ANSI S12.42: 2010 for the cases of a helmet with and without a visor. Maximum IL results from referenced papers and those measured for the helmet and earplugs (dual protection) are summarised in Figure 4-24. The IL at 8000 Hz for the helmet and earplugs may have been higher if not for the speaker distortion measurement artefact (see Section 4.4.5).

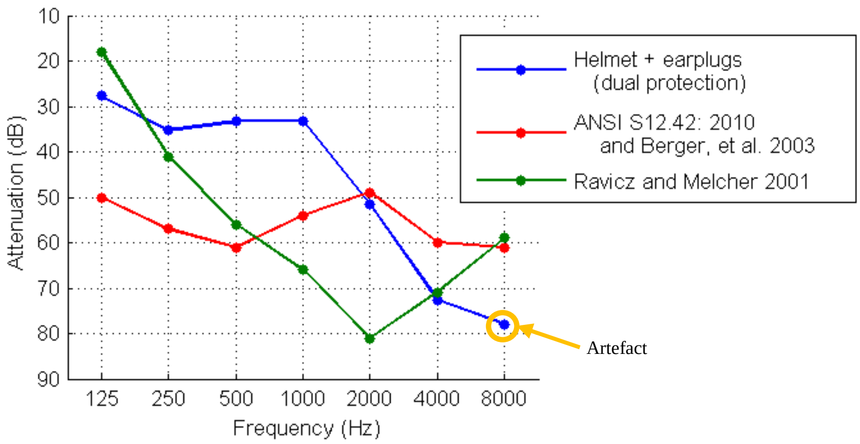


Figure 4-24: Comparison of the maximum IL measured and reported in the literature.[68]

Berger, et al. [33] reported the highest IL at low frequencies (125, 250 and 500 Hz), whereas Ravicz and Melcher [32] reported the highest IL at mid frequencies (1000 and 2000 Hz). The

[67] The mouth, chin and jaw were not covered.

[68] Data from Ravicz and Melcher [32] was the maximum IL of objective measurements.

measurements for the helmet worn with earplugs (dual protection) exceed the IL reported in the literature at 4000 Hz and 8000 Hz. All measurements of the abrasive blasting helmet were carried out with the blast jacket fitted which is a possible reason for the increased IL at the higher frequencies. Measurements in [33] were determined by a REAT method whereas [32] used REAT from 500 to 2800 Hz and MIRE measurements at the higher frequencies. Berger, et al. [33] did not report the MIRE measurements of Ravicz and Melcher [32] and noted their REAT method was non-conventional due to the use of tone bursts of MRI noise[69], rather than the more conventional test signals of one-third octave bands of noise.

There was reasonably good agreement for measurements of the helmet IL determined by the REAT, MIRE and ATF methods between 1000 Hz and 4000 Hz. The agreement was not good below 1000 Hz and at 8000 Hz and above. The methods deviated most at and below 250 Hz where the MIRE and ATF methods determined negative IL. Negative IL at low frequencies (typically below 500 Hz) has been reported by previous authors for abrasive blasting helmets [105, 106] and motorcycle helmets [107, 108], but the mechanism does not appear to have been explored. A potential explanation for the negative IL at low frequencies is the analogous example of partial (or unsealed) enclosures which report similar negative IL. Enclosures are analogous to the abrasive blasting helmet as the helmet sits freely over the head with only minimal contact at the top of the head. Negative IL at low frequencies for partial enclosures has been attributed to a coupling of the structural resonances and acoustic cavity resonances as in [109] and/or the Helmholtz effect [110]. It is unclear why the REAT method does not measure negative IL as in the MIRE and ATF methods but physiological noise is suspected to be a measurement artefact.

REAT assessments of the helmet were uncomfortable for participants as the head was completely covered. Participants reported having to time their breathing to hear the test signal in the occluded condition. It is possible that the occluded ear thresholds were masked due to physiological noise but this was not quantified. Ideally the helmet would have been assessed with the ventilation system connected for participant comfort and to represent the real-world use; however, the ventilation system introduced additional noise and consequently was not used here. Addition of ventilation could be done for future assessments using the REAT method to improve participant comfort, but should be implemented with caution to ensure occluded ear thresholds would not be masked.

[69] Tone-bursts of recorded MRI noise had frequency components from 500 to 2800 Hz.

4.5.6 Comments

Only a limited number of models were assessed for each HPD due to the laborious nature of the REAT method. Assessment of additional models should be considered in future work. The participant numbers were low relative to the required participant numbers in AS/NZS 1270: 2002. The number of participants required for REAT testing has been explored by previous authors and is also defined in REAT standards. Earplugs typically require more participants as they are more difficult to fit than earmuffs. Subject-fit REAT methods in AS/NZS 1270: 2002 and ISO/TS 4869-5: 2006 require 16 participants for earmuffs and 20 participants for earplugs, whereas ANSI S12.6: 1997 Method B requires 10 participants for earmuffs and 20 participants for earplugs. A study as part of the development of ANSI S12.6: 2008 found high variability for some earplug models with up to thirty participants required for a 6 dB resolution [95] using a prediction calculation statistically equivalent to the SLC 80 calculation. Another study reported the test / re-test repeatability of the REAT method by AS/NZS 1270: 2002 to be less than 1 dB [111], but this was for an earmuff with the same group of twenty participants and the test / re-test was conducted in the same session for each participant, thus the good agreement achieved could reasonably be expected. The literature suggests that the participant numbers reported in this study are insufficient, but the reported measurements were considered suitable for this work as comparisons of the measured results with the published attenuation and example calculations of SLC 80 were carried out for discussion purposes. Additional participants would have improved the statistical significance of reported measurements but numbers were limited given available resources and time. It is unclear how the original number of participants recommended by AS/NZS 1270: 2002 was determined, but to make a new recommendation a more exhaustive study than that presented here would be required.

Discussion on participant numbers and the topic of subject experience in previous sections leads to the question of how to define a suitable test population. A suitable test population should be one that represents the population of end-users. A suitable population for the subject-fit method (Method B) in ANSI S12.6: 1997 has been described as motivated users of HPDs [95]. For AS/NZS 1270: 2002 untrained might be a more appropriate description for the test population due to the specifications in AS/NZS 1270: 2002 that participants must have little experience with using HPDs and have not previously had any training in fitting HPDs. It is difficult to assess a small population of users and apply the results to a large and diverse population of end-users. The large variability between field and laboratory attenuations is one of the main reasons fit-testing has been developed [67], but has yet to be applied in New Zealand workplaces to the author’s knowledge.

Reported measurements using the ATF method for assessing conventional HPDs and non-conventional HPDs at elevated sound pressure levels reported measurements for a single cup. ANSI S12.42: 2010 suggests reporting the IL determined in both earmuff cups if the between cup difference is greater than 5 dB. One-third octave band differences between earmuff cups were found to be up to 10 dB in the worst case, but only a single cup has been reported here. In future, the IL of both earmuff cups should be assessed.

Comparisons between REAT and ATF attenuations presented in this work did not take into account corrections for bone conduction or physiological noise masking. It is considered good practice to include the corrections by summing the energy that would be present if bone conduction were present (as in [100]). Consideration should also be given for physiological noise corrections (as in [72]) which can somewhat account for differences at low frequencies (at 250 Hz and below), due to masking of the test signals in REAT assessments (see Section 1.1.5.1). Such corrections should be carried out in future comparisons between the REAT and ATF methods.

4.6 Summary

An evaluation of a selection of conventional and specialist HPDs was carried out using the REAT, MIRE and ATF assessment methods. The HPDs evaluated included conventional earplugs and earmuffs, an EMST earmuff, an ANR earmuff and an abrasive blasting helmet. REAT assessments were conducted in a modified audiology booth (see Chapter 2) in accordance with AS/NZS 1270: 2002. Two ATFs (G.R.A.S. 45CA and Brüel & Kjær HATS Type 4100) were used to assess HPDs in the REAT booth and in a reverberation room. MIRE assessments were carried out using instrumented participants in the REAT booth. The real-ear attenuation of conventional earplugs was highly variable amongst participants suggesting participants as the main source of variance. Earplug attenuation measured using the G.R.A.S. 45CA (IEC 60711) was high compared to REAT measurements as the ATF construction was not representative of the human head. The real-ear attenuation of earplugs was generally lower than the published attenuation, whereas there was better agreement between the measured real-ear attenuation and the published attenuation for earmuffs. Additional participants are required to improve the statistical significance of the reported real-ear attenuation. For earmuffs, the MIRE method was found to give the best agreement with assessments by the REAT method, whereas ATF measurements generally gave poor agreement with REAT. ATFs were used to assess an EMST earmuff and an ANR headphone as they were not suited to the REAT method. The EMST earmuff was evaluated at high sound pressure levels, but the system could not be fully characterised as the maximum continuous sound pressure levels were not high enough. The

EMST system was found to be functioning and offering sufficient protection up to the generation limit in the room (105 dB). The ANR system demonstrated improved attenuation at low frequencies by up to 12 dB at 250 Hz and was stable up to an overall sound pressure level of 105 dB. An abrasive blasting helmet was also assessed and in combination with earplugs (dual protection). The dual protection case provided high IL, exceeding maximum levels reported in the literature at 4000 and 8000 Hz. High IL was attributed to the helmet construction and the head and face being completely covered by the helmet. The helmet on its own had low IL below 1000 Hz (less than 10 dB), but the IL improved above 1000 Hz. Further research is needed to identify the underlying mechanism and explain the negative IL determined by the MIRE and ATF methods at low frequencies.

The main limitations of the REAT measurements presented here were low participant numbers and in general relatively few types and models of HPD. Furthermore, assessments were only conducted in continuous noise for MIRE and ATF assessment methods and corrections to account for bone conduction and physiological noise were not included as noted in the previous section (Section 4.5.6). Assessment of HPDs in impulsive noise is another important consideration for those types of HPD which find use in loud intermittent noise environments such as EMST and passive amplitude-sensitive type which should also be considered in future. Future assessments should also cover a wider range of HPD types, a range of different HPD models within the type of HPD and a larger pool of participants for assessments using the REAT method.

As identified by Berger [25], and addressed at least in part in this chapter, there is no one assessment method that is suited to all types of HPD. The REAT method is the internationally recognised benchmark method for assessing HPD attenuation (see Section 1.1.5.1). The main advantages of the REAT method are that it somewhat accounts for the anatomical variations common with human participants, it also incorporates the subjective element of fitting HPDs and includes sound transmitted via the bone conduction transmission path. In addition, external influences from sources such as interaction with the experimenter or the fitting of instrumentation (e.g. the MIRE method) can be minimised. Using an untrained population for the REAT method can exhibit significant variation which depends on factors such as the participants' physiology and experience with HPDs, but untrained is more representative of the population of end-users (real-world conditions). The MIRE method is useful for assessing HPD attenuation in elevated noise levels when fitted to participants; however, typical sound pressure levels that would warrant use of HPs are difficult to produce in a laboratory environment and also potentially dangerous for participants. ATFs are most useful for assessments of HPDs in high level continuous noise levels (and potentially impulse noise). The MIRE method is potentially useful for assessing the attenuation of HPDs at high sound pressure levels but risks to the safety of participants makes the ATF method more suitable. The MIRE method may be useful for assessment of the ANR component of IL; however, ANR HPDs are useful in only specific cases of low frequency dominated noise exposures and so the assessment of ANR type HPDs is considered a low priority. The need for laboratory based assessments of HPDs appears to be satisfied by the REAT method for conventional HPDs and the ATF method for high level continuous noise.

5. Development of a field assessment device

Investigations into the field attenuation of HPDs have typically reported attenuations less than that assessed in laboratory settings (see Section 1.1.9). Reasons for this discrepancy have been attributed to a range of factors, such as how the HPD fits each individual and the behaviour of the wearer. Behavioural factors include readjustment or modification of the HPD for comfort or safety reasons, such as the wearing of other personal protective equipment, and/or modifying the HPD to reduce the attenuation so as to better hear communications or other auditory cues. This chapter presents the development of a prototype device to assess the field attenuation of an earmuff.

5.1 Approach

The work presented in this chapter applies methods in the literature to assess the field attenuation of an earmuff as a demonstration of the field assessment of HPDs. The implementation of a prototype device was focused upon, to determine whether the device could be used to quantify the effect of common field artefacts, which are expected to reduce the field attenuation of HPDs. The field assessment focused on a single earmuff with one instrumented cup worn by the author. The developed prototype field device was used to estimate real-ear attenuation which was then compared to the measured real-ear attenuation for the earmuff worn with the field artefacts. The effect of artefacts has not been quantified and compared in both field and laboratory settings to the author's knowledge.

5.2 Equipment

Two microphones were used to assess the attenuation of a single cup of a single earmuff (3M™ Peltor™ H7F 290) using a NR[70] paradigm. One microphone was located inside the earmuff cup and the other microphone was located outside the earmuff cup. The inside and outside microphones were both electret microphones (Type AM4011[71]). The microphones had an omni-directional response pattern [112]. Each microphone had a diameter of 10 mm and a depth of 7 mm. Each microphone was connected to a microphone amplifier module and then to a USB sound card. The sound card was connected to a Raspberry Pi[72] which was used to record the signals from each microphone on an SD card. The signals were recorded as .wav files, with a resolution of 16-bit and a sampling frequency of 22050 Hz. The duration of each file was five minutes and files were numbered sequentially. The

[70] Noise reduction (NR) is a measurement of HPD attenuation by the simultaneous measurement of the sound pressure levels incident to and beneath the seal of a HPD. See Section 1.1.5 for further information.

[71] The electret microphones were sourced from South Island Component Centre (www.sicom.co.nz).

[72] A Raspberry Pi is a small single board computer (www.raspberrypi.org/help/faqs/#introWhatIs).

recorded files were post-processed to determine the sound pressure level for each microphone and thus the attenuation of the earmuff (see Section 5.2.1). The device was powered by a small 10 Ah battery. A capacitor was wired between the battery and the Raspberry Pi to attenuate an electrical tone at approximately 2.5 kHz which was affecting the recorded voltage signals. A photo of the recording hardware is shown in Figure 5-1. Figure 5-2 shows the recording hardware worn as a backpack with elastic used to secure it to the wearer.

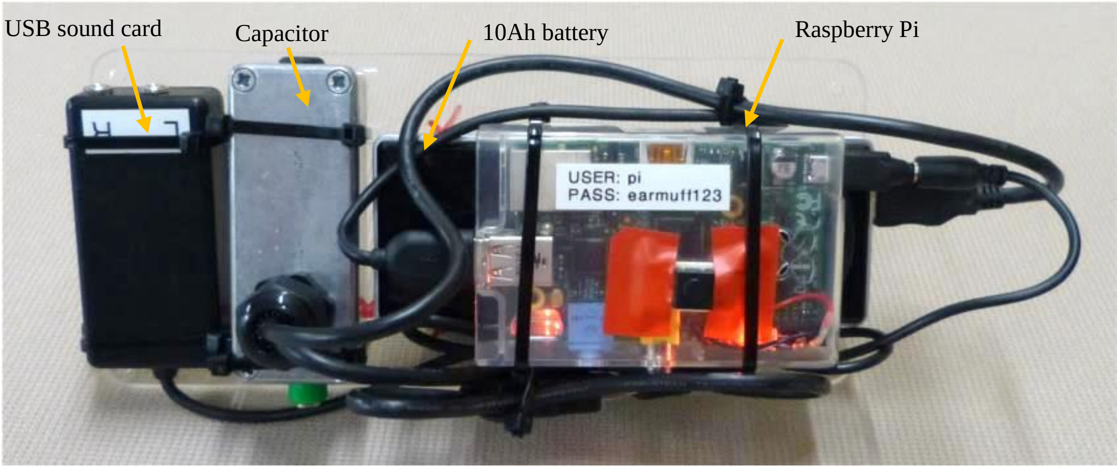


Figure 5-1: Recording equipment used for the field assessment of the earmuff.

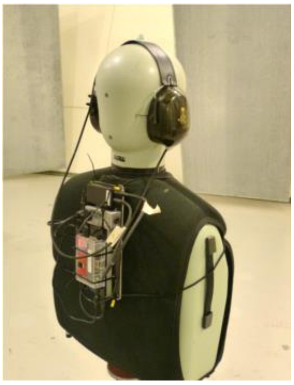


Figure 5-2: Earmuff and recording equipment fitted to the Brüel & Kjær HATS Type 4100.

5.2.1 Calculations

The voltage-time history for the outside and inside microphone was recorded as a single .wav file with one channel per microphone. The organisation of files and normalisation of the voltage-time history was carried out using the program Audacity®[73] with the following steps:

1. Load, organise and order all files into a single .wav file.
2. Normalise the .wav file (each channel normalised individually).
3. Export a single .wav file containing data for both microphones as channel 1 and 2.

The next steps were carried out with a MATLAB® script:

[73] Audacity® v2.0.5 is a program used for audio editing and recording (audacity.sourceforge.net)

4. Load .wav file with left and right channels representing the inside and outside microphones.
5. Extract voltage vs. time signals for each channel.
6. Apply one-third octave band filters to each channel. One-third octave band filters were designed using MATLAB®'s filter design toolbox[74] with centre frequencies up to 8000 Hz. The 8000 Hz one-third octave band was the maximum band able to be assessed due to the relatively low sampling frequency.
7. Determine level in dBV* for each channel as in Eq. 5.1. The unit dBV* is marked with an asterisk as the recorded voltage signal was not calibrated. The overall and one-third octave band level was determined for the full duration of the recording within memory limitations and/or in 30 s increments of the .wav file. No reference value is shown in Eq. 5.1 as a nominal reference level of 1 dBV* was used.

$$L_{Veq,T} = 10\log_{10}\left[\frac{1}{T}\right]\int_{t_1}^{t_2} V(t)^2\,dt \qquad \text{Eq. 5.1}$$

Where: T = Duration typically in hours but can be also be in seconds

V = Voltage of recorded signal

8. Convert dBV* to dB SPL. The conversion from dBV* to dB SPL was carried out by simple addition of a correction term in dB which was determined from calibration measurements in one-third octave bands.
9. The sound pressure level for each channel in octave bands was determined by logarithmic addition of one-third octave band levels so that no information was discarded from the measurements. For the 8000 Hz octave band, only the 6300 and 8000 Hz centred one-third octave bands were summed due to the relatively low sampling frequency.
10. The attenuation of the earmuff was determined based on the difference between the sound pressure level at the inside and outside microphone in octave bands.

5.2.2 Calibration

The level determined in dBV* was corrected to sound pressure level by addition of the difference between the level measured by a diffuse-field microphone (Brüel & Kjær Type 4942) and the level determined with the electret microphones (dB re 1V). The level differences were determined by measuring the sound pressure level for each microphone at approximately the same position in a reverberation room over a range of sound pressure levels. The sound field was generated using a single speaker (JBL CBT 70J) and broadband white noise to achieve higher sound pressure levels at the higher frequencies. The sound pressure level was measured for each microphone with no frequency weighting and an averaging time of 60 s ($L_{eq,60s}$). The sound pressure level of the diffuse-field microphone was determined using a signal analyser (Brüel & Kjær PULSE 3560-C). The frequency response and inherent noise of both electret microphones are indicated in Figure 5-3

[74] One-third octave band filters were designed using the filter design toolbox in MATLAB® with settings of Class 1, Order 3 and Fs of 22050 Hz and were implemented as Butterworth filters.

relative to a diffuse-field microphone (Brüel & Kjær 4942). The inherent noise indicated for the diffuse microphone is a combination of the ambient noise in the room and the inherent noise of the microphone.

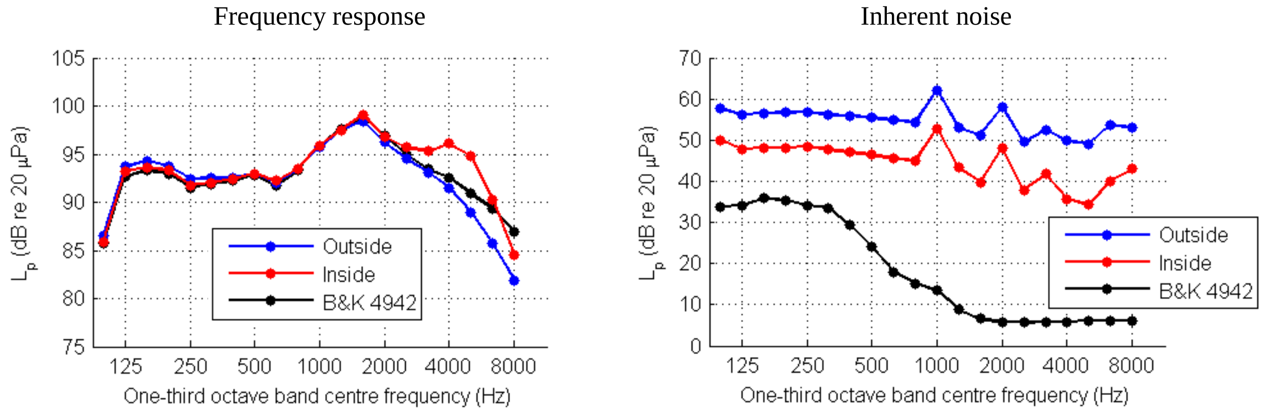


Figure 5-3: Uncorrected frequency response and inherent noise of the electret microphones.

The higher inherent noise level for the outside microphone was partially due to an increased gain for the outside microphone in an attempt to reduce the inherent noise. The inherent noise levels shown in Figure 5-3 are attributed to the microphone hardware rather than the signal acquisition hardware. Each electret microphone response was corrected relative to the sound pressure level determined by the diffuse-field microphone in one-third octave bands. The inherent noise levels and frequency responses of the inside and outside microphones are relatively high compared to other measurement microphones, but are reasonable considering their low cost and small size.

5.2.3 Microphone location

The location of the outside microphone has been shown to have an influence on the measured sound pressure level depending on the direction of incident sound for earmuffs assessed using a NR paradigm [113, 114]. Le Cocq, et al. [113] identified the top of the earmuff cup to be the most suitable on-cup microphone position due to the top position having the lowest variation in sound pressure level with various head orientations and various sound fields. The top of the earmuff cup and the top of the earmuff headband were evaluated in this work, using a method adapted from [113]. The microphones were attached with reusable modelling compound, as indicated in Figure 5-4. The top of the headband position was included in the assessment as it was likely to be less influenced by shadowing due to head orientation. The headband and earmuff cup microphone were assessed at the same time.

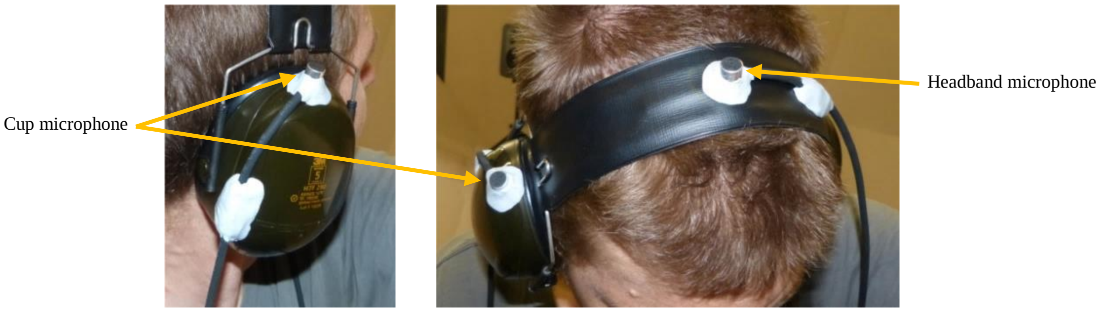


Figure 5-4: Outside microphone positions considered for the prototype device.

The author sat and turned his whole body and head to align with the eight orientations (labelled as compass points) shown in Figure 5-5 to assess the variation for each microphone position. The incident sound was considered a free-field and the orientations were within the horizontal plane. A 10 s sample was recorded for each microphone at each orientation and was repeated three times. The sound pressure level was also assessed at the head-centre with the participant absent using a diffuse-field microphone (Brüel & Kjær Type 4942).

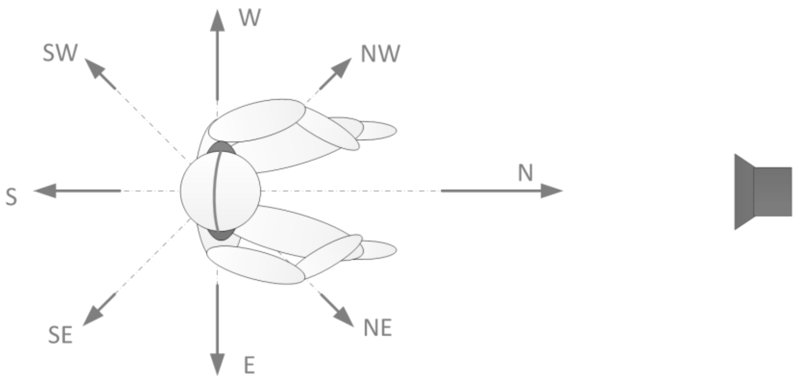


Figure 5-5: Illustration of directions used for assessing the outside microphone position.

The assessment of the outside microphone positions was conducted in the reverberation room and a semi-anechoic room[75]. An omni-directional sound source (Brüel & Kjær Type 4296) was used in the reverberation room and a conventional powered speaker (JBL EON Power 10) was used in the semi-anechoic room. A signal generator (NTI Neutrik Minirator type MR1) was used to produce broadband pink noise for measurements in the reverberation room and the semi-anechoic room without frequency response corrections. The experimental setup is shown in Figure 5-6. Results from the assessment of the outside microphone directionality are shown in Figure 5-7. Shaded areas indicate 95 % confidence intervals for a single participant and three repetitions.

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[75] The semi-anechoic room is in the Department of Mechanical Engineering at the University of Canterbury. The room has approximate dimensions of 4 x 12 x 3.7 m and a room volume of 180 m^3. Sound absorption material (50 mm thick) was distributed around the sides and floor of the room. The anechoic chamber was not available at the time but would have been ideal for this work.

Reverberation room Semi-anechoic room

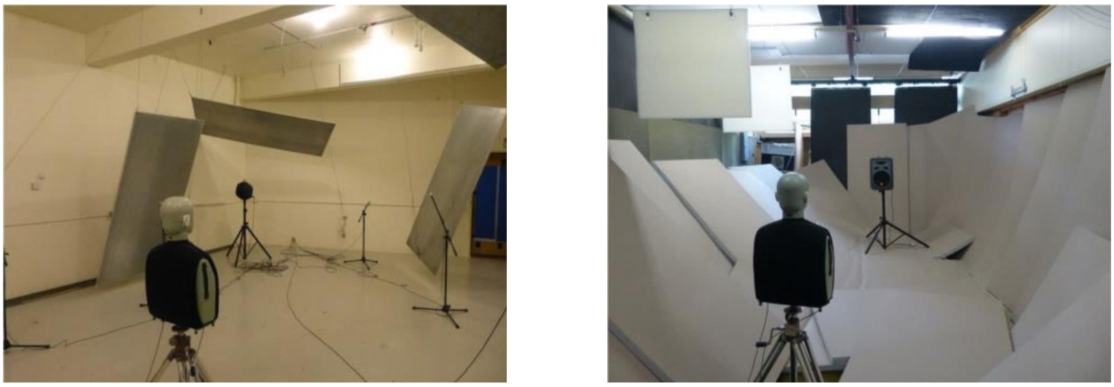

Figure 5-6: Experimental setup for assessing the outside microphone directionality.

Reverberation room Semi-anechoic room

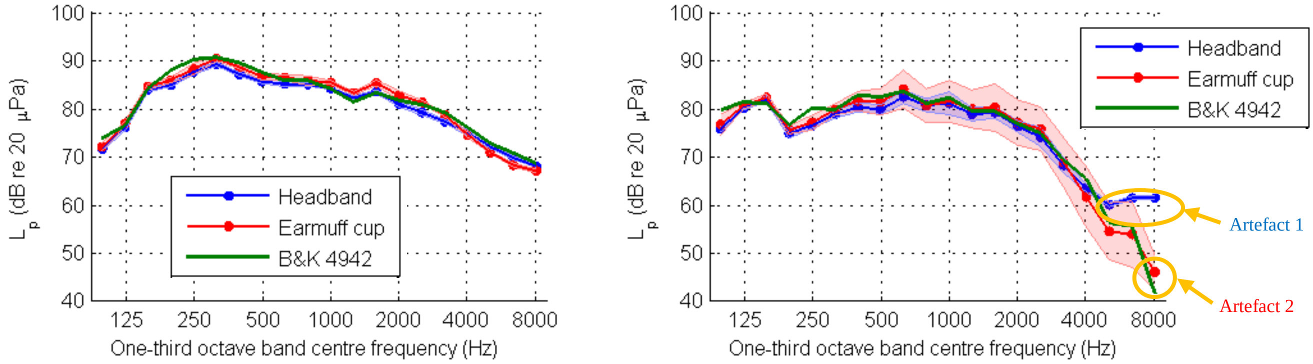

Figure 5-7: Sound pressure levels determined from assessment of the outside microphone position.

Artefact 1 in Figure 5-7 is due to the high inherent noise levels of the headband microphone at frequencies 4000 Hz and above and Artefact 2 is due to the high inherent noise of the cup microphone at 8000 Hz. The high inherent noise in Figure 5-7 was partly due to a faulty connection which was corrected for all other measurements reported in this chapter. There was a low variation with orientation for measurements conducted in the REAT booth and reverberation room. The REAT booth had slightly higher variation compared to the reverberation room but was still considered to be acceptably low. The earmuff cup microphone had increased variation compared to the headband microphone in the semi-anechoic room. This is as expected as the head would shadow the cup microphone more than the headband. Le Cocq, et al. [113] used binaural measurements to determine if diffuse-field corrections or free-field type corrections should be used, but this was not possible in this work as only a single cup was used. The headband microphone was used for this work as it had lower variability with head orientation as assessed in a free-field in a horizontal plane.

The internal microphone was recessed in the foam liner at the approximate centre of the earmuff cup. A hole was drilled through the earmuff cup for the cable of the inside cup microphone to pass through and was sealed with a reusable modelling compound. The location and attachment used for the inside cup microphone and cable are pictured in Figure 5-8.

Figure 5-8: Location and attachment of the inside cup microphone.

5.2.4 Practicalities

The motivation for this section was from Kusy and Châtillon [71] who found movement influenced the measured attenuation during a field assessment of custom moulded earplugs. An assessment of the effect of movement was carried out in the reverberation room so as to quantify some of the effects of movement on the measured sound pressure level. The author wore the instrumented earmuff in the reverberation room with no noise present to assess movement artefacts. The reverberation room was used as it was a convenient space and had suitably low background noise levels. Walking and moving the head side to side were assessed and compared to no movement (stationary). Results are summarised in Figure 5-9. The inside microphone is only presented as the outside microphone was not affected by movement noise attributed to a more secure mounting of the microphone cable. Voltage is marked with an * as it is the voltage recorded by the device.

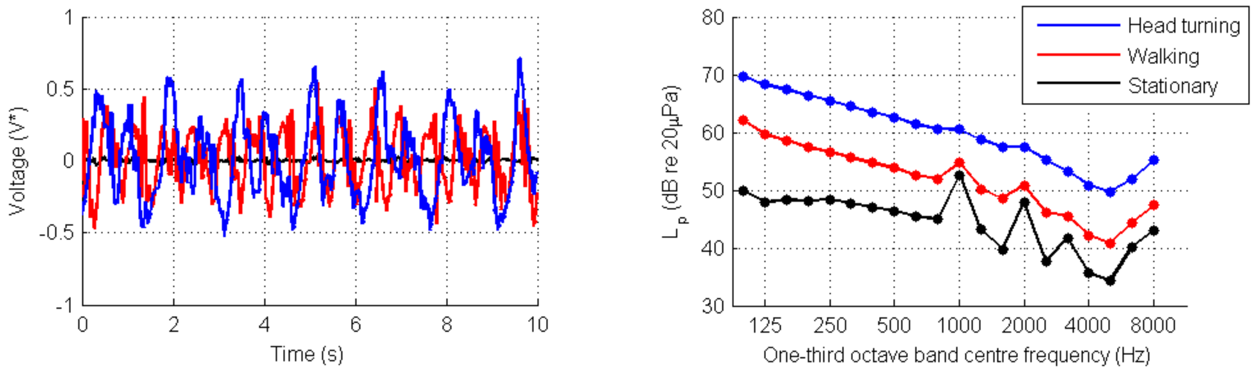

Figure 5-9: Noise attributed to movement for the inside microphone.

The simplest approach to address the movement noise was to exclude segments of noise from calculations based on listening to the recording.

5.2.5 Assessing the effect of earmuff modifications

The earmuff attenuation was assessed prior to and after modifications to determine the effect of modifications on earmuff attenuation. Assessments of earmuff attenuation were carried out using the ATF and REAT methods. ATF assessments were carried out using the G.R.A.S. 45CA (ISO 4869-3). The author was the only participant in the REAT method, carried out via-self testing. The HPD was fitted first before proceeding into the booth for threshold determinations. Thresholds were determined using an automatic procedure which was started outside the booth. The first three reversals were discarded instead of only ignoring the first reversal as in Chapter 2 to allow for some settling time. The REAT method was carried out as a typical binaural assessment and as a monaural assessment as only one cup was instrumented for the prototype device. The monaural REAT method was used to assess the change in attenuation due to modifications of the earmuff cup. The binaural real-ear attenuation was determined prior to modifying the earmuff and the monaural real-ear attenuation was carried out prior to and after the earmuff modifications. The assessment of monaural real-ear attenuation was carried out by occluding the other ear (left) with an earplug. The binaural real-ear attenuation of the earplugs was determined first to ensure the earplugs achieved high real-ear attenuation. Deeply inserted roll-down foam earplugs (3M™ E-A-Rsoft™ Yellow Neons™) were used to occlude the ear. The test procedure for to assess the single earmuff cup was as follows:

Binaural:

1. Fit the earmuff and carry out occluded threshold test.
2. Remove the earmuff and carry out open-ear threshold test.
3. Deeply insert earplugs into both ears and assess occluded threshold.
4. With earplugs still in place, fit the earmuff and test dual protection threshold.

Monaural:

5. Remove the right side earplug (leaving the left earplug in place) and carry out an open-ear threshold test.
6. Without touching the left earplug, fit the earmuff and carry out a threshold test.

Steps 1 to 6 were carried out prior to earmuff modifications. Steps 2, 3, 5 and 6 were carried out post-modifications (monaural) as only the modified cup was of interest. Each threshold determination was repeated three times. Results from binaural testing prior to earmuff modifications are summarised in Figure 5-10. Shaded areas indicate 95 % confidence intervals for a single participant and three repetitions.

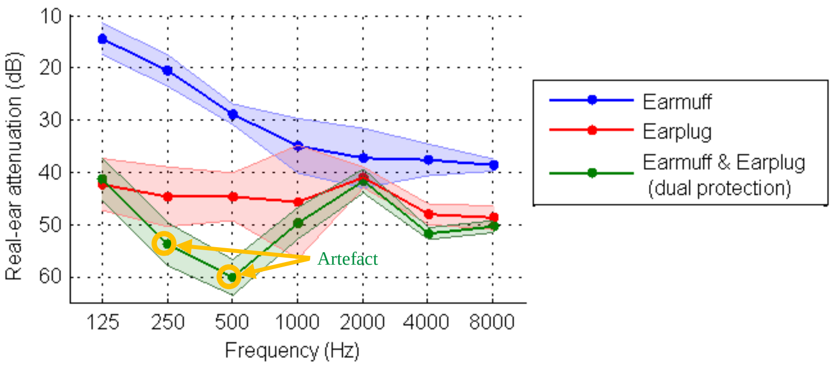

Figure 5-10: The binaural real-ear attenuation (n = 1) of the earmuff, deeply inserted earplugs and earmuff and earplugs (dual protection).

The upper dynamic range limit of the REAT test facility was encountered for the 250 Hz (maximum peaks for the bracketing procedure) and 500 Hz (no response at 70 dB) test signals, indicated as artefacts in Figure 5-10. The measurement artefacts were not of concern for these assessments as the dual protection attenuation was much higher than the earmuff attenuation. The IL for the deeply inserted earplug and the combination of the earmuff and earplug (dual protection) was essentially equivalent at 2000 Hz. This 2000 Hz limit is common in the literature for high IL HPDs [33, 96] and has been attributed to a middle-ear resonance excited by the bone conduction transmission path [96, 115]. A deeply inserted earplug provides sufficient occlusion (at least 10 dB) to carry out monaural measurements of the single earmuff cup for all test signals except 2000 Hz. The occlusion provided by the earplug for the 2000 Hz test signal is at the approximate maximum IL able to be achieved with human participants for the REAT method. A comparison between the binaural and monaural real-ear attenuation for the earmuff measurements is shown in Figure 5-11. Shaded areas indicate 95 % confidence intervals for a single participant and three repetitions.

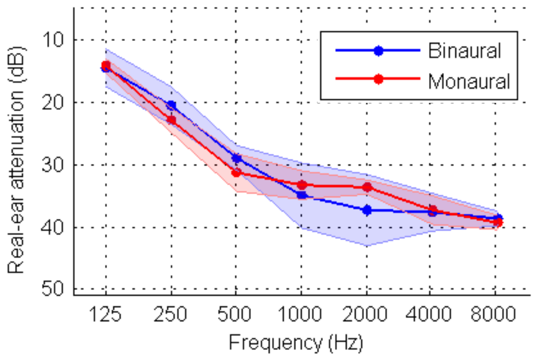

Figure 5-11: Comparison of binaural and monaural real-ear attenuation[76] (n = 1) for the unmodified earmuff.

There was a slightly higher variation in the binaural measurements which was attributed to the binaural assessment being carried out first to determine the binaural IL of the earplugs. It is possible that this was exacerbated by the low number of trials. The mean differences were small to insignificant. There is a possibility that there may be differences between binaural and monaural assessments due to differences in sound pressure level between left and right ears and/or binaural advantage but was not further explored and was somewhat limited due to the single participant and low number of trials. The comparison between monaural real-ear attenuation prior to and after earmuff modifications is shown in Figure 5-12. REAT assessments were carried out for a single participant and three repetitions and shaded areas indicate 95 % confidence intervals.

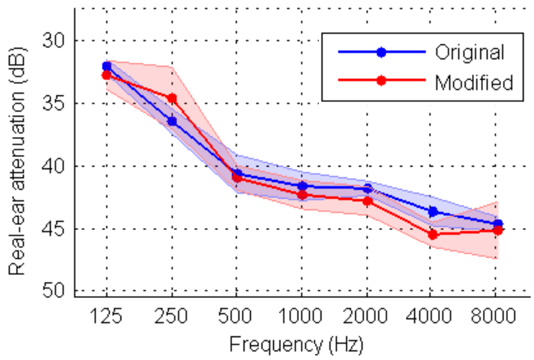

Figure 5-12: Comparison of monaural real-ear attenuation[76] (n = 1) for the unmodified and modified earmuff.

The earmuff attenuation was also determined by the ATF method prior to and after modifications using a single side (right) of the G.R.A.S. 45CA (ISO 4869-3) in the REAT booth (see Section 4.3.2). The method involved determining the difference between the open-ear and occluded sound pressure levels with no frequency weighting and an averaging time of 30 s ($L_{eq,30s}$). Each open-ear and occluded measurement was repeated three times where the earmuff was re-fitted for each occluded measurement. The comparison between monaural IL determined by the ATF method

[76] The graph has been labelled “Real-ear attenuation”. However, the measurements presented include monaural assessments which are not a true REAT method type measurement.

prior to and after earmuff modifications is shown in Figure 5-13 determined from octave band sound pressure levels. Shaded areas indicate 95 % confidence intervals with a single participant and three repetitions.

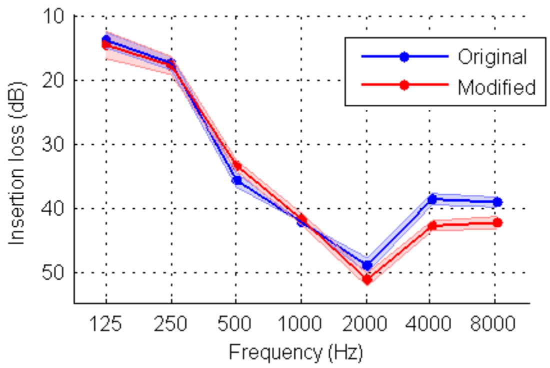

Figure 5-13: IL of the unmodified and modified earmuff cup determined using the G.R.A.S. 45CA.

The small differences between the original and modified earmuff vary depending on the assessment method for reasons unknown. The main difference common to measurements carried out in accordance with the REAT method and the ATF method was a higher IL post modification for the 2000 to 8000 Hz frequencies. This was in contrast to what was expected given some of the sound absorption material was removed to fit the inside microphone.

5.3 Estimating real-ear attenuation

The goal of the developed device was to measure the attenuation of an HPD relative to the standard REAT method (AS/NZS 1270: 2002). An example implemented in Voix and Laville [69] for custom-moulded earplugs was adapted for this work to estimate real-ear attenuation from the measured attenuation. The background for estimating real-ear attenuation from the measured attenuation is outlined in the equations below with reference to Figure 5-14. The sound pressure level measured at the centre of the participant's head with them absent is represented by p [25]. Point p_0' represents the sound pressure level measured at a reference location outside the earmuff [69]. Point p_2' is measured beneath the HPD and point p_3 and p_3' represent the sound pressure level measured as close as possible to the ear drum for the open-ear and occluded cases respectively [69].

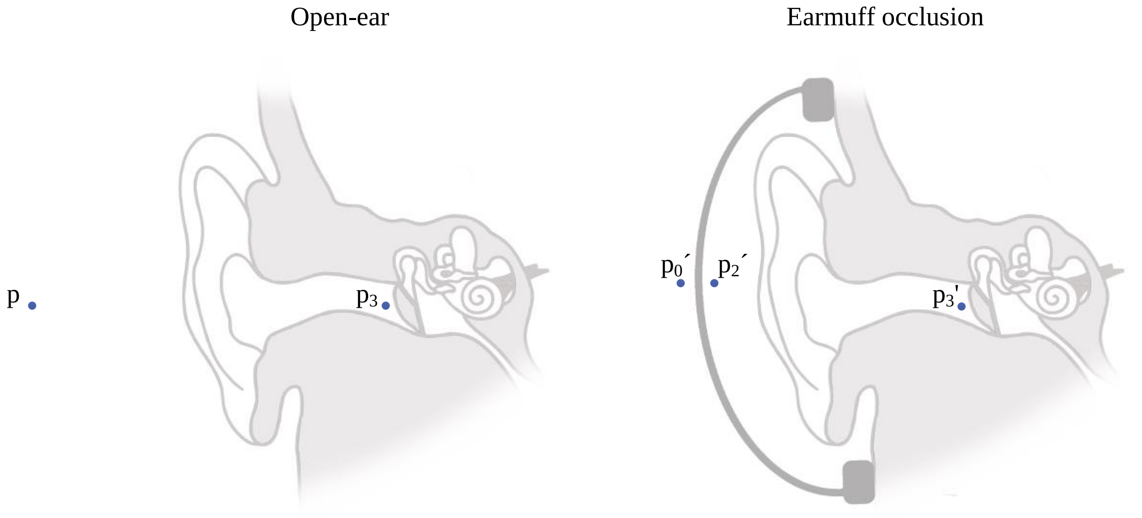

Figure 5-14: Measurement positions used to assess the attenuation of HPDs.[77]

The IL of an HPD is defined by Eq. 5.2.

$$\mathrm{IL} \triangleq 20\log_{10}\left(\frac{\mathrm{p}_3}{\mathrm{p}_3'}\right) \qquad \text{Eq. 5.2}$$

Theoretical noise reduction (NR_0) is defined by Eq. 5.3.

$$\mathrm{NR}_0 \triangleq 20\log_{10}\left(\frac{\mathrm{p}}{\mathrm{p}_3'}\right) \qquad \text{Eq. 5.3}$$

The transfer function of the open-ear is defined by Eq. 5.4.

$$\mathrm{TFOE} \triangleq 20\log_{10}\left(\frac{\mathrm{p}_3}{\mathrm{p}}\right) \qquad \text{Eq. 5.4}$$

Voix and Laville [69] defined a direct relation between IL and NR_0 by Eq. 5.5 and REAT and theoretical IL by Eq. 5.6. REAT and IL are near equivalent except for the physiological noise (PN) artefact which leads to an underestimate of attenuation by the REAT method at 250 Hz and below.

$$\mathrm{IL} \triangleq \mathrm{NR}_0 + \mathrm{TFOE} \qquad \text{Eq. 5.5}$$

$$\mathrm{REAT} \triangleq \mathrm{IL} + \mathrm{PN} \qquad \text{Eq. 5.6}$$

The measured noise reduction NR^* is defined by Eq. 5.7.

$$\mathrm{NR}^* \triangleq 20\log_{10}\left(\frac{\mathrm{p}_0'}{\mathrm{p}_2'}\right) \qquad \text{Eq. 5.7}$$

Theoretical noise reduction NR_0 can be defined by Eq. 5.8.

[77] Adapted from Voix and Laville [69].

$$\mathrm{NR_0} \triangleq \mathrm{NR}^* + 20\log_{10}\left(\frac{p_2'}{p_3'}\right) + 20\log_{10}\left(\frac{p}{p_0'}\right) \quad \text{Eq. 5.8}$$

The equation to correct measured earmuff attenuation to REAT is summarised by Eq. 5.9.

$$\mathrm{REAT} \triangleq \mathrm{NR}^* + \underbrace{20\log_{10}\left(\frac{p_2'}{p_3'}\right)}_{\textbf{(1)}} + \underbrace{20\log_{10}\left(\frac{p}{p_0'}\right)}_{\textbf{(2)}} + \underbrace{\mathrm{TFOE}}_{\textbf{(3)}} + \underbrace{\mathrm{PN}}_{\textbf{(4)}} \quad \text{Eq. 5.9}$$

Voix and Laville [69] treated the four terms in Eq. 5.9 (numbered 1 to 4 above) as a single term and determined the difference between REAT and NR* for two groups of twenty participants. The use of the grouped correction term was validated by proving the correction term was normally distributed for each group of participants. An MIRE method was used to estimate REAT, in a laboratory setting by de Almeida-Agurto, et al. [50], in an alternative adaptation of the work by Voix and Laville. The difference between REAT and MIRE was used to compute a correction term by averaging the difference across four different earmuffs; however, there appeared to be no consistent correction term which was suited to all the earmuffs using the MIRE methodology. Grouping the corrections is said to be a practical approach to apply corrections between the measured attenuation (NR*) and REAT as individual assessment of each correction factor was identified to be laborious and difficult [69]. Treating the corrections as individual terms was considered for this work but was found to be impractical to implement. Implementing the corrections between the measured attenuation (NR*) and real-ear attenuation as a single grouped term was used in this work.

In order to address the corrections as a single grouped term, the earmuff attenuation had to be determined by the REAT method (IL) and by the field measurement device (NR*). The determination of the binaural real-ear attenuation was relatively straightforward and was carried out with the author as the only participant via self-testing in the REAT booth. Real-ear attenuation was determined prior to modifications (see Section 5.2.5). By assessing the real-ear attenuation prior to modifications the effect of modifications was taken into account by the correction term. The assessment of the earmuff attenuation (NR*) was less straightforward. As addressed in Section 5.2.3, the sound pressure level determined by the outside microphone varies with microphone location and the incident sound field. The outside microphone location was chosen as it was the least susceptible to shadowing effects due to head (or microphone) orientation to the sound source in an approximate free-field. The experimental setup used in Section 5.2.3 was re-used to assess the variation in earmuff attenuation (NR*). The assessment was carried out in the semi-anechoic room and the reverberation room for eight orientations in a horizontal plane (see Figure 5-5). The sound pressure level at each position was measured with an averaging time of 30 s ($L_{eq,30s}$) and each orientation was repeated three times. The measured attenuation (NR*) in the reverberation (diffuse-field) and semi-anechoic (free-field) rooms for octave band centre frequencies is shown in Figure 5-15. Shaded areas indicate 95 % confidence intervals for a single participant and three repetitions. The attenuation for octave band centre frequencies was determined after logarithmic addition of the one-third octave band sound pressure levels (as in Section 5.2.1).

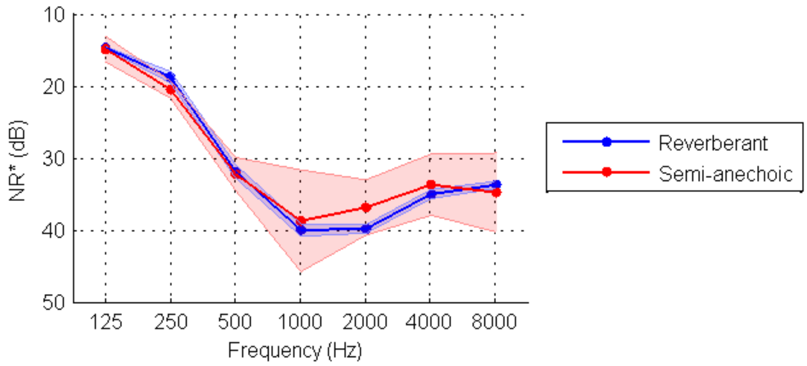

Figure 5-15: Measured attenuation (NR*) for various orientations of noise in a horizontal plane.

The NR* measured in the reverberation room was relatively consistent for all orientations which can be attributed to the diffuse incident sound field. The NR* measured in the semi-anechoic room (free-field) varied by up to 10 dB for the 500 to 8000 Hz octave bands and the variation was dependent on head orientation and frequency. The results in Figure 5-15 indicate the measured attenuation should attempt to account for the incident sound field to estimate real-ear attenuation. The variation in measured attenuation appears to be inadequately addressed by selecting the outside microphone position based on the least variation with sound field. The mean of the mean NR* determined in the reverberation room and the mean of NR* determined in the semi-anechoic room was consequently used as the correction.

5.4 Assessment of earmuff artefacts

A pair of safety glasses and a thin woollen helmet liner worn beneath an earmuff were assessed as examples of common field artefacts. The safety glasses and thin woollen helmet liner were worn beneath an earmuff compromising the seal of the cushion as shown in Figure 5-16.

Figure 5-16: A pair of safety glasses and a thin woollen helmet liner worn beneath an earmuff.

The effect of the artefacts was assessed by the REAT method (author via-self testing as in Section 5.2.5) and also in the reverberation room using the instrumented earmuff. The field device was used in the reverberation room as the variation in attenuation (NR*) due to orientation of the head and microphone measurement positions (see Section 5.3) was low relative to the semi-anechoic room. The assessment of the safety glasses and thin woollen helmet liner were used to determine whether the corrections could be used to estimate the real-ear attenuation of the unmodified earmuff and quantify the effect of the assessed artefacts.

The effect of the artefacts was first assessed using the standard REAT method for an unmodified earmuff. Another earmuff of the same model (3M™ Peltor™ H7F 290) was used for these measurements as they were carried out after the earmuff had been modified. The binaural real-ear attenuation was assessed for the unmodified earmuff and with safety glasses worn beneath the earmuff and a thin woollen helmet liner worn beneath the earmuff. The author was the only participant in these assessments and each threshold assessment had three repetitions. Results from the measured earmuff attenuation with and without modifications are summarised in Figure 5-17. Shaded areas indicate 95 % confidence intervals for a single participant and three repetitions.

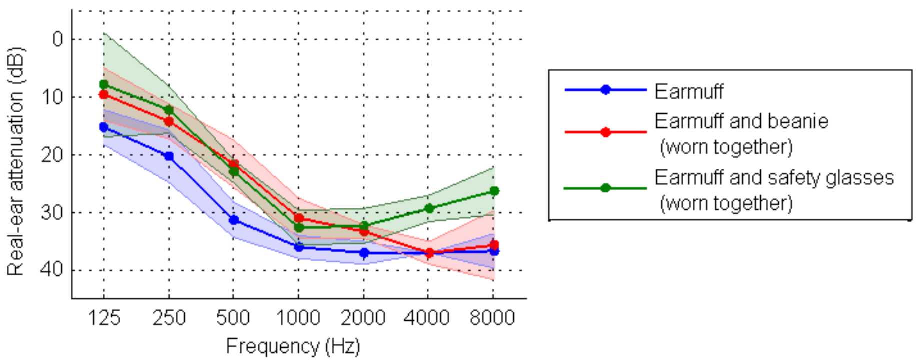

Figure 5-17: The binaural real-ear attenuation of an earmuff with normal fit and with safety glasses or a thin woollen helmet liner worn individually beneath the earmuff.

A pair of safety glasses worn beneath the earmuff decreased the real-ear attenuation by approximately 5 to 10 dB across the frequency range. The helmet liner worn beneath the earmuff reduced the real-ear attenuation for 125 to 2000 Hz by up to 10 dB. Results shown in Figure 5-17 also indicate high variation for the earmuff and safety glasses at 125 Hz and for the earmuff and thin woollen helmet liner at 125 and 8000 Hz. This is most likely due to using only three repetitions and reflects the variation common with REAT assessments.

Next, the artefacts were assessed in the reverberation room with the developed prototype field device. The instrumented earmuff was assessed on its own and with each artefact worn beneath the earmuff cushion and assessed individually. Assessments in the reverberation room were carried out with the earmuff fitted (with artefact if being assessed) with the participant seated in the reverberation room. The participant was required to be still due to the practical issues of movement noise (see Section 5.2.4). Measurements were carried out with a time averaging of at least 30 s and were repeated three times with the earmuff refitted for each assessment. The measured attenuation (NR*) was used to estimate the binaural real-ear attenuation. The estimated real-ear attenuation for a normal fit (no artefacts) is shown in Figure 5-18. Shaded areas indicate 95 % confidence intervals for a single participant with three repetitions.

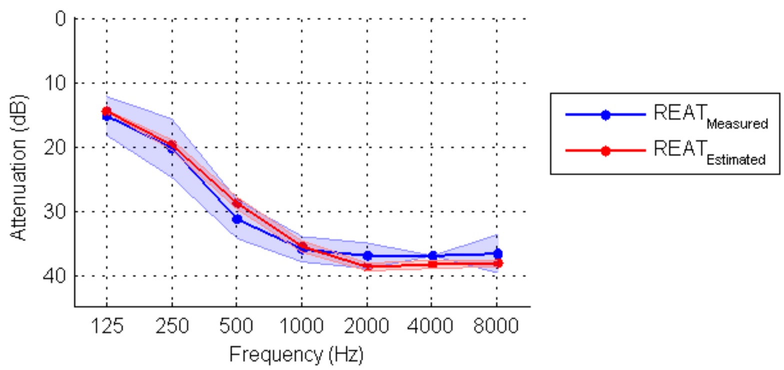

Figure 5-18: Comparison of the measured (n = 1) and estimated real-ear attenuation for an earmuff.

The estimated real-ear attenuation has reasonable agreement with the measured binaural real-ear attenuation which is expected as the correction is based on the difference between the measured real-ear attenuation and the measured attenuation (NR*) in the reverberation room with the author as the only participant. The estimated and measured effect of the measurement artefacts on real-ear attenuation are shown in Figure 5-19 for each earmuff artefact in comparison to the artefacts assessed by the REAT method. Shaded areas indicate 95 % confidence intervals for a single participant and three repetitions.

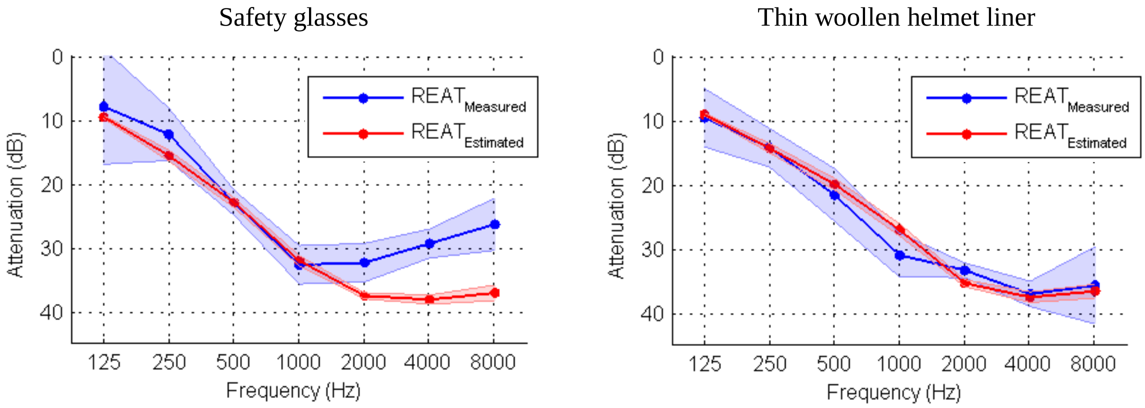

Figure 5-19: Comparison of the measured (n = 1) and the estimated real-ear attenuation with artefacts worn beneath the earmuff.

The estimated and measured real-ear attenuation with safety glasses worn beneath the earmuff showed reasonable agreement at and below 1000 Hz with significant deviations at 2000 Hz and higher frequencies. The estimated and measured real-ear attenuation at high frequencies deviated by up to 10 dB. The estimated and measured real-ear attenuation with the thin woollen helmet liner worn beneath the earmuff obtained reasonable agreement. The largest difference between the estimated and measured real-ear attenuation for the thin woollen helmet liner was obtained at 1000 Hz and was approximately 5 dB.

5.5 Discussion

5.5.1 Current implementation

The reduction in real-ear attenuation due to the wearing of safety glasses was of a similar magnitude and trend for thick framed glasses reported by Wells, et al. [116]. The reduction in real-ear attenuation for the thin woollen hat worn beneath the earmuff was also similar for thin hair net type headwear also reported by Wells, et al. [116]. Nixon and Knoblach [117] reported reductions in earmuff attenuation of up to 10 dB with glasses worn beneath earmuffs assessed by a REAT method. The reductions were found to vary with frequency and earmuff type. It is also possible that the safety glasses beneath the seal introduce attenuation which varies with directionality due to the location of the break beneath the cushion. Abel, et al. assessed safety glasses and a half-mask respirator worn both individually and in combination beneath an earmuff [118]. The individual artefacts reduced attenuation by up to 5 dB, whereas the combination of safety glasses and respirator reduced attenuation by up to 9 dB. Abel and Odell [119] assessed a balaclava worn beneath earmuffs by a REAT method. The balaclava reduced attenuation by up to 18 dB below 6300 Hz. Brueck [120] assessed a range of safety equipment (hats, eye glasses, goggles, visors and dust masks) worn beneath earmuffs but reported measurements as SNR reductions of up to 15 dB. The MIRE method used was unclear and so was not easily compared to measurements reported here. Studies which have assessed earmuffs with compromised fit in accordance with a REAT method were found to be rare, possibly due to the laborious nature of REAT assessments and the wide variety of HPDs and personal protective equipment. Real-ear attenuations reported here for artefacts worn beneath an earmuff compare reasonably well with the literature.

The estimated real-ear attenuation achieved good agreement with the measured real-ear attenuation for the normal fit and when worn with the helmet liner. The agreement between estimated and measured real-ear attenuation for the safety glasses worn beneath earmuffs was poor above 2000 Hz and it was not clear what the underlying reason for this discrepancy was. It is proposed that the location of the inside microphone on the shell of the earmuff, surrounded by the earmuff liner, contributed to the discrepancy. A possible reason for this discrepancy is the location of the internal microphone relative to maxima and minima within the earmuff cup due to acoustic resonances within the cup but requires further investigation.

Although the headband position for the outside microphone displayed the least variation in sound pressure level for noise from various directions, the earmuff cup experienced a shadowing effect shown by the variation in measured attenuation (NR*) when the attenuation was assessed with noise from various directions. The use of a single correction factor for the sound field was used in this work but should be addressed in future work. Only using a single participant (the author via self-testing) for all assessments was not ideal; however this was considered to be appropriate for purposes of this work.

5.5.2 Future work

Improvements to the current assessment include: assessing a larger variety of HPDs, assessing a variety of artefacts worn beneath the HPD (e.g. different types of safety glasses, helmet liner and/or other artefacts) and carrying out determination of corrections with additional participants. As the corrections require a REAT and NR* assessment for each HPD of interest, the implementation presented is mainly useful as a prototype device for investigating aspects of field assessment of HPDs (e.g. effect of sound from various directions). The implementation has limited use for implementing field assessments in a real workplace.

It is proposed that future work reconsiders the outside and inside microphone positions. The inside microphone location should be studied further to identify the most suitable location with consideration for the type of HPD to be assessed (i.e. earmuffs or earplugs) and the effect of different measurement locations. At or near the ear entrance point or within the earmuff cup should be considered. An ideal inside microphone would be one which can non-invasively measure the sound pressure level near the eardrum, as identified by Voix and Laville [69], but this is a significant challenge. The outside microphone position is proposed to be relocated from the HPD to be shoulder mounted, as is commonly used for personal noise dosimetry. Furthermore, it is proposed that the outside microphone should approximate the directionality of the incident sound field in relation to the wearer and the noise incident on the earmuff. The advantages of such a directional outside microphone are anticipated to be an improved approximation of the noise directionality, thus a better estimate of the attenuation of the earmuff. If the inside and outside microphone were reasonably non-invasive and not attached to the HPD, the HPD could be assessed in “normal use” environments. Furthermore, such an implementation would be independent of the HPD, making it more practical to implement in the field. In addition, it is proposed that the least variation in attenuation is assessed for the inside and outside microphone pair, rather than the single outside microphone position. This proposal is based upon the assumption that the earmuff attenuation will be consistent with various incidences of noise, but should first be quantified. Hardware development should also consider the performance of the microphones with variations in temperature, humidity, direct moisture, field calibration and hygiene considerations as well as minimisation of movement noise. Future work should also consider comparison to or adoption of and/ or possible modification of commercially available fit-testing systems and/or personal noise dosimeters.

5.6 Summary

A prototype field device was developed and qualification measurements have been presented. The incident sound field was found to influence the measured attenuation (NR*) due to shadowing of the head. The assessment of artefacts was carried out to estimate the real-ear attenuation and achieved reasonable agreement with the measured real-ear attenuation except for an overestimate of real-ear attenuation at frequencies of 2000 Hz and above. An alternative hardware implementation and areas for future investigation have been proposed based on the findings of this work. It is anticipated that work presented in this chapter will form a basis for future investigations into the field attenuation of earmuffs and other types of HPD.

6. Conclusion

6.1 REAT test facility

A test facility was developed to assess the attenuation of HPDs using the REAT method in AS/NZS 1270: 2002. An audiology booth was modified, hardware developed, and a LabVIEW test program was developed to carry out the assessment of HPDs in accordance with AS/NZS 1270: 2002. Distortion requirements were found to be difficult to quantify below -20 dB. Not determining these low sound pressure levels was considered to not affect the determination of open-ear thresholds for normal hearing (-10 to 20 dB HL) participants. The threshold determination method used an automatic bracketing procedure which was validated by comparison with a manual ascending method. Improvements to the assessment procedure and instructions were identified as improvements for future assessments in accordance with the REAT method. The developed facility was considered sufficient to meet the requirements of the project, but improvements to the test procedure were identified for future REAT assessments.

6.2 Evaluation of HPD assessment methods

Laboratory-based HPD assessment methods for conventional and specialist HPDs were evaluated. The evaluation of laboratory-based assessment methods was addressed in two parts. The first was a review of the REAT method specifications in AS/NZS 1270: 2002 with consideration of the published literature and experience setting up the REAT test facility. The second was a general evaluation of HPD assessment methods for conventional and specialist (or non-conventional) HPDs.

The maximum background noise levels in AS/NZS 1270: 2002 were identified as potentially too high, such that test signals near the threshold of hearing may be masked if the maximum allowable background noise levels in AS/NZS 1270: 2002 were present in the room. New maximum allowable background noise levels were calculated and proposed; however, further work is required to make a valid recommendation. The distortion requirement was found to be impractical to meet for low sound pressure levels (below -20 dB). As an alternative to the current dynamic range specifications, it is proposed that the lower limit of dynamic range be 10 dB below the open-ear threshold of hearing, as in the dynamic range specification in ANSI S12.6: 1997, and distortion requirements should be met at no less than 20 dB below the open-ear threshold of hearing. The diffuse-field hearing thresholds in ISO 389-7 would be a suitable reference for open-ear thresholds. The use of electrical calibration for sound pressure levels should also be allowed below the background noise of the room and/or the inherent noise of the microphone. A suggested replacement wording for when electrical calibration may be used is: *Electrical calibration may be used for any sound pressure levels below the background noise levels of the room or the inherent noise of the microphone.* Overall the modifications required are considered minor.

The evaluation of HPD assessment methods involved the REAT, MIRE and ATF methods for conventional earmuffs and earplugs, an EMST earmuff (level-dependent), an ANR headphone and a full head covering helmet. No one method was suited to all types of HPD but the REAT method is the most widely used HPD assessment method. The main advantages with the REAT method are that it includes subjective variation in head and ear canal shape and size and the fitting behaviour of the test population, as well as including sound transmitted by the bone conduction sound transmission path. The MIRE method gave reasonable agreement with REAT measurements (above 250 Hz) but was limited to assessing earmuffs in this case. MIRE and ATF methods were useful for the assessment of HPDs at high sound pressure levels which is required for assessing level-dependent or ANR HPDs.

6.3 Field assessment of an earmuff

A prototype device to assess the field attenuation of HPDs was developed. The device was developed to assess the attenuation of a single cup of a single earmuff. The outside microphone position was chosen to be on the top of the headband as it measured the least variation with various incidences of sound in a free-field. The use of the headband microphone position was identified to lead to variation in the measured attenuation of the earmuff. The developed device was used to assess the effect of a pair of safety glasses and a thin woollen helmet liner each worn individually beneath earmuffs. The device estimated real-ear attenuation for the helmet liner with reasonable agreement to measured real-ear attenuation; however, the estimate of real-ear attenuation for the safety glasses and earmuffs did not agree. This could be possibly due to the inside microphone location. The work identified aspects of the developed equipment which should be addressed in future work. An alternative implementation with consideration for future work has been proposed.

6.4 Comments

A range of HPD assessment methods have been covered in this work, yet there are still other assessment methods and investigations to pursue, such as impulse noise. One underlying question through this work is: what level of complexity is appropriate for assessment of HPDs? This question arises because the goal of assessing HPD attenuation is to make the assessment relative to the end-user. This question is most evident when trying to define a suitable test population for assessment by the REAT method. The definition of the test population needs to be considered at a regulatory level and should consider what is practical from a laboratory testing point of view. Further evaluation of assessment methods for HPDs has been proposed in this study (e.g. impulse noise) as reflected in the literature; however, the cost of such assessment methods needs to be carefully considered. It was interesting to note that well-fitted roll-down foam earplugs provide near the highest levels of attenuation attainable, yet such fits were never observed by the author amongst test participants. It is anticipated that the high levels of attenuation would be unlikely to be obtained in the field due to lack of training and/or feeling of isolation or loss of auditory cues due to the high attenuation. Further field assessments should be carried out to assess the use of HPDs in the field. Assessments may be as simple as observing the insertion depth of earplugs to estimate the attenuation. Should there be a need to improve the use of HPDs the focus should be on training and providing a range of HPDs for end-users with consideration for fit and overall usability.

6.5 Future work

Immediate future work should focus on refining the current REAT method in terms of hardware, test procedure and technical specifications. There would be an advantage in implementing a faster threshold determination method to reduce the overall testing time and improve productivity. Longer term work should address whether Australasia should maintain their own REAT assessment method or adopt ISO or ANSI standards to align with international practice. Further development of the test facility to carry out impulse noise measurement or continuous noise assessment at higher sound levels is also possible. Any facility development is likely to require room and equipment development and should include robust test procedures and ethics approval if involving participants at high sound pressure levels. If the REAT method can be implemented in the same facilities then there are obvious advantages in a single facility. The development of improved hardware for the field assessment of HPDs has been discussed in Section 5.5. Such equipment may also find use in laboratory assessments of HPDs at elevated sound levels or impulse noise by the MIRE method. The goal of field assessments, independent of device and wearer, is still to be realised.

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A Appendices

A.1 Equipment

A.1.1 Low-noise microphone (G.R.A.S. 40HF)

The G.R.A.S. 40HF low-noise measurement system was used to measure background noise levels in the REAT booth. The measurement system consisted of a G.R.A.S. 40EH microphone and a G.R.A.S. 12HF power module. The microphone signal was acquired and analysed using a signal analyser (Brüel & Kjær PULSE 3560-C). The laptop and signal analyser were both run on battery power to reduce the influence of electrical noise. In addition, the 22 Hz high pass filter could not be used as the filter introduced noise at 50 Hz and its harmonics which affected background noise measurements. The auto-range function was used to scale the dynamic range of the signal analyser to the appropriate signal level which was important for background noise measurements.

The microphone power module has two frequency responses: pressure and free-field. The pressure response was used for all measurements with the G.R.A.S. 40HF microphone. A microphone calibration was carried out prior to each measurement using a Brüel & Kjær 4231 calibrator, and the level was confirmed using an FFT with 1 Hz wide bands. Sound pressure level measurements were corrected for microphone frequency response and directionality characteristics in post-processing as described below. G.R.A.S. provides frequency response correction data in 1/40th of a decade frequency increments from 251.2 Hz to 12590 Hz for both pressure and free-field responses. The pressure frequency response is shown in Figure A-1.

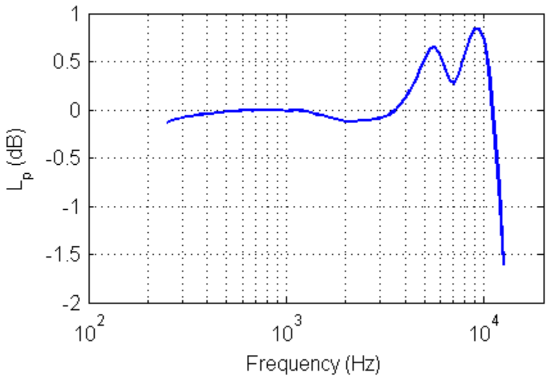


Figure A-1: Low-noise microphone frequency response corrections for pressure response.

One-third octave band frequency response corrections were read off tabulated data at the closest 1/40th of a decade centre frequency as it was considered to be more accurate than trying to read off values from Figure A-1 at one-third octave band centre frequencies. Corrections were not provided below 250 Hz so were assumed to be equal to the value provided for 250 Hz. This assumption appears to be incorrect as the trend appears to be more negative if the curve were extrapolated below 250 Hz;

however, assuming a correction of -0.11 dB was deemed to be appropriate as opposed to extrapolating below 250 Hz and introducing larger unknown values. Corrections were normalized to 1000 Hz as the microphone was calibrated using the Brüel and Kjær Type 4231 calibrator prior to any measurements. One-third octave band frequency response corrections are shown in Figure A-2.

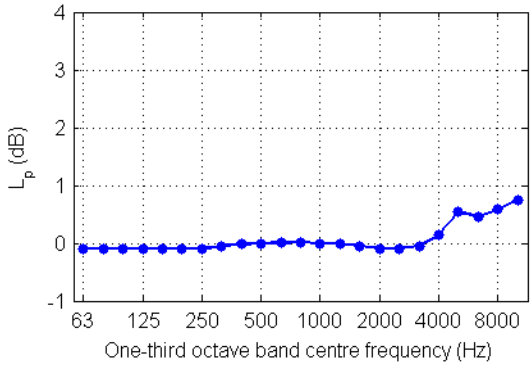


Figure A-2: Frequency response corrections for the low-noise microphone.

Directionality corrections were obtained by reading values off the diffuse-field directionality specifications [121]. Directionality corrections for a diffuse-field in one-third octave bands are summarised in Figure A-3. Random incident corrections were deemed to be appropriate as the sound field met the requirements of an approximate diffuse-field.

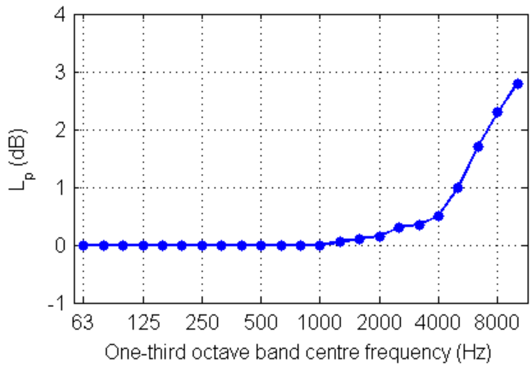


Figure A-3: Directionality corrections for the low-noise microphone in a diffuse-field.

The total corrections for the pressure response of the low-noise microphone used in a diffuse sound field are summarised in Figure A-4.

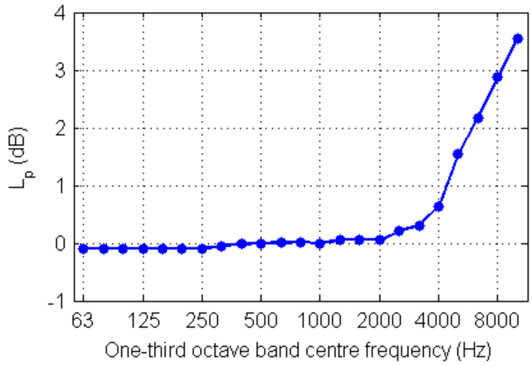


Figure A-4: Total microphone corrections for the low-noise microphone in a diffuse field.

Corrections were applied to measured sound pressure levels using Eq. A.1.

$$L_{p,c} = L_{p,m} - (L_{f,P} + L_{d,R}) \qquad \text{Eq. A.1}$$

Where: $L_{p,c}$ = Corrected sound pressure level.

$L_{p,m}$ = Measured sound pressure level.

$L_{f,P}$ = Microphone frequency response correction.

$L_{d,R}$ = Microphone directionality correction for random incident sound field.

A further check was carried out by comparison of the low-noise microphone (G.R.A.S. 40HF) with a diffuse-field microphone (Brüel & Kjær Type 4942). Each microphone was tested individually by placing it at the reference point of the REAT booth (see Chapter 2) while generating broadband pink noise. Results are summarised in Figure A-5.

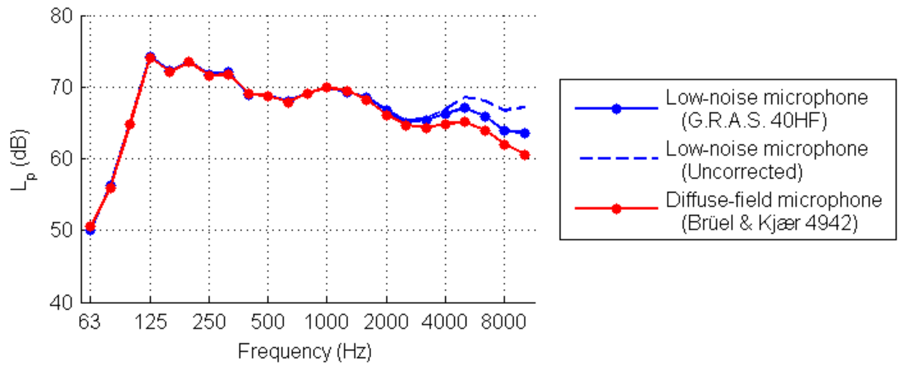


Figure A-5: Comparison of the low-noise microphone and the diffuse-field microphone in broadband pink noise.

It was expected that the corrected low-noise microphone and diffuse-field microphone responses would match if the assumption of a diffuse sound field was correct. There is disagreement between the two microphone responses above approximately 2000 Hz suggesting the diffuse sound field assumption was not entirely correct, however the trend with the corrections appears correct. As the low-noise microphone was used for assessing the maximum permissible background noise levels, possible over estimation of the sound pressure levels was deemed to be permissible.

A.1.2 Directional microphone (OKTAVA 012)

A cardioid response microphone (OKTAVA 012) was used for directionality measurements. The microphone was assessed to determine if it was suitable for directionality measurements. The microphone linearity was determined by comparison with a diffuse-field microphone (Brüel & Kjær Type 4942). The microphones were placed side by side in an anechoic room[78] as shown in Figure A-6.

Figure A-6: Experimental setup to qualify the OKTAVA 012 microphone.

Both microphones were located 2.7 m away from the sound source (JBL EON Power 10), with source and microphones at an approximate height of 1.25 m. The minimum distance between source and measurement position to achieve an approximate free-field in an anechoic room was determined to be 1.98 m based on Eq. A.2, Eq. A.3 and Eq. A.4 [122].

$$r > 3\lambda/(2\pi) \qquad \text{Eq. A.2}$$

$$r > 3l \qquad \text{Eq. A.3}$$

$$r > 3\,\pi l^2/(2\,\lambda) \qquad \text{Eq. A.4}$$

Where:	r	=	Distance from the source to the measurement position.
	λ	=	Wavelength of radiated sound λ = 0.86 m @ 400 Hz.
	l	=	Characteristic source dimension conservatively estimated 0.66 m based on approximate sound source dimensions 0.5 x 0.5 x 0.3 m.

A broadband pink noise was produced and the level was varied in approximately 20 dB steps. Sound pressure levels were measured in one-third octave bands for each microphone with results summarised in Figure A-7. Colour is used to indicate different sound pressure levels. The results were considered sufficient to establish the microphone had suitable linearity and dynamic range for directionality measurements.

[78] The anechoic chamber was in the Electrical Engineering Department at the University of Canterbury.

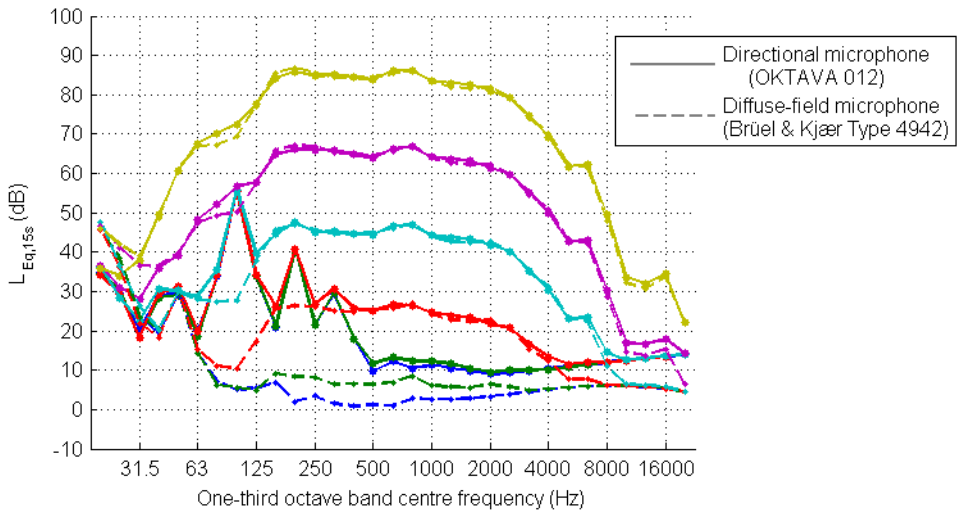


Figure A-7: Dynamic range comparison of diffuse-field and directional microphones.

The diffuse-field microphone was removed and the directional microphone was repositioned to be in line with and facing the JBL speaker. A rotating arm was used to rotate the microphone about the microphone diaphragm in the horizontal plane to assess the directional characteristics. A schematic of the measurement setup is shown in Figure A-8.

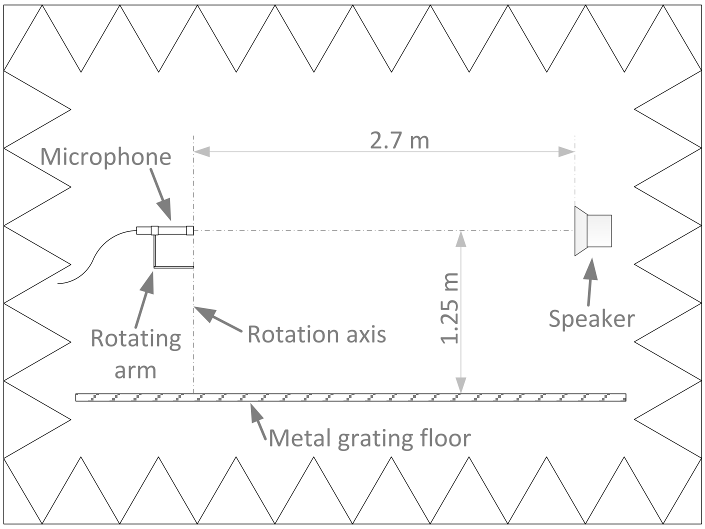


Figure A-8: Measurement setup to assess microphone directionality.[79]

AS/NZS 1270: 2002 specifies that directionality can be assessed by rotating the microphone in 15° increments, but 10° increments were used in this case as they were the available marks on the rotating assembly. Directionality was assumed to be symmetrical about the longitudinal axis of the microphone. The measured directional response is shown in Figure A-9.

[79] Directionality measurements were carried out in the anechoic chamber in the Electrical Engineering Department at the University of Canterbury.

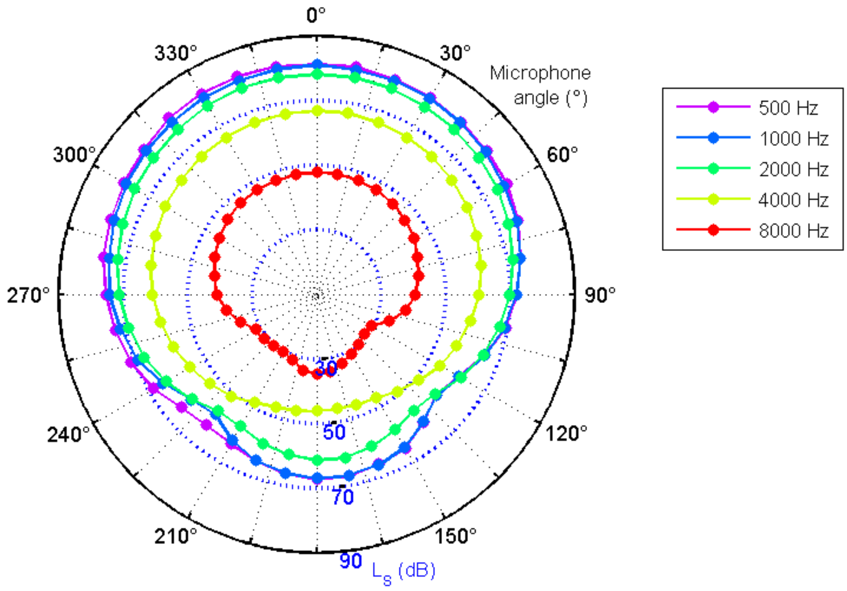


Figure A-9: Directionality of the OKTAVA 012 microphone with cardioid response capsule.

The microphone free field rejection was taken to be the difference between the measured sound pressure level at 0° and 180° orientations. The maximum allowable variation calculated in accordance with AS/NZS 1270: 2002 is summarised in Table A-1.

Table A-1: Allowable in-plane variation based on the directional response of the OKTAVA 012 microphone.

f (Hz)	0° to 180° difference	Allowable variation (dB)
500	14.0	3.8
1000	14.0	3.8
2000	16.9	4.4
4000	20.7	5.1
8000	12.9	3.6

A.2 Addendum to Chapter 2

A.2.1 Test signals

Test signals were filtered from a broadband pink noise source using 3rd order Butterworth filters. Signal processing was carried out within the HPD test program using in-built function blocks in LabVIEW. Filters were evaluated in accordance with AS/NZS 4476: 1997 [73] using a separate LabVIEW program with calculations and results presented below.

The bandwidth designator (b) is used to specify the fraction of the octave (1/b) for fractional octave-band filters or b = 3 for one-third octave band filters. A base-ten system was used for filter calculations so the octave ratio (G) was calculated by Eq. A.5:

$$G_{10} = 10^{b/10} \qquad \text{Eq. A.5}$$

AS/NZS 1270: 2002 specifies mid-band frequencies which are assumed to be nominal values. Exact mid-band frequency (f_m) can be calculated by Eq. A.6.

$$f_m = G^{(x/b)} f_r \qquad \text{Eq. A.6}$$

Where: x = Any positive or negative integer including zero.

f_r = Reference frequency = 1000 Hz.

Band-edge frequencies f_1 (lower) and f_2 (upper) were then calculated by Eq. A.7 and Eq. A.8.

$$f_1 = (G^{-1/2b})(f_m) \qquad \text{Eq. A.7}$$

$$f_2 = (G^{+1/2b})(f_m) \qquad \text{Eq. A.8}$$

Table A-2 summarises the band-pass frequencies for the implemented third order Butterworth band-pass filters rounded to 4 SF.

Table A-2: Centre and edge frequencies of test signal band-pass filters.

x	f_c	f_m	f_1	f_2
-9	125	125.9	112.2	141.3
-6	250	251.2	223.9	281.8
-3	500	501.2	446.7	562.3
0	1000	1000	891.3	1122
3	2000	1995	1778	2239
6	4000	3981	3548	4467
9	8000	7943	7079	8913

AS/NZS 1270: 2002 specifies that filters must meet the Class 1 relative attenuation requirements in AS/NZS 4476: 1997. Relative attenuation (ΔA) was calculated using Eq. A.9.

$$\Delta A(f/f_m) = A(f/f_m) - A_{ref} \qquad \text{Eq. A.9}$$

Where $A_{ref} = 0$ was assumed as the filter was implemented in software. Filter attenuation (A) in dB, was calculated by Eq. A.10.

$$A = L_{in} - L_{out} \qquad \text{Eq. A.10}$$

Where L is the time mean square signal level in dB for the input and output signals defined by:

$$L = 10 \log_{10}\left(\frac{\left[\left(\frac{1}{T}\right)\int_0^T V^2(t)dt\right]}{V_0^2}\right) \qquad \text{Eq. A.11}$$

Where: $V(t)$ = Instantaneous input or output signal.

T = Elapsed time integration time.

V_0 = Reference quantity = 20 μV.

A $\pm 1\ V_{p-p}$ sine wave was generated and band-pass filtered to determine the filter attenuation for that frequency. The sine wave frequency was varied over a range centred about the band-pass centre frequency which will be defined soon. The first half of the filtered signal was discarded where the filter was found to ring. The ringing effect is illustrated in Figure A-10 by the output (or filtered signal) for a 125 Hz one-third octave band filter with a 50 Hz sine wave input.

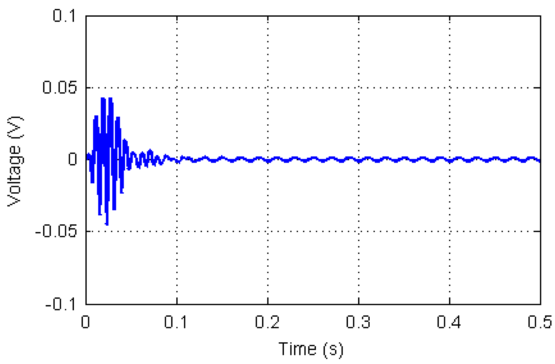


Figure A-10: Example of filter ringing effect.

Filter ringing was considered to be an insignificant factor as filter ringing was only present in the first filtered sample (at a level below normal hearing thresholds). Furthermore, the test signal was cropped and windowed which would further reduce the amplitude of the ringing. Relative attenuation was calculated between the filtered and original signal at discrete frequencies in steps distributed evenly around the band-pass centre frequency. Test frequencies for each band-pass filter were calculated using Eq. A.12.

$$f_i/f_m = \left[G^{1/(bS)}\right]^i \qquad \text{Eq. A.12}$$

Where: i = Any positive or negative integer including zero.

S = The number of test frequencies within the band-pass limits.

According to AS/NZS 4476: 1997, S must not be less than 24 and shall be increased in steps of 12 until the calculated filter integrated response is independent of S to the nearest 0.1 dB. The filter integrated response (ΔB) is calculated by:

$$\Delta B = 10\log(B_e/B_r) \qquad \text{Eq. A.13}$$

Where the normalised reference bandwidth (B_e) is defined by Eq. A.14 and the normalised effective bandwidth (B_e) is defined by Eq. A.15:

$$B_r = (f_2 - f_1)/f_m \qquad \text{Eq. A.14}$$

$$B_e = \int_0^{\infty} 10^{-0.1\Delta A(f/f_m)}\, d(f/f_m) \qquad \text{Eq. A.15}$$

Where B_e is typically evaluated numerically by Eq. A.16:

$$\sum_{i=-N}^{i=N} \frac{1}{2}\left\{10^{-0.1\Delta A(f_i/f_m)} + 10^{-0.1\Delta A(f_{i+1}/f_m)}\right\}[(f_i/f_m) - (f_{i+1}/f_m)] \qquad \text{Eq. A.16}$$

Where: $\Delta A(f_i/f_m)$ = Relative attenuation (dB) measured at the i^{th} normalized test frequency.

N = Number of discrete frequencies tested.

In addition to being independent of S, the integrated response (ΔB) must not exceed ± 0.3 dB. The filter integrated response was independent of S and all filters had an integrated response of approximately 0.2 dB as in Table A-3 for N = 301.

Table A-3: Filter integrated response.

One-third octave band centre frequency (Hz)	Filter integrated response ΔB (dB)	
	S = 24	S = 36
125	0.201	0.200
250	0.201	0.201
500	0.200	0.200
1000	0.200	0.200
2000	0.200	0.200
4000	0.200	0.200
8000	0.198	0.198

For Class 1 octave and fractional-octave band filters, the relative attenuation of any filter must be within the limits defined in Table A-4.

Table A-4: Minimum and maximum relative attenuation limits.

<table>
<tr><th rowspan="2">Normalized frequency $f/f_m = \Omega$</th><th colspan="2">Class 1 filter's relative attenuation limits</th></tr>
<tr><th>Min</th><th>Max</th></tr>
<tr><td>G^{0}</td><td>-0.3</td><td>$+0.3$</td></tr>
<tr><td>$G^{\pm 1/8}$</td><td>-0.3</td><td>$+0.4$</td></tr>
<tr><td>$G^{\pm 1/4}$</td><td>-0.3</td><td>$+0.6$</td></tr>
<tr><td>$G^{\pm 3/8}$</td><td>-0.3</td><td>$+1.3$</td></tr>
<tr><td>$< G^{+1/2}$</td><td rowspan="2">-0.3</td><td rowspan="2">$+5.0$</td></tr>
<tr><td>$> G^{-1/2}$</td></tr>
<tr><td>$G^{\pm 1/2*}$</td><td>$+2.0$</td><td>$+5.0$</td></tr>
<tr><td>$G^{\pm 1}$</td><td>$+17.5$</td><td>$+\infty$</td></tr>
<tr><td>$G^{\pm 2}$</td><td>$+42$</td><td>$+\infty$</td></tr>
<tr><td>$G^{\pm 3}$</td><td>$+61$</td><td>$+\infty$</td></tr>
<tr><td>$\geq G^{+4}$</td><td>$+70$</td><td>$+\infty$</td></tr>
<tr><td>$\leq G^{-4}$</td><td>$+70$</td><td>$+\infty$</td></tr>
</table>

According to AS/NZS 4476: 1997 for a fractional-octave band filter, the high frequency fractional octave band normalised frequency ($\Omega_{h(1/b)}$) corresponding to a finite relative attenuation limit for the accuracy class shall be calculated for $\Omega \geq 1$ using Eq. A.17:

$$\Omega_{h(1/b)} = 1 + [(G^{1/2b} - 1)/(G^{1/2} - 1)](\Omega - 1) \qquad \text{Eq. A.17}$$

For $\Omega < 1$, the low frequency fractional octave band normalised ($\Omega_{l(1/b)}$) shall be calculated using Eq. A.18:

$$\Omega_{l(1/b)} = 1/\Omega_{h(1/b)} \qquad \text{Eq. A.18}$$

3rd order Butterworth filters with exact centre frequencies and band-pass edge frequencies summarised in Table A-2 were found to meet Class 1 relative attenuation (ΔA) requirements of AS/NZS 4476: 1997.

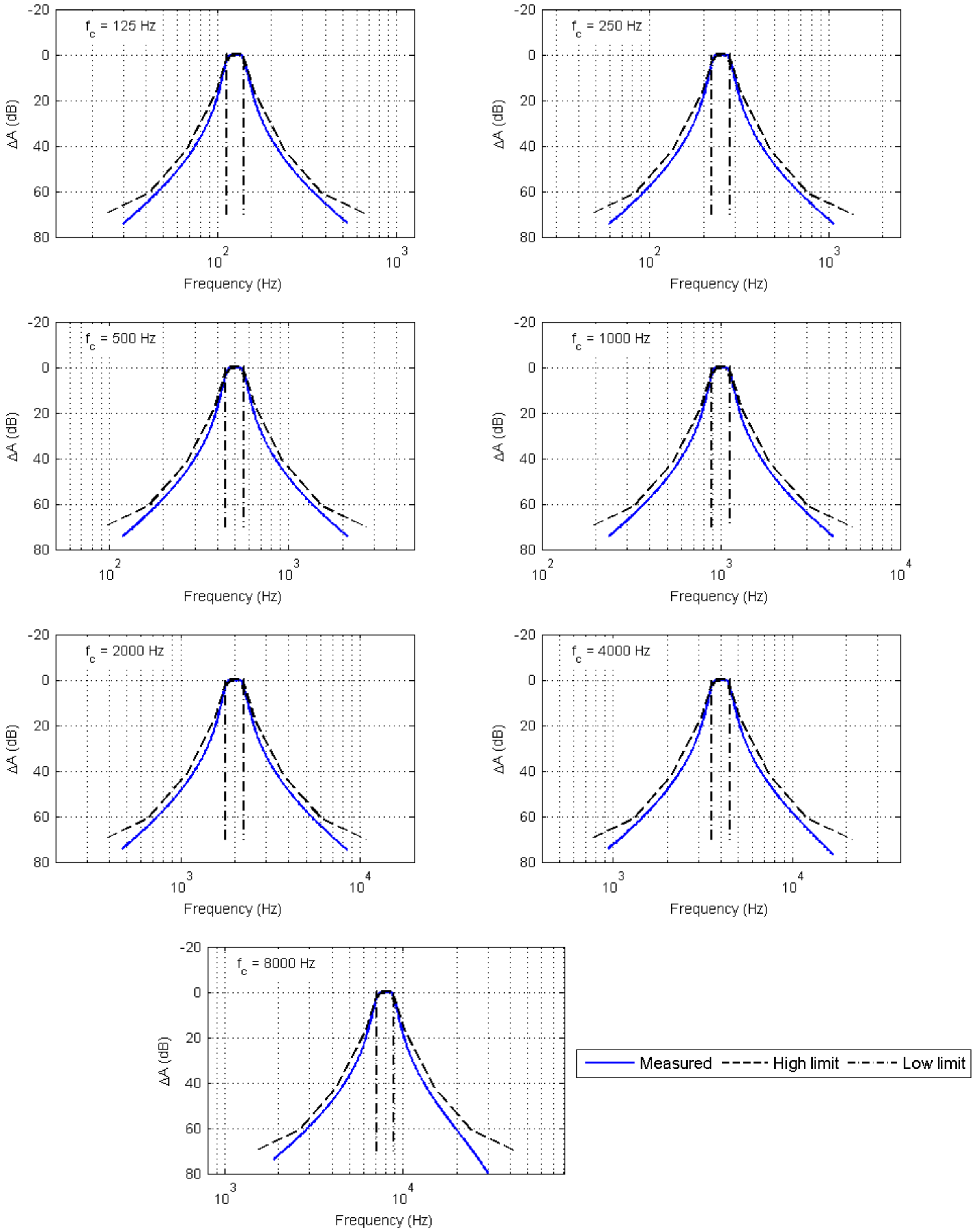


Figure A-11: Relative attenuation for the test signal filters used for REAT assessments.

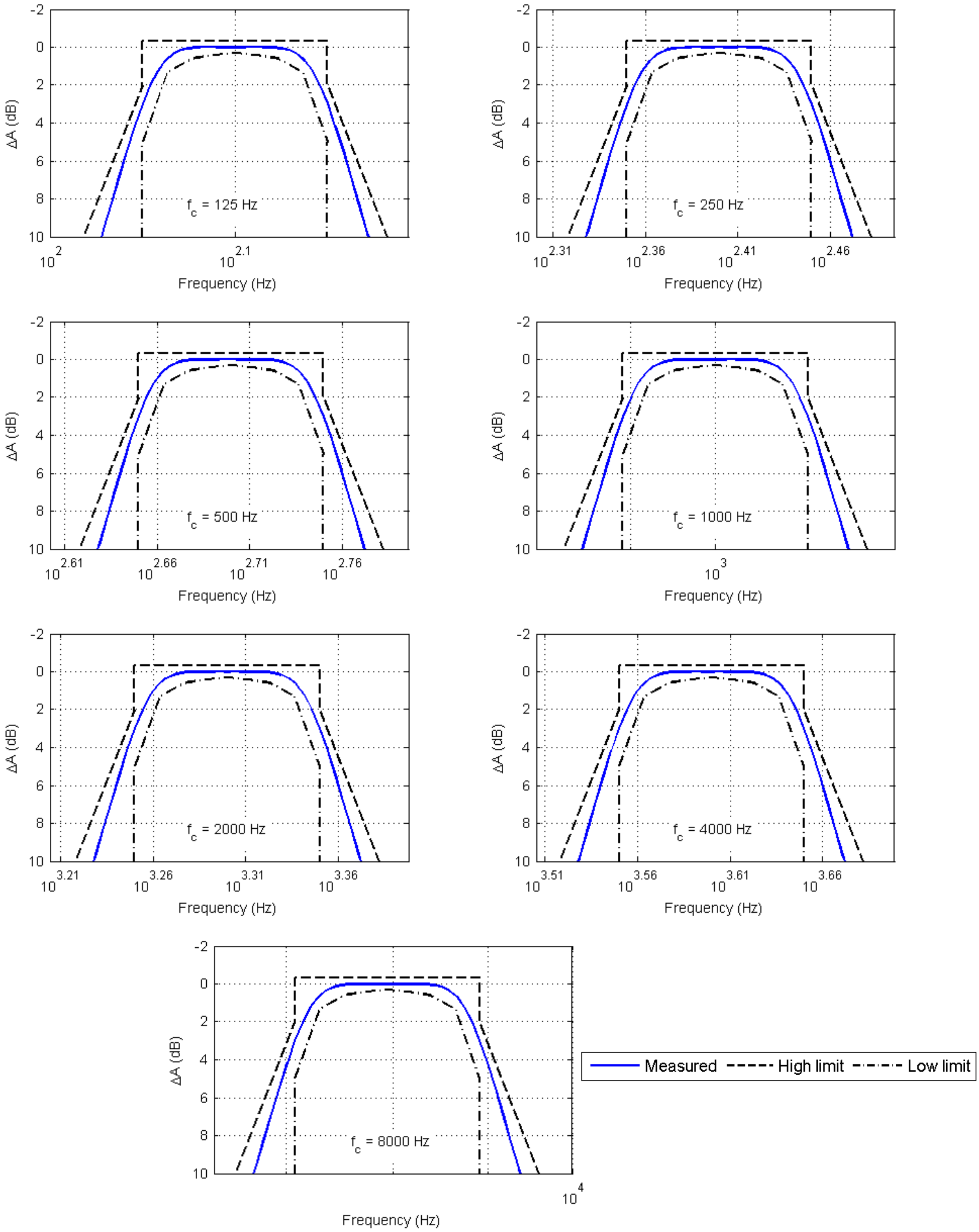


Figure A-12: Alternative view of Figure A-11 showing close to the band-pass limits.

A.2.2 Test site

A.2.2.1 Uniformity

Results from the uniformity measurements are summarised in Table A-5 below where ΔL_p represents the sound pressure level relative to the sound pressure level at the reference point.

Table A-5: Summary of uniformity measurements.

One-third octave band centre frequency (Hz)	Reference point		Front			Back			Up			Down			Left			Right			Left/Right
	L_p	σ	L_p	σ	ΔL_p	L_p	σ	ΔL_p	L_p	σ	ΔL_p	L_p	σ	ΔL_p	L_p	σ	ΔL_p	L_p	σ	ΔL_p	ΔL_p
125	54.7	0.2	54.5	0.3	-1.2	54.7	0.2	-0.8	55.0	0.3	0.7	54.2	0.3	-1.4	54.4	0.1	-1.0	54.5	0.2	-1.1	-0.1
250	51.2	0.2	51.3	0.1	0.4	50.8	0.1	-0.9	49.3	0.1	-2.4	52.1	0.2	-0.2	51.6	0.1	0.2	51.2	0.3	-0.9	0.4
500	48.7	0.1	48.4	0.1	-0.5	49.2	0.1	1.0	47.5	0.1	-1.6	48.7	0.2	0.6	50.1	-0.3	1.8	47.6	0.1	-1.4	2.6
1000	50.0	0.1	50.1	0.1	0.5	50.9	0.1	1.2	49.1	0.1	-1.2	50.0	0.1	-0.5	50.0	0.0	-0.3	50.2	0.1	0.6	-0.3
2000	46.5	0.1	46.4	0.1	-0.4	46.2	0.0	-0.5	46.2	0.1	-0.5	47.1	0.1	0.9	46.5	0.1	-0.4	46.4	0.1	-0.5	0.1
4000	45.0	0.1	45.1	0.0	0.3	45.0	0.0	-0.2	44.6	0.1	-0.6	45.2	0.0	0.3	45.2	0.0	0.4	45.5	0.0	0.6	-0.3
8000	42.4	0.0	42.3	0.0	-0.2	42.3	0.0	-0.1	41.9	0.0	-0.7	42.6	0.0	-0.1	42.0	0.0	-0.5	42.3	0.0	-0.3	-0.3

A.2.2.2 Directionality

Directionality was assessed by rotating a directional microphone through 360° in each of the three orthogonal planes in the room. Results are plotted as sound pressure level (L_S) vs. microphone angle for each of the three planes for test signals from 500 to 8000 Hz.

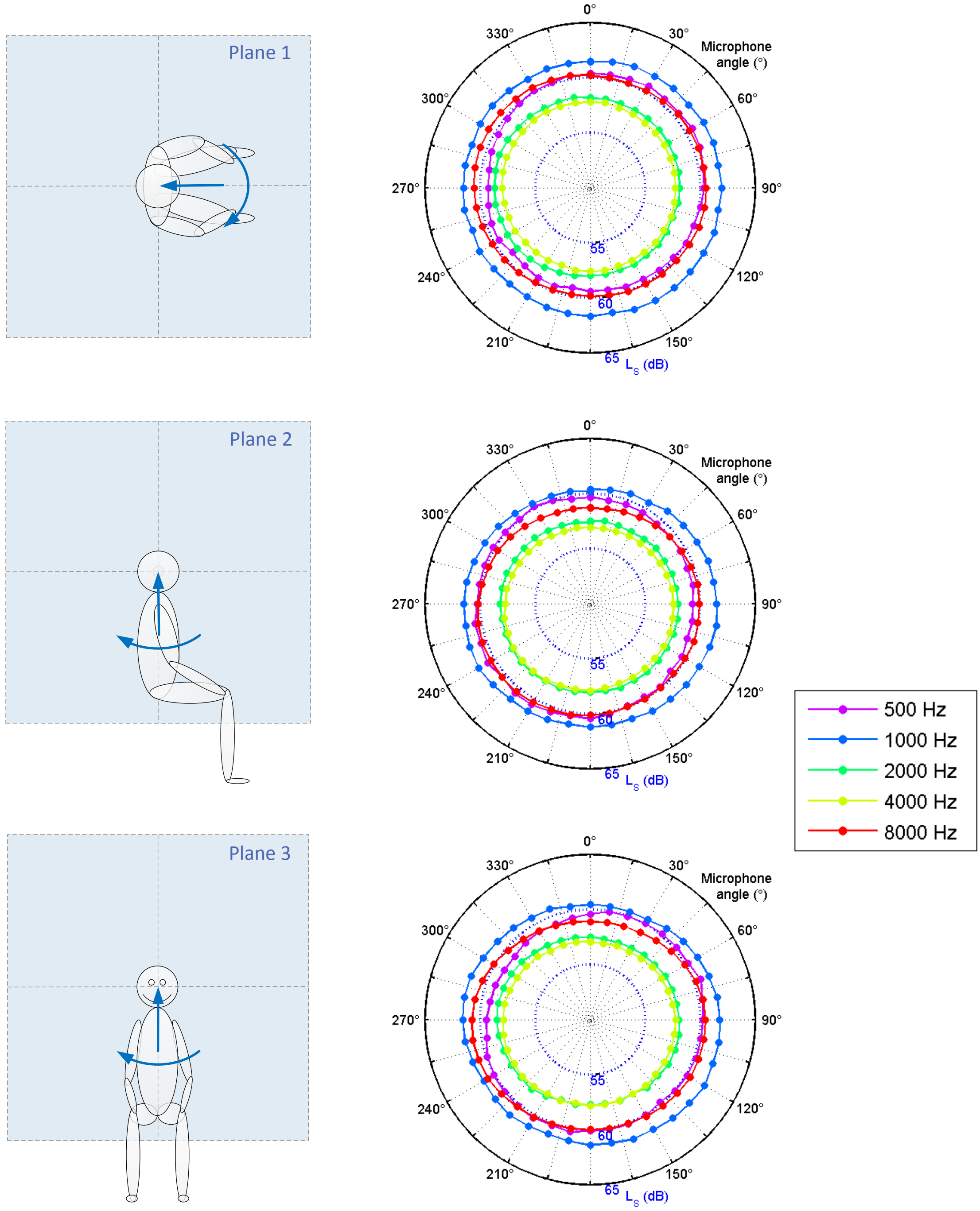


Figure A-13: Directionality results for the three orthogonal room planes.

A.2.2.3 Reverberation time

ISO 354: 2003 was used as a guideline for measuring reverberation time using the interrupted noise method. Measurement settings were qualified to ensure the sound field decay was measured instead of the time weighting decay as reverberation times were typically less than 1 s. Reverberation time was measured using a diffuse-field microphone (Brüel & Kjær Type 4942) and a signal analyser (Brüel & Kjær PULSE 3560-C). Time between samples (dt) was fixed at approximately 90 % of the time constant (τ) to maintain a consistent relationship between τ and dt. For each τ and dt pair, a 125 Hz one-third octave band of pink noise was generated in the room at an approximate level of 80 dB for a minimum of 5 s before being interrupted. The 125 Hz one-third octave band was used as it had the shortest reverberation time. A single decay for each pair of settings was recorded and the decay was interpolated for its slope and reverberation times were calculated from the slope. Results in Table A-6 indicate a convergence of reverberation time at approximately 0.25 s. In this case τ = 1/128 s and dt = 0.0070 s were considered to be suitable measurement settings.

Table A-6: Reverberation time measurement settings.

τ (s)		dt (s)	T60 (s)
1/16	0.0625	0.056	0.86
1/32	0.0313	0.028	0.43
1/64	0.0156	0.014	0.24
1/128	0.00781	0.0070	0.27
1/256	0.00391	0.0035	0.24
1/512	0.00195	0.0018	0.25

The results from reverberation time testing are summarised in Table A-7 and a single example of the interpolation used to determine reverberation time for each one-third octave band test signal is summarised in Figure A-14.

Table A-7: Reverberation times at the reference point.

		One-third octave band centre frequency						
		125	250	500	1000	2000	4000	8000
T60 (s)	1	0.25	0.37	0.63	0.94	1.10	1.00	0.85
	2	0.26	0.48	0.53	1.10	1.20	1.00	0.78
	3	0.30	0.32	0.52	1.20	1.10	1.00	0.81
	4	0.25	0.53	0.51	0.99	1.10	0.97	0.82
	5	0.29	0.60	0.45	0.86	1.10	0.94	0.83

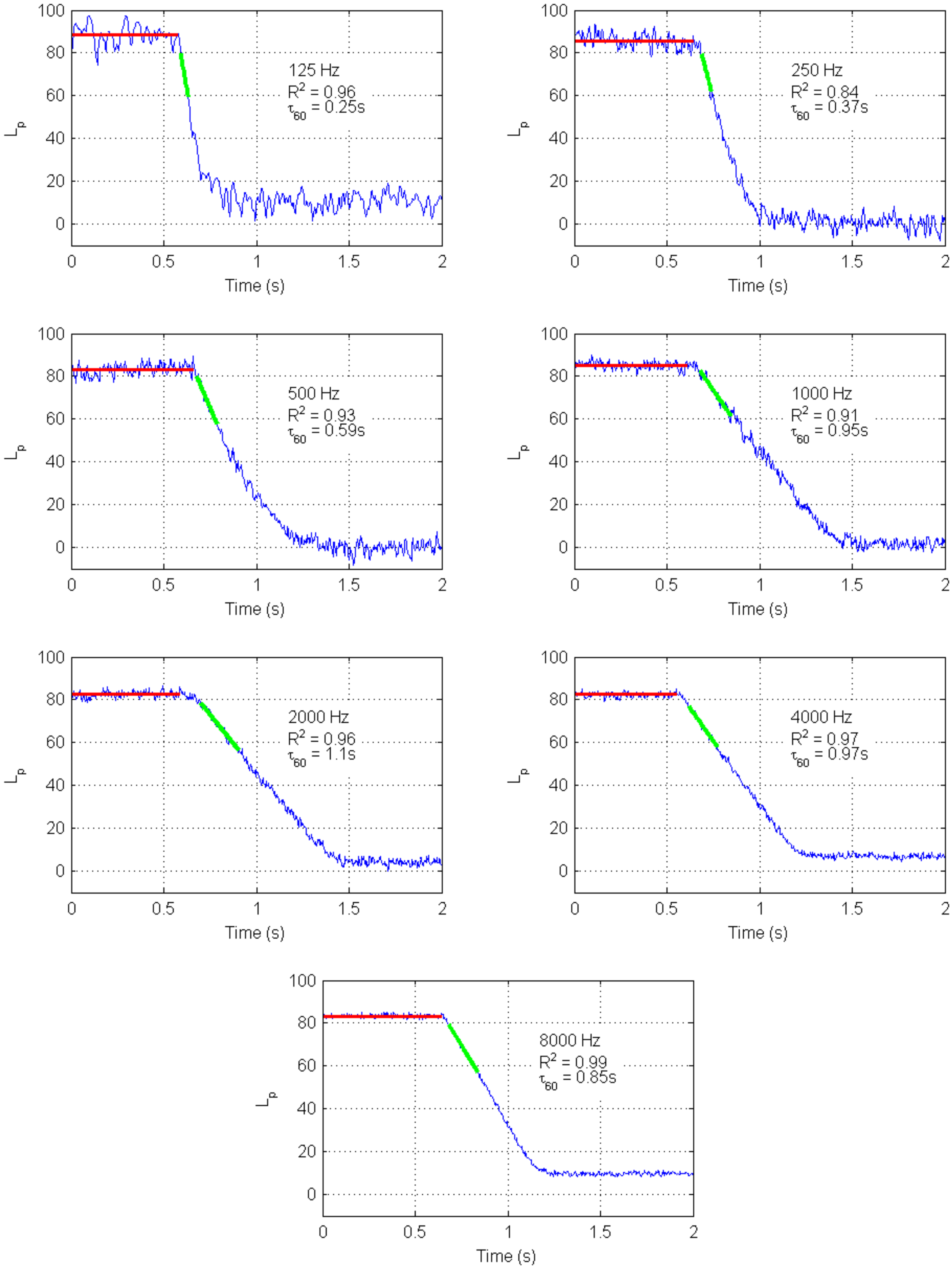


Figure A-14: Examples of recorded decays for reverberation time measurements.

A.2.3 Test equipment

A.2.3.1 Electrical calibration

Sound pressure levels must be at least 40 dB below the in-band level for bands two octaves or more removed from the test signal, according to distortion requirements in AS/NZS 1270: 2002. The lowest in-band level is -25 dB for the 4000 Hz test signal and so far away bands must be -65 dB or lower. The minimum sound pressure levels measured by the available microphones in the REAT booth after-hours are shown in Figure A-15.

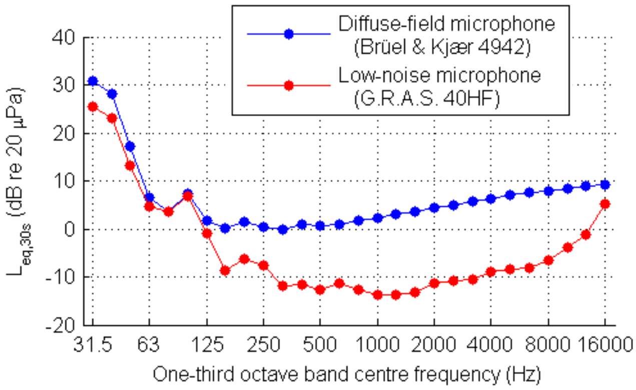


Figure A-15: Minimum sound pressure levels measured by diffuse-field and low-noise microphones.

The sound pressure levels indicated are due to the ambient noise in the room below approximately 250 Hz, whereas above 250 Hz the indicated sound pressure levels are due to the inherent noise of the respective microphones. The diffuse-field microphone had an inherent noise level of approximately 0 dB in one-third octave bands whereas the low-noise microphone had an inherent noise level of approximately -13 dB. AS/NZS 1270: 2002 allows sound pressure levels below 0 dB to be determined on the basis of electrical calibration. Background noise levels during daytime hours below and including the 160 Hz one-third octave band were all above 0 dB yet met the background noise requirements of AS/NZS 1270: 2002 (Section 2.3.2.4) in the developed test facility. It was assumed that electrical calibration could be applied to determine levels below the inherent noise of the measurement system including if that level was above 0 dB. Speaker terminal[80] voltage ($V_{ST,rms}$) was measured to determine sound pressure levels via electrical calibration. Continuous noise was generated for each test signal frequency individually and the level was varied in 5 dB steps using various combinations of A_{DAC} and A_{AMP} to cover the required dynamic range. Sound pressure level measurements were made using a diffuse-field microphone (Brüel & Kjær Type 4942). The low-noise microphone had a lower inherent noise level than the diffuse-field microphone however neither microphone had low enough inherent noise levels such that electrical calibration would be

[80] Rear terminals on speaker housing were used rather than terminals of the speaker drivers.

unnecessary. Measurements were conducted after hours to reduce the influence of background noise. Sound pressure level at the reference point (L_P) and voltages across the speaker terminals ($V_{ST,rms}$) were measured in one-third octave bands from 31.5 Hz to 16 kHz with a time averaging of 30 s and no frequency weighting. Results are shown in Figure A-16. Omitted points were not included in the linear interpolation due to the influence of inherent noise.

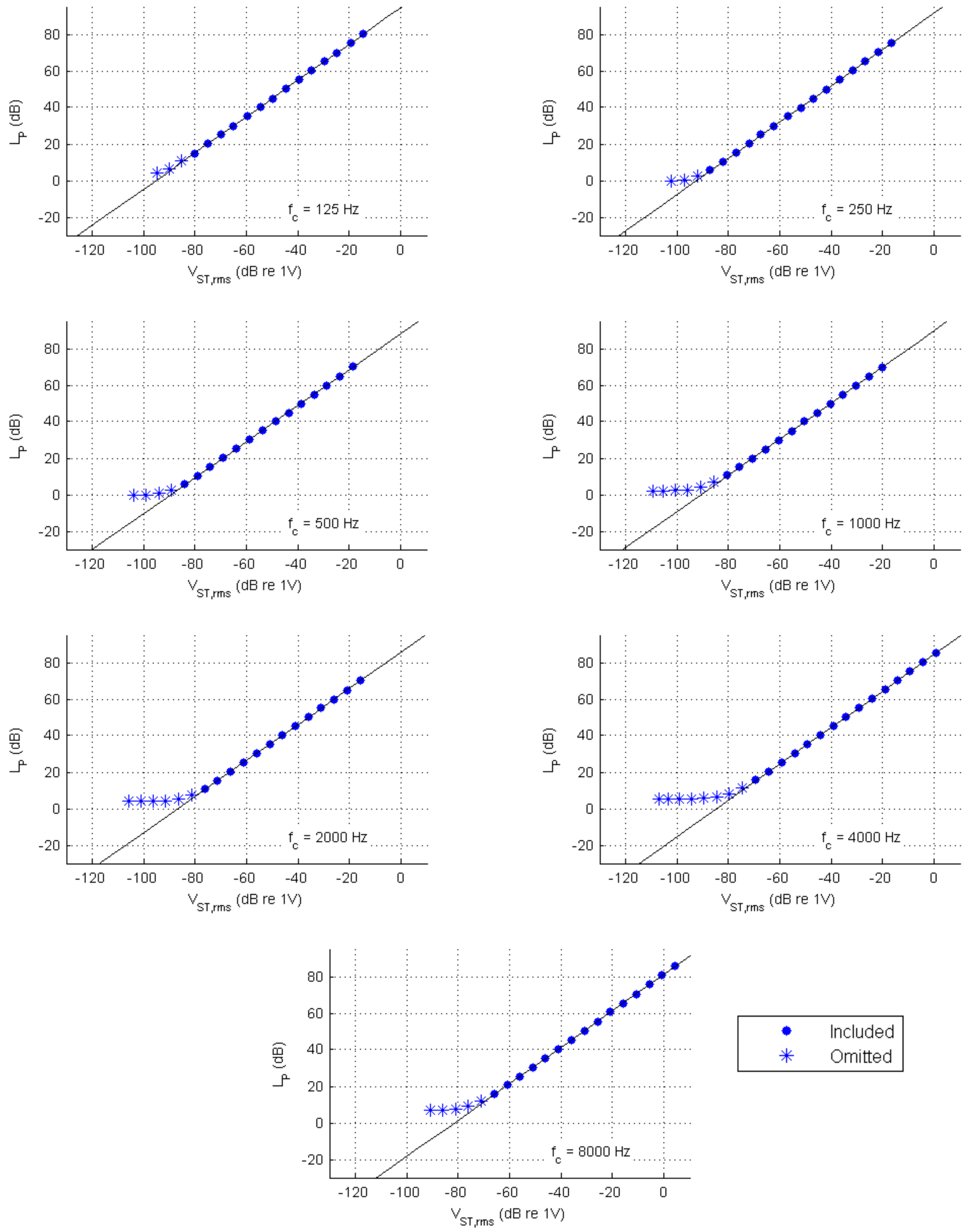


Figure A-16: In-band sound pressure level vs. in-band speaker terminal voltage.

The relationship was linear (R^2 = 1.00 to 2dp) for all test signals when measurement points influenced by ambient or measurement equipment noise were omitted. Sound pressure levels below the ambient noise in the booth or microphone noise was then determined by extrapolation. A lower in-band level of -65 dB was required to be established, but measurement of speaker terminal voltages encountered a noise floor limitation. The amplifier output was attenuated by A_{AMP} so the amplifier operation did not affect the background noise levels in the booth measured by the low-noise microphone (G.R.A.S. 40HF). Attenuating the levels further was considered to be unnecessary considering the sound pressure levels able to be determined were already at an approximate sound pressure level of - 20 dB and should be sufficient for determining open-ear thresholds. Minimum voltage levels able to be measured at speaker terminals and the signal analyser (by shorting the input terminal) are shown in Figure A-17.

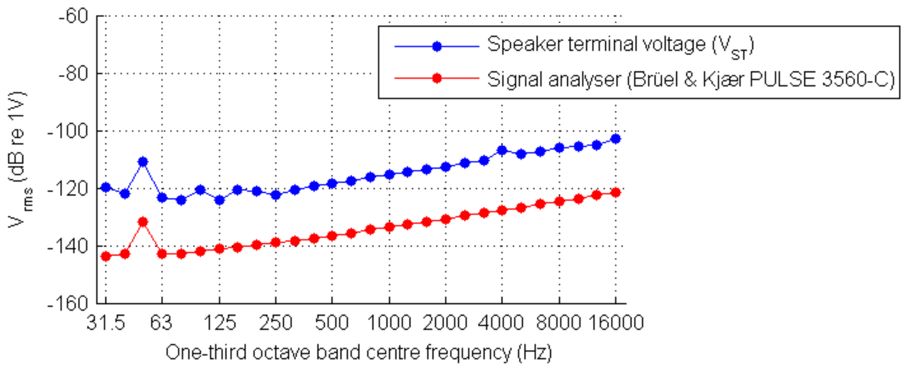


Figure A-17: Inherent noise limitations for voltage measurements.

The minimum voltage levels able to be measured by the signal analyser (Brüel & Kjær PULSE 3560-C) would be encountered if the full requirements of dynamic range and distortion were to be determined. Sound pressure levels could be determined to a lower limit of approximately -30 dB for the 1000 Hz test signal by extrapolating the relationship in Figure A-16 and considering the lower limits in Figure A-17. Other test signals were similar. This limitation meant that the full specifications in AS/NZS 1270: 2002 were unable to be met by measurement of sound pressure levels or measurement of speaker terminal voltage.

A.2.3.2 Distortion

Each test signal was produced in 5 dB steps over the required dynamic range of the system. The resulting sound pressure level (L_p) and speaker terminal voltage ($L_{p,V}$) were measured and are summarised in Figure A-18 and Figure A-19 respectively. Sound pressure level is coloured to indicate level with low to high sound pressure level coloured dark to light.

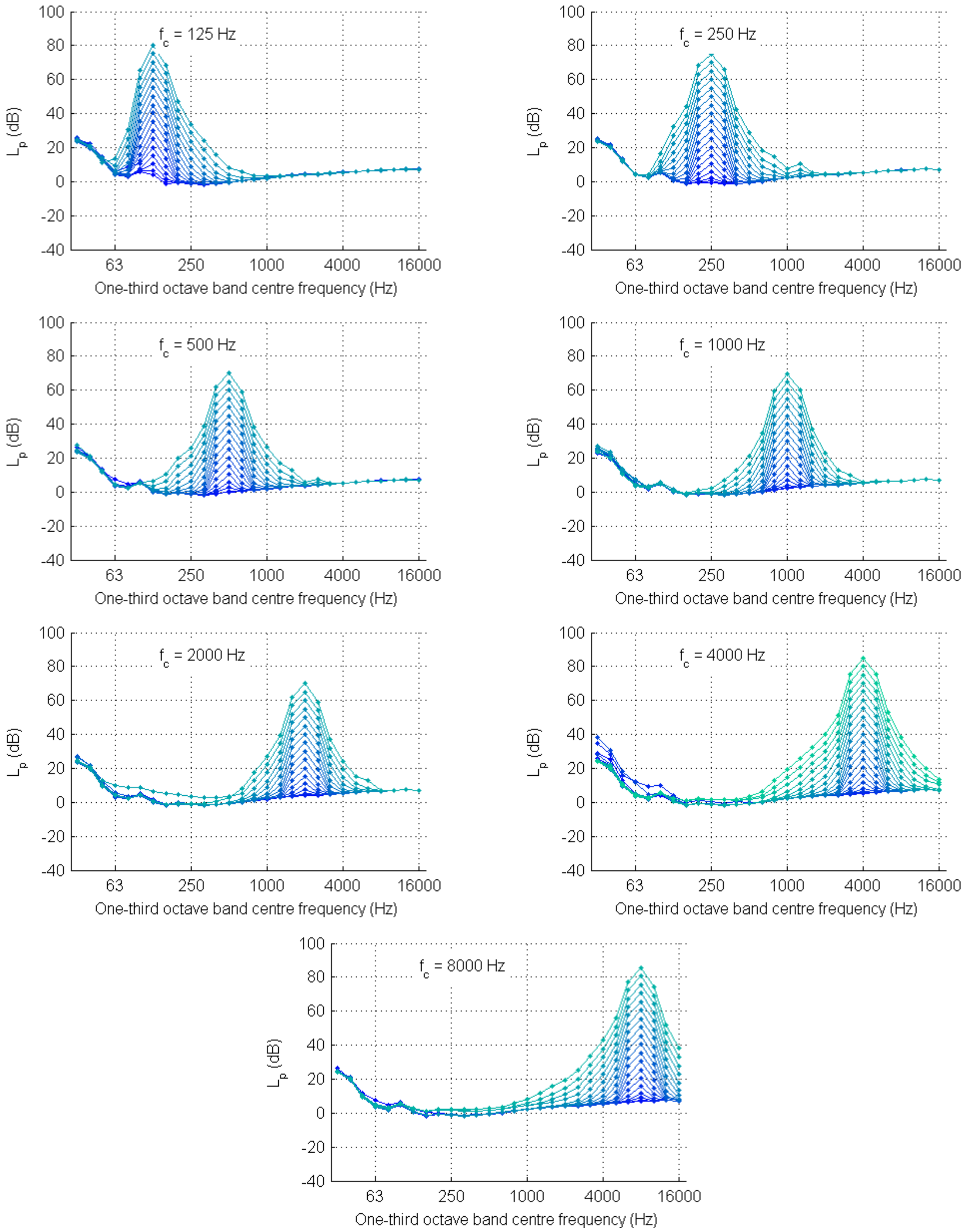


Figure A-18: Sound pressure levels used for REAT assessments determined by measurement with a diffuse-field microphone.

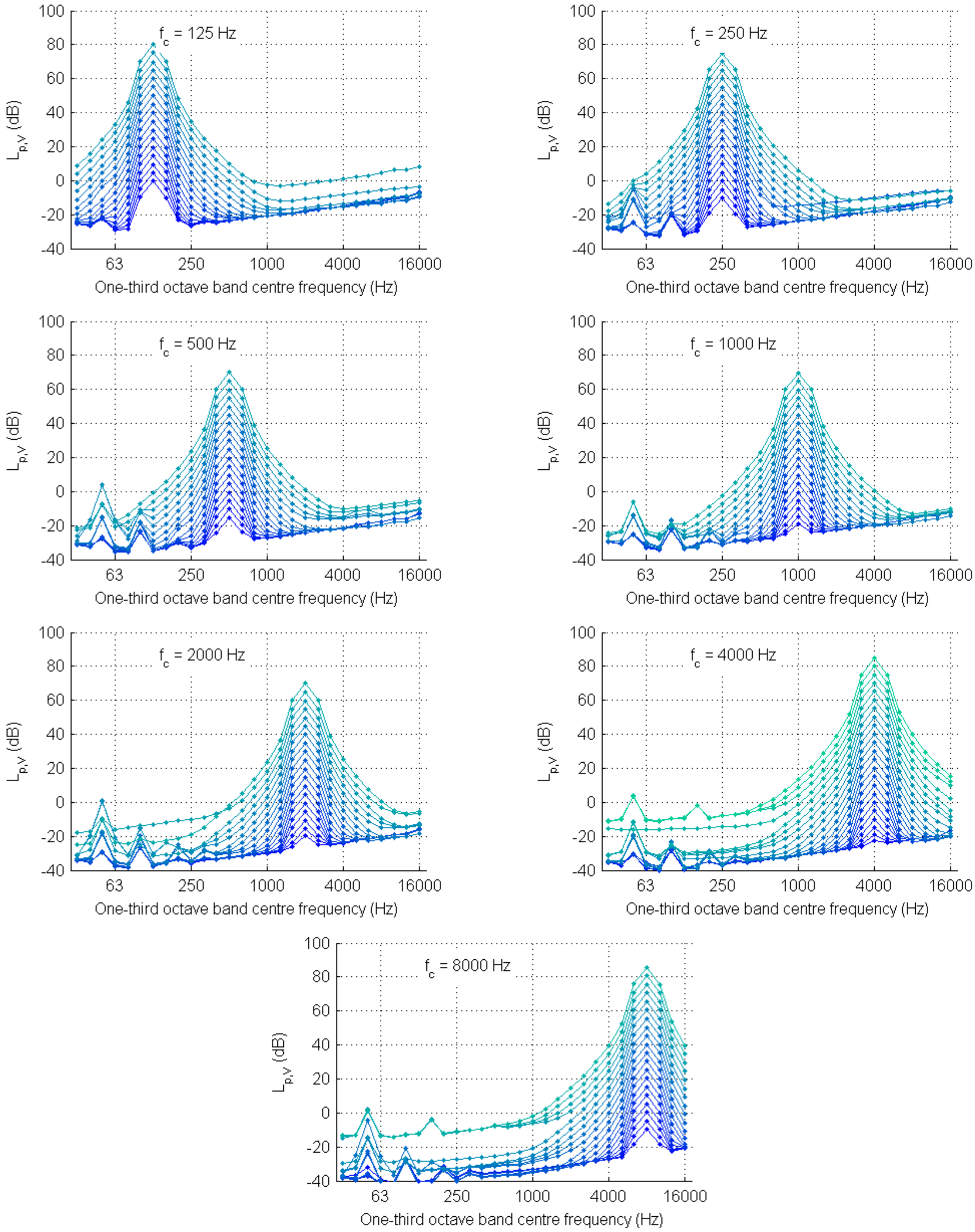


Figure A-19: Sound pressure levels used for REAT assessments determined by measurement of speaker terminal voltage.

The above results are re-plotted as Figure A-20 and Figure A-21 by normalising to the test signal level to better illustrate distortion limits. Distortion limits are indicated by the thick black line. If a test signal level meets the limits then that coloured line should be below the black line.

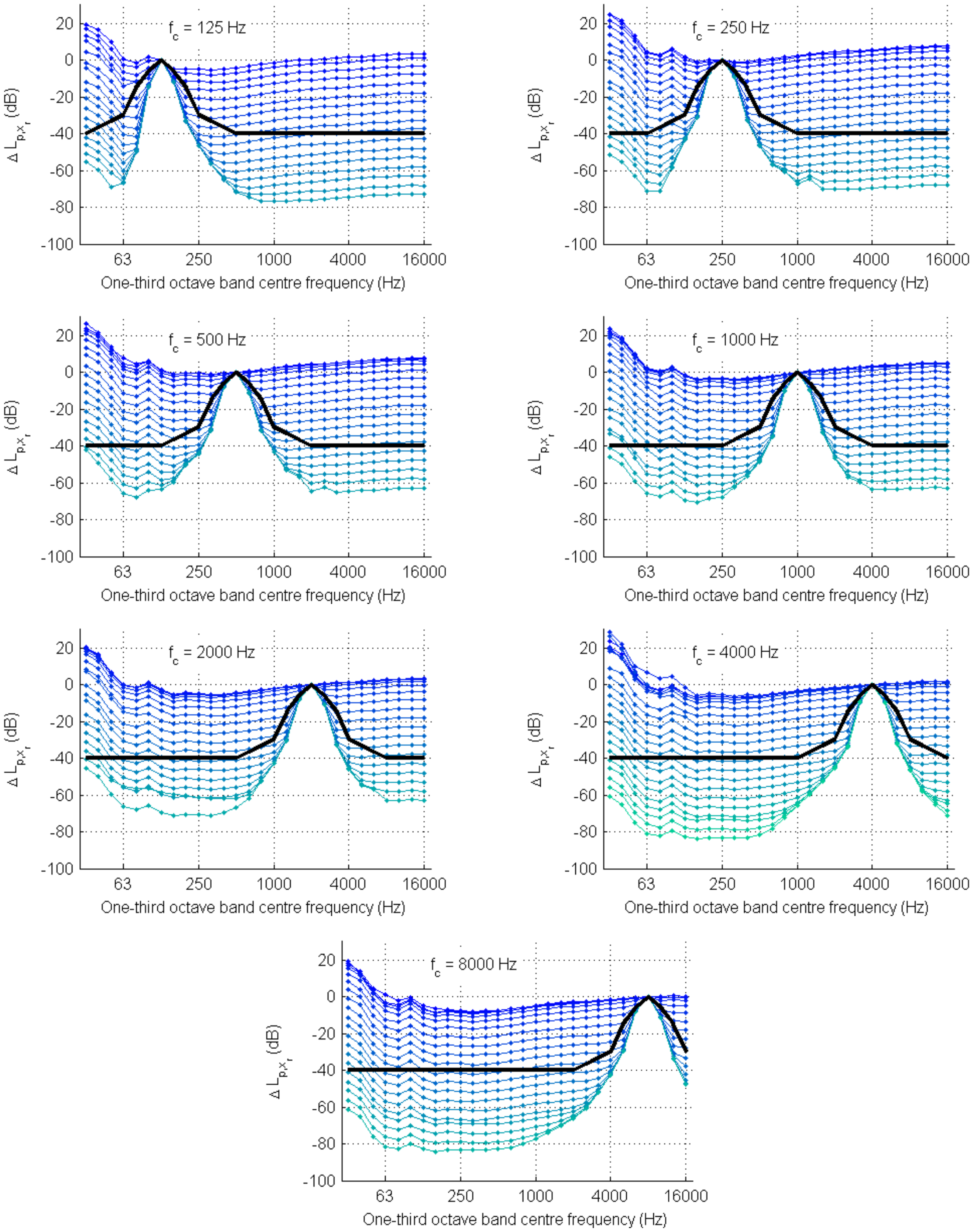


Figure A-20: Summary of distortion requirements determined by diffuse-field microphone.

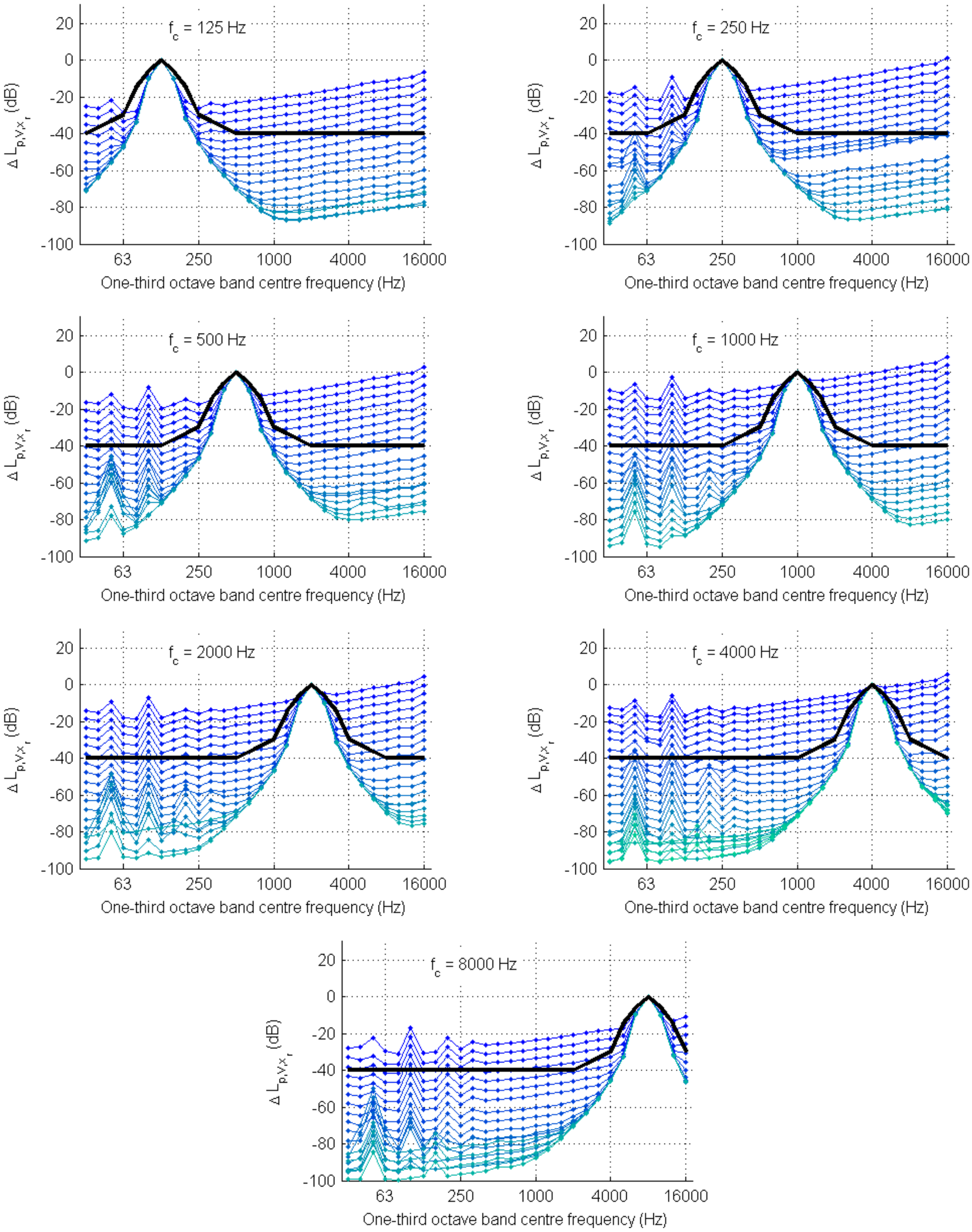
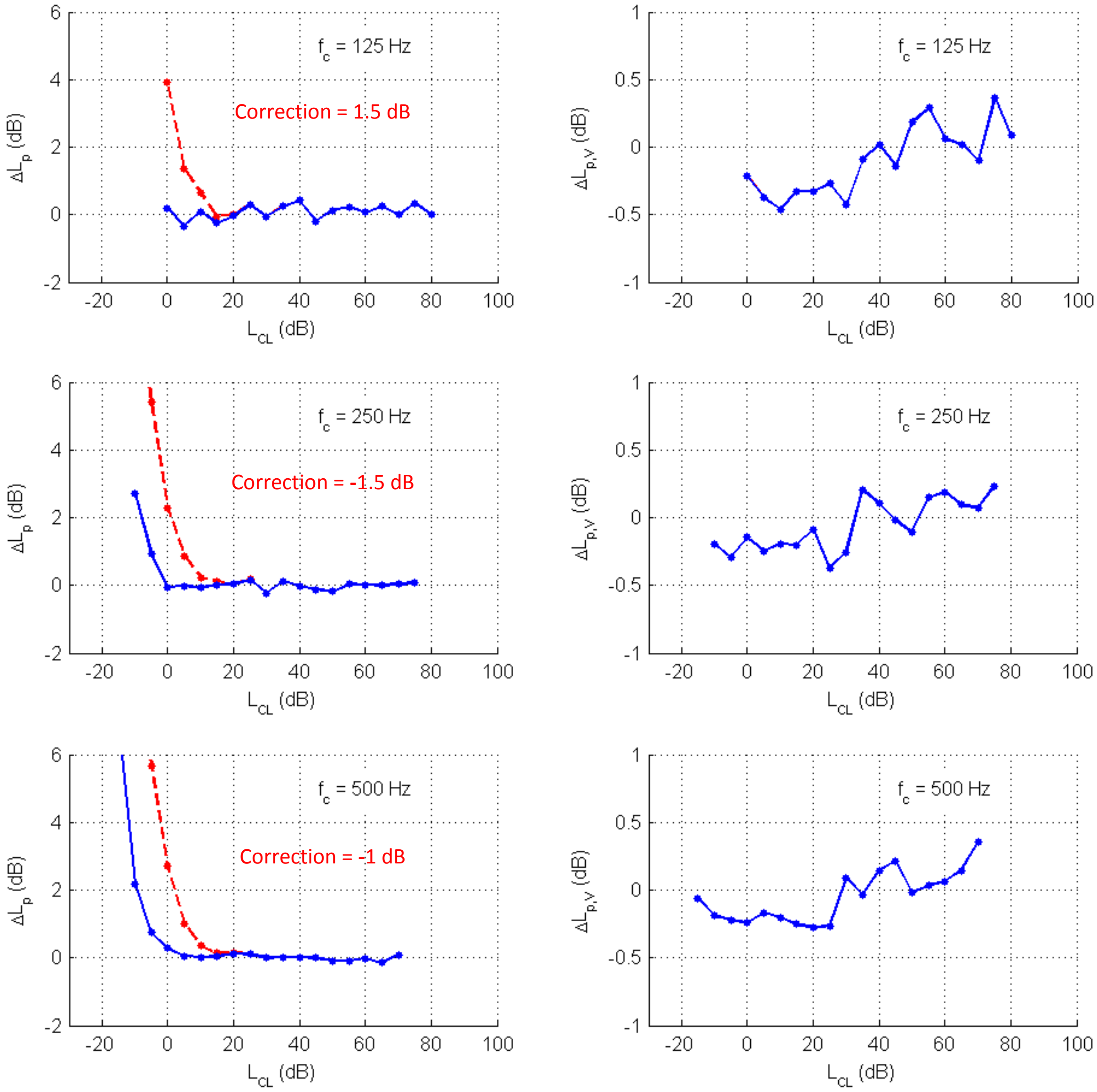


Figure A-21: Summary of distortion requirements determined by measurement of speaker terminal voltages.

A.2.3.3 Attenuator characteristics

Results shown below for the attenuator characteristics were re-plotted from results presented in Section A.2.3.2 for the in-band sound pressure level for each test signal. Results are plotted as ΔL_p and $\Delta L_{p,V}$ against the calibrated sound pressure level (L_{CL}). Uncorrected and corrected measurements indicate where background noise or inherent noise has been subtracted. The amount of correction is noted for on each figure. The correction for the speaker terminal voltage measurement is noted in dB re 1V.



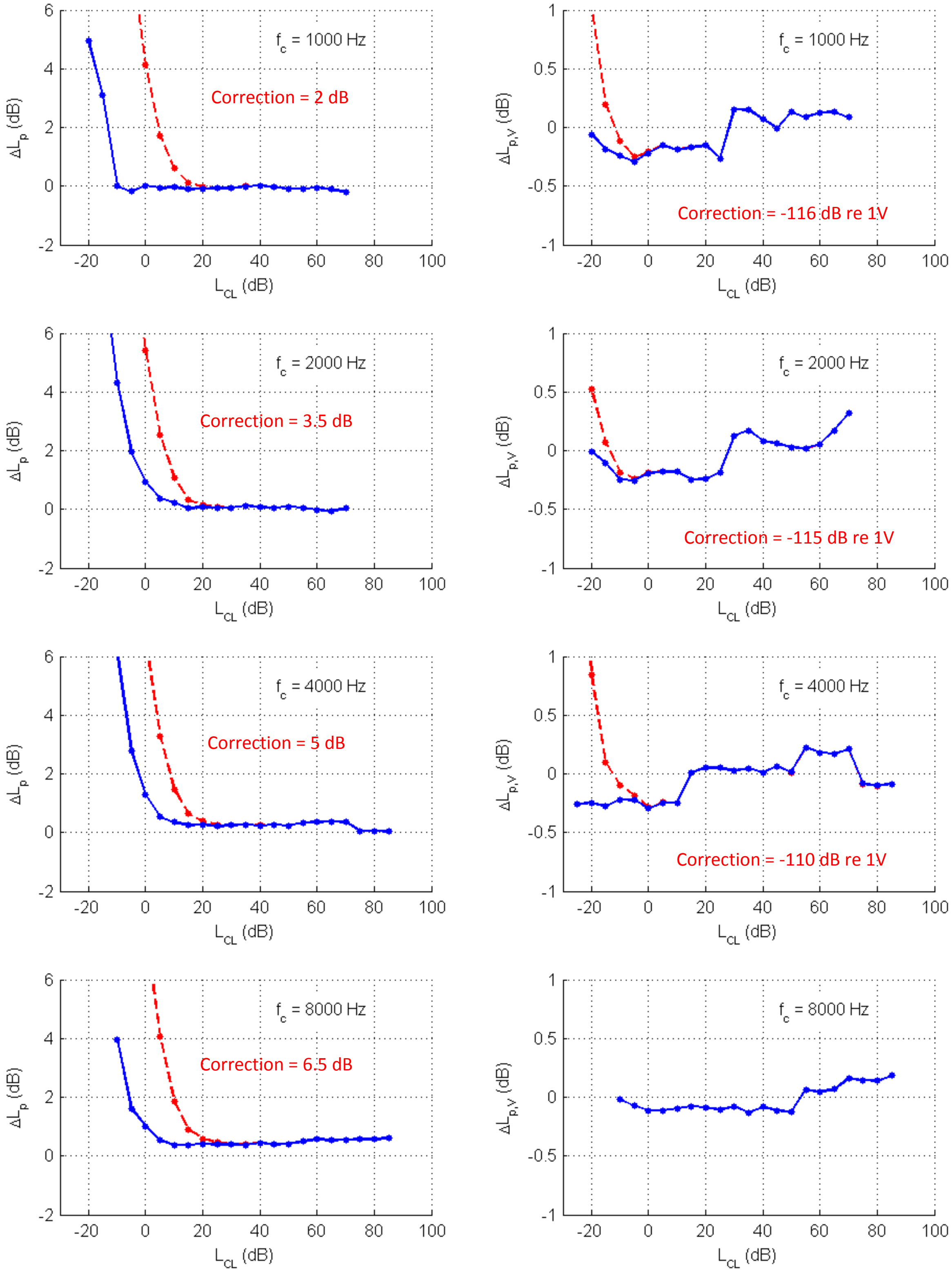


Figure A-22: Attenuator characteristics for test signals.

A.2.3.4 Signal pulsing

Signal pulsing characteristics were determined by measurement of the speaker terminal voltage (V_{ST}) with a pure tone produced at the exact centre frequency (e.g. 125.9 Hz for the 125 Hz one-third octave band as in Table A-2) for each one-third octave band test signal. Refer to Section 2.3.3.5 for further description of the measurement setup.

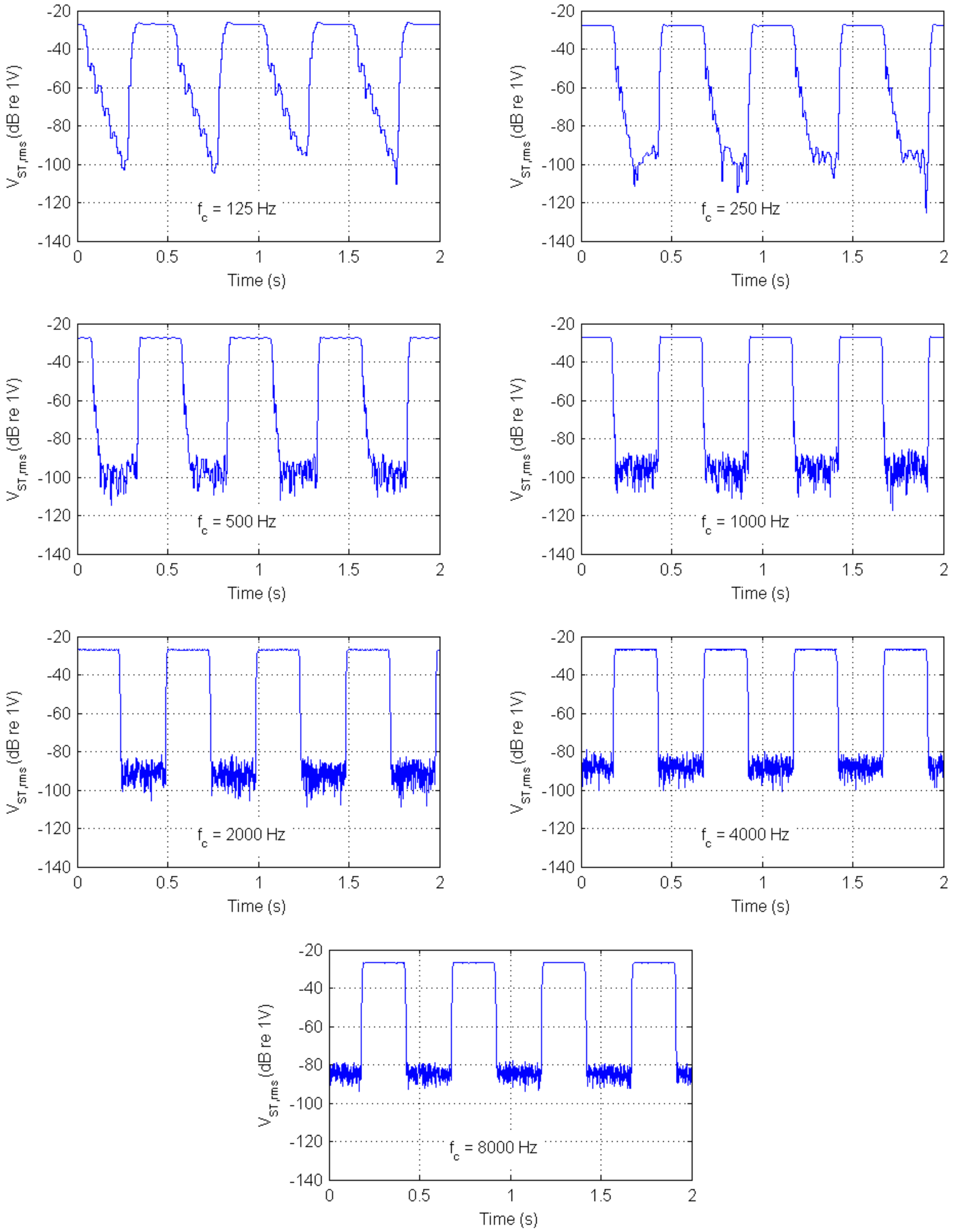


Figure A-23: Signal pulsing characteristics.

A.3 Logarithmic subtraction

The influence of a secondary source can be subtracted logarithmically assuming the two sources are uncorrelated. This calculation is only applicable if the main source is at least 3 dB above the secondary source [123]. The main use in this work was removal of unwanted background noise or the inherent noise of measurement systems from sound pressure level or voltage measurement. Logarithmic subtraction is described by Eq. A.19 [123].

$$L_c = 10\log_{10}(10^{L_1/10} - 10^{L_2/10}) \qquad \text{Eq. A.19}$$

Where:

	L_c	=	Main source level (dB)
	L_1	=	Main source level including secondary source influence (dB)
	L_2	=	Secondary source level (dB)

A.4 Ethics approval

Ethics approval was obtained through the low risk process of the University of Canterbury Human Ethics Committee. The letters of acceptance for testing with participants for the REAT method and the MIRE method are shown in Figure A-24 and Figure A-25.

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Lynda Griffioen
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2013/36/LR-PS

2 October 2013

Ben Scott
Department of Mechanical Engineering
UNIVERSITY OF CANTERBURY

Dear Ben

Thank you for forwarding to the Human Ethics Committee a copy of the low risk application you have recently made for your research proposal "Performance of earmuff type hearing protectors".

I am pleased to advise that this application has been reviewed and I confirm support of the Department's approval for this project.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 30 September 2013.

With best wishes for your project.

Yours sincerely

Lindsey MacDonald
Chair, Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. www.canterbury.ac.nz

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Figure A-24: Low-risk ethics approval for REAT testing.

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Lynda Griffioen
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2014/18/LR-PS

25 September 2014

Ben Scott
Department of Mechanical Engineering
UNIVERSITY OF CANTERBURY

Dear Ben

Thank you for forwarding to the Human Ethics Committee a copy of the low risk application you have recently made for your research proposal "Earmuff field performance".

I am pleased to advise that this application has been reviewed and I confirm support of the Department's approval for this project.

With best wishes for your project.

Yours sincerely

Lindsey MacDonald
Chair, Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. www.canterbury.ac.nz

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Figure A-25: Low rick ethics approval for MIRE testing.