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Development of a Sonar Equation Formalism for Fireground Acoustics

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Development of a Sonar Equation Formalism for Fireground Acoustics

by

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THESIS

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To my wonderful grandparents

Robert and Dotty Wood

Thomas and Johnnie-Lou Suits

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"No man is an island," begins John Donne's famous poem. Everyone has people who help them along in life. This chapter in my life is an accumulation of the chapters before, and many people have helped me this far. First and foremost, I must lay my success and being at the feet of the Creator. Without whom none of this would be possible, and through whom all things are possible.

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Thank you everyone,

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Development of a Sonar Equation Formalism for Fireground Acoustics

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Firefighters wear a plethora of personal protective equipment (PPE) including a Personal Alert Safety System (PASS) device. This device produces an audible alarm signal when it senses a lack of movement to help rescue teams detect and find firefighters who have become incapacitated on the fireground. Although this alarm works the majority of the time, there are instances where it has failed to be detected or found. Using a passive sonar approach, this study begins to provide a scientific background to improve the signal. The construct of the passive sonar equation helps to define a signal-to-noise ratio with information about the environment, source and receiver. This work presents studies of the noise level of the environment (NL), source level (SL) of the PASS device, and detection threshold of the receiver (DT) on the fire scene.

To study NL and SL, equipment used by firefighters was recorded and analyzed for the sound pressure level, frequency content, and directionality compared to the PASS alarm. The NL on a fire scene has been found to be broadband, high intensity noise. The loudest piece of equipment was found to be a chainsaw and the quietest to be a pumper truck. The DT involves the ability of firefighters to detect and classify the PASS signal. Physical acoustic experiments, using an acoustic manikin, show that PPE gear affects the sound reaching the ear by reducing the average received level and introducing peaks and nulls in head related transfer functions. In audiological tests on normal-hearing human subjects, this manifested itself by increasing the sound pressure level required to detect the PASS alarm while wearing PPE gear. Recommendations based on these findings are provided

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Chapter 1

Introduction

Firefighting is a dangerous profession. Eighty-two firefighters died while on duty in 2012. [1] Of those, 28% were on a fire scene and 19.5% died inside a single family dwelling. Firefighters rely on their training and equipment to stay safe. One piece of safety equipment that is commonly used is the Personal Alert Safety System (PASS) device.

When firefighters are inside a burning structure, there are many ways they can become disoriented, incapacitated, or trapped. When this happens, it is imperative for rescuers to find the downed firefighter in a timely fashion. Because of smoke filling the structure, location by visible means is very limited. Auditory localization and communication hence becomes imperative. The PASS device emits an alarm tone when a firefighter stops moving, that helps in alerting other personnel and localizing the downed firefighter. A picture of a PASS device attached to an self-contained breathing apparatus (SCBA) and the location of the source of the alarm can be seen in Figures 1.1 and 1.2.

Figure 1.1: PASS/SCBA on KEMAR. The red box is the area of the close-up view presented in Figure 1.2.

1.1 History of PASS

As with much of the equipment used in the fire service, the development of the PASS device was a result of fireground experiences of firefighters. The fireground refers to the area where firefighting operations are being conducted, According to the International Association of Firefighters, the necessity for an audible way to locate a downed firefighter resulted from a study of line-of-duty deaths (LODD). This study was conducted after three incidents in 1978 and 1979. In 1978, four firefighters in Syracuse, NY, died in a dormitory fire after getting lost and disoriented in a smoke-filled room. In 1979, three firefighters died in a restaurant fire in Lubbock, TX, after getting lost in the smoke-filled restaurant. Later that year in Los Angeles, a firefighter died in a warehouse

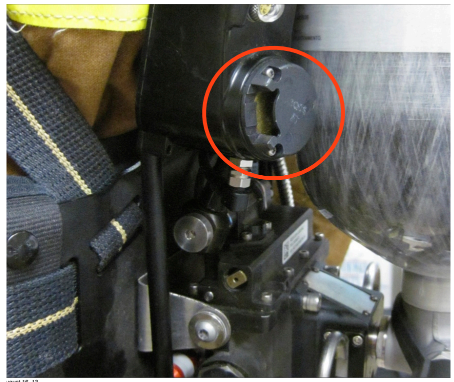


Figure 1.2: A close-up of the source of the audible alarm. The piezo buzzer that produces the alarm is under the protective cover circled in red. There are two such buzzers, one located on each side of the tank.

fire where his would-be rescuers were close, but could not see through the smoke. [2] As a result in 1980, the fire service requested that the National Fire Protection Association (NFPA) develop a device (and subsequently a standard specification document for the device) that would emit an audible signal when a firefighter became incapacitated. The first edition of NFPA 1982: Standard on Personal Alert Safety Systems (PASS) was issued in June of 1983. [3]

There have been five revisions to the standard since 1983. The 1998 revision included PASS devices that were integrated with the Self Contained Breathing Apparatus (SCBA) used by firefighters, and the PASS devices were required to be automatically activated. The 2007 edition of NFPA 1982 took into consideration recommendations made by the National Institute for Occupational Safety and Health (NIOSH) about testing protocols for heat exposure and water ingress. Throughout these revisions, the audible alarm of the PASS device went through several progressive developments resulting in the standards used in the fifth revision released in 2007. [3]

1.2 Description of NFPA 1982

The Technical Committee on Electronic Safety Equipment of the National Fire Protection Association (NFPA) is in charge of revising the standard on the PASS device, NFPA 1982. This standard specifies the signal that the PASS device must use as well as other technical and testing requirements. The requirements, as of the edition released in 2007, include specifications of frequencies and levels for the audible alarm and pre-alarm for the PASS device.

The standard specifies that the PASS device will go into pre-alarm mode 20 seconds after the firefighter stops moving and full alarm mode at 30 seconds. The alarm can also be activated manually. The pre-alarm is required to reach a maximum level between 100 dBA[1] and 110 dBA in six seconds. Also, two primary frequencies are required between 1 kHz and 2 kHz.

NFPA 1982 requires that the primary alarm have a minimum level of 95 dBA at one meter, and be able to maintain the level for at least an hour. the standard specifies three primary frequencies: one frequency at 500 Hz and two frequencies between 1 kHz and 4 kHz.

This non-unique specification of alarm signals has led to a variety of PASS alarm signals appearing in the commercial market and thus on the fire-

[1]When characterizing sound related to human hearing, A-weighting is often used to compensate for the frequency dependence of the human ear, and it is referred to as dBA. It is calculated in reference to 20 μPa. [4]

ground. This issue was brought to the attention of the technical committee and is part of the endeavor to find an optimized PASS signal through scientific research.

1.3 Sonar Equation Formalism

The present study was conducted using the paradigm of passive sonar and the sonar equation. A thorough discussion of the sonar equation is available to the interested reader in References [5] and [6], but a concise and sufficient discussion is given here for convenience. Passive sonar refers to the problem where a receiver is listening for a signal. To design such a system, the source signal, transmission through the medium, the receiver, and noise levels must be known. This information is used in an energy balance analysis using the passive sonar equation,

$$\mathrm{SL} - \mathrm{TL} = \mathrm{NL} - \mathrm{DI} + \mathrm{DT}, \tag{1.1}$$

where SL is the source level; TL is the transmission loss through the medium; NL is the noise level in the environment at the receiver; DI is the directivity index associated with the receiver; and DT is the detection threshold of the receiver. The conditions that just satisfy the equality in equation (1.1) results in detection of the target. In underwater passive sonar, the receiver is a vessel, usually a ship or a submarine using a sonar system to detect, classify, and localize a noise-emitting target of interest. The transmission loss comes from the energy lost to the environment. The background noise comes from shipping, fishing, bubbles, rain, etc. The detection threshold and directivity index is determined by the sensitivity of the system and the self noise of the listening vessel. A simple representation of this in the underwater acoustics environment can be seen in Figure 1.3.

Applying the sonar equation to the fireground results in the following: The SL is the source level of the PASS acoustic output explored in Chapter 2. The TL is the transmission loss as the signal propagates through the fireground, suffering attenuation due to the medium and interaction with boundaries in the environment. The NL represents all other sounds on the fireground, which include all other firefighting equipment, the sound of the fire itself, fire alarm sounds, voices and radio communication sounds etc. Recordings of some of the loudest firefighter equipment are analyzed and reported in Chapter 2. The DI will be excluded in this work, which is focused on un-aided human hearing, with essentially no array gain due to receiver aperture or directivity. DT relates to the auditory properties of the firefighters studied in the context of physical acoustic measurements and audiology in Chapter 3 and Chapter 4, respectively. A simple representation of the sonar equation on a fireground is presented in Figure 1.4.

1.4 Alarm Sounds

There are two main tasks that the PASS alarm must accomplish. The first is to alert personnel on the fireground about a firefighter in trouble (a

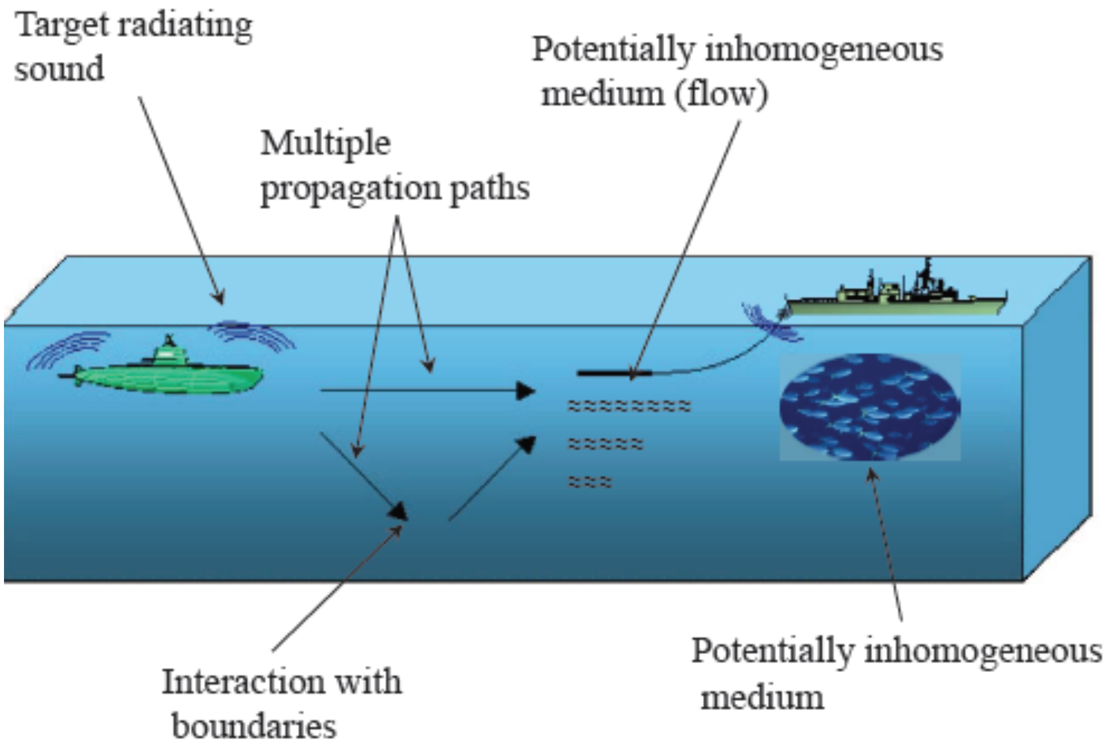


Figure 1.3: A cartoon representation of the sonar equation as used in underwater research, equation (1.1), depicting the individual terms with objects in the ocean. The target radiating sound is the SL. The boundary interaction, multiple paths, and in-homogenous medium are related to the TL. The towed sonar array of the ship relates to DI. The DT depends on the operator, whether it be human or machine.

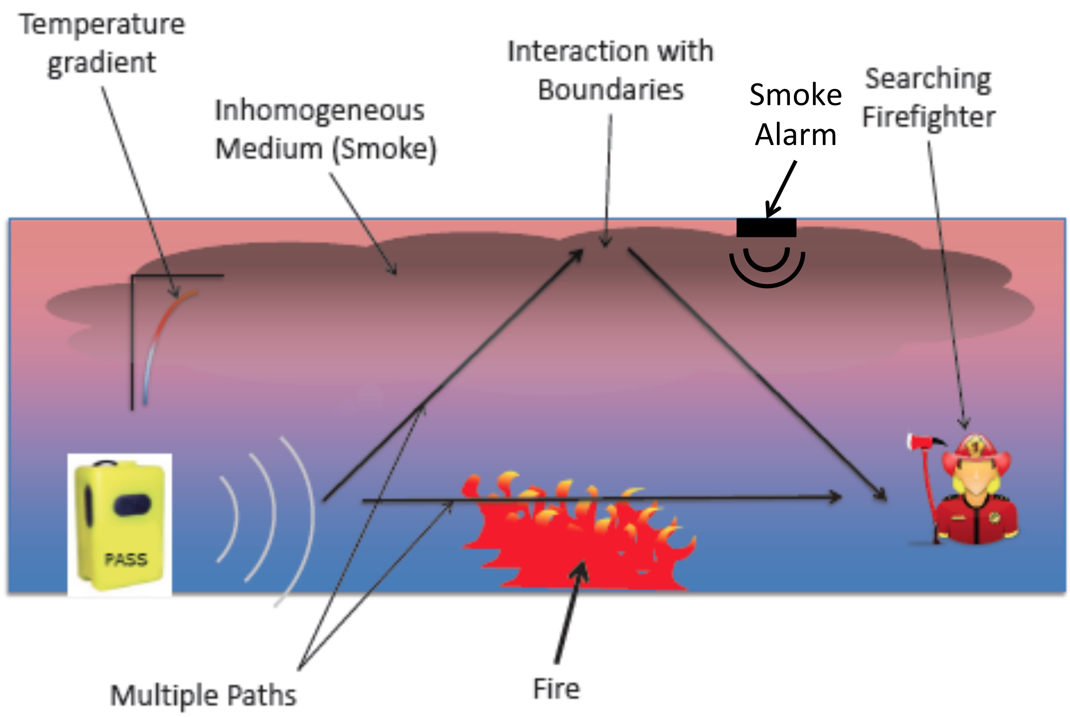


Figure 1.4: A cartoon representation of the sonar equation as defined by this project, equation (1.1), depicting the individual terms with objects found on the fireground. The PASS signal is the SL. The in-homogenous medium, boundary interactions, and temperature gradient are related to the TL. The searching firefighter relates to the DI and the DT. The smoke alarm relates to the NL.

detection and classification task). The second task is to help rescuers to find the downed firefighter (a localization task). This means that the PASS alarm signal itself must be detectable and localizable. The primary receiver is the human auditory system of the firefighter, but in the future may include automated, machine-based or augmented reception.

The human hearing response is frequency dependent, and the human ear is most sensitive between 1 kHz to 3 kHz. Unfortunately, because of size of the human head and torso, the hardest frequencies to localize are the frequencies between 1500 Hz to 5000 Hz. [7]

There are other considerations that must be made based on additional aspects of human hearing. According to the Handbook of Warning Signals by M.S. Wogalter, [8] the signal rise and fall time need to be slow enough (between 20 ms to 30 ms) to prevent "startle reactions." Also, pulsating sounds should be used that have a periodicity of 0.2 Hz to 5 Hz. Variation in the temporal pattern of an alarm also leads to enhanced detection and localization.

Since the PASS signal will need to be detected in the presence of noise, the absolute level of the noise must be accounted for. According to Laroche et. al., [9] the alarm sound should be at least 10 dB to 15 dB above the background noise within the 1/3-octave band[2] of the alarm signal for optimum detection.

[2] 1/3 octave band analysis is a frequency dependent analysis of sound pressure level. The spectrum is split into 24 notch filters with three bands per octave. The center frequencies of the filters are: 25 Hz, 31.5 Hz, 40 Hz, 50 Hz, 63 Hz, 80 Hz, 100 Hz, 125 Hz, 160 Hz, 200 Hz, 250 Hz, 315 Hz, 400 Hz, 500 Hz, 630 Hz, 800 Hz, 1000 Hz, 1250 Hz, 1600 Hz, 2000 Hz, 2500 Hz, 3150 Hz, 4000 Hz, 5000 Hz, 6300 Hz, 8000 Hz, 10000 Hz, 12500 Hz, 16000 Hz, 20000 Hz. [10]

It should be noted that these guidelines of References [8] and [9] are for locations and situations are the same everyday and where the level of the background noise and relative location of workers is known a priori and hence may not directly apply to the fireground, which has a high degree of spacial and temporal variability.

Chapter 2

Acoustical Analysis of Firefighting Equipment Used on the Fireground

2.1 Introduction

Two components of the passive sonar equation are the signal level (SL) and noise level (NL). The SL is the far-field measured sound pressure level of the PASS device, scaled via the spherical spreading law back to one meter from the source. The NL for this system is sound pressure level at the receiver due to everything on the fireground that is not the PASS device. The equipment being used by firefighters whilst fighting a structural fire includes chain saws, circular saws, positive pressure ventilation fans, and water pumps. All of this equipment emits high intensity noise that could mask the signal of the PASS device. Research has been conducted on the overall sound pressure levels of this equipment, but has not considered the frequency content. [11] Noise emitted by fire engines has been investigated with respect to hearing damage of firefighters in the cab. [12] In order to optimize the PASS signal, amplitude, frequency, and directionality of all these noise sources must be studied.

In this chapter, measurements of the source level SL of one particular commercially-available PASS device are described. In addition, measurement of the source levels of some of the loudest pieces of fireground equipment are also described. For the former, these measurements of SL can be used directly in the sonar equation for future optimization of the PASS system. For the latter, knowledge of the source level of the equipment that comprises the background noise can be used to analyze and model the noise level NL present at potential receiving locations on the fireground. This will provide knowledge of the NL terms in future sonar equation based analyses.

2.2 Protocol

For these measurements, a protocol was defined to use for each piece of equipment. The protocol and subsequent analysis was adapted from ANSI standards S12.15, S12.18, and S12.23 used to measure portable and fixed equipment in outdoor environments. [13–15]

The protocol developed for this analysis utilized opportunistic open, flat surfaced environments, namely asphalt covered parking lots. A center point was designated where the geometric center of the source equipment was placed. The recording equipment was placed 3.65 meters from this point, in the redial direction, and not moved for the duration of the recording (except in the case of the pumper truck, described later). The noise-generating equipment was rotated about the center and four recordings were taken with the fireground equipment pointing in each of the four major angles: 0 °, 90°, 180°, and 270°.

A Tascam DR007 compact digital recorder was used to record the acoustic signals. The recorder was calibrated using the technique described in Appendix A. Using the 44.1 kHz sampling rate setting, which was used throughout this study, the DR007 has a frequency response which is flat within $\pm 1/3$ dB from 20 Hz to 20 kHz. The recorder was placed on a tripod to ensure a repeatable and stable position, to eliminate the effect of a person being in the sound field, and to eliminate the associated handling noise generated when a person holds the recorder by hand. For each position, at least 20 seconds of data was recorded and stored. The DR007 saves two channels. This study only used the measurement from the left microphone. The equipment was operated by a trained firefighter in accordance with standard practice for each piece of equipment. The firefighter held the equipment in operating position and at full throttle. This arrangement can be seen in Figure 2.1.

A different spatial layout was needed for measuring the noise radiated by the pumper truck. The truck remained stationary and the recording equipment was moved such that it always remained 3.65 meters away from the edge of the truck, as can be seen in Figure 2.2.

2.3 Description of Equipment Recorded

The equipment noise was recorded in two separate sessions. One session was conducted at the Austin Fire Department Station 3 (201 W 30th St Austin, TX 78705). The other session was conducted at the Austin Fire Department maintenance shop (2011 East 51st St Austin, TX 78723). The ambient noise was measured during the test at Fire Station three, after the equipment, and during the test at the maintenance shop, before and after the equipment. The

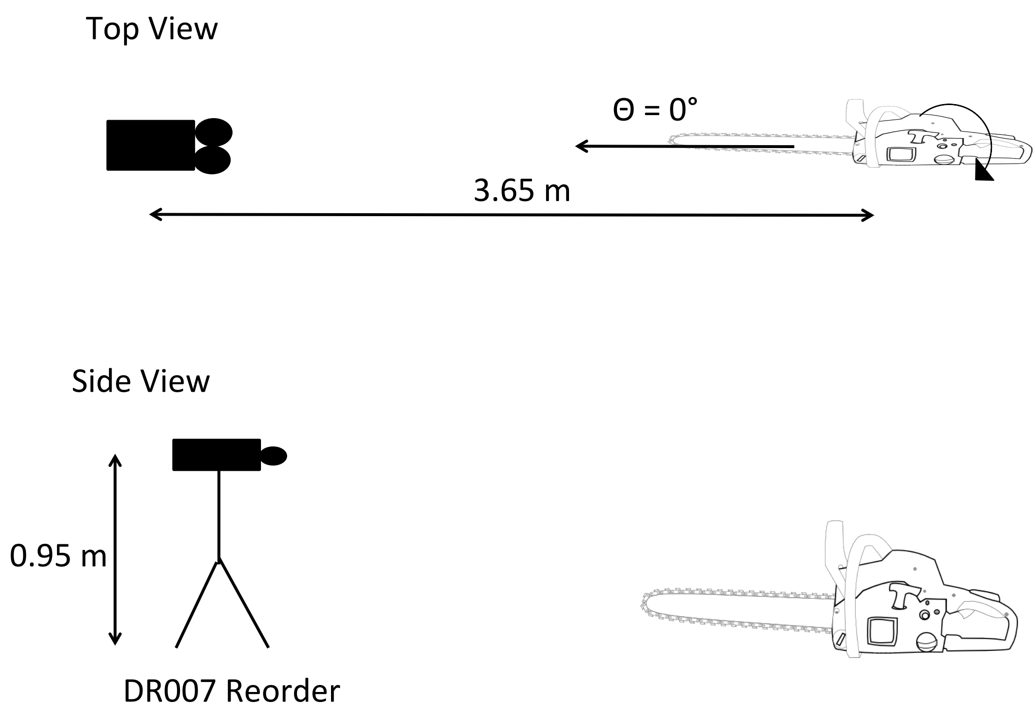


Figure 2.1: Top view of the recording arrangement with the DR007 and the firefighting equipment. Note that the DR007 is a stereo recorder possessing two microphones. Only the left channel was used in this work.

ambient noise in both locations consisted of nearby roadway and wind noise. Both of these measurements can be seen in Figure 2.3. The measurements followed the protocol outlined in Section 2.2.

During the first session, five pieces of equipment were recorded: one chain saw, one rescue saw, two positive pressure ventilation (PPV) fans, and a PASS device attached to a self-contained breathing apparatus (SCBA). In the second session, seven pieces of equipment were recorded: one chain saw, one

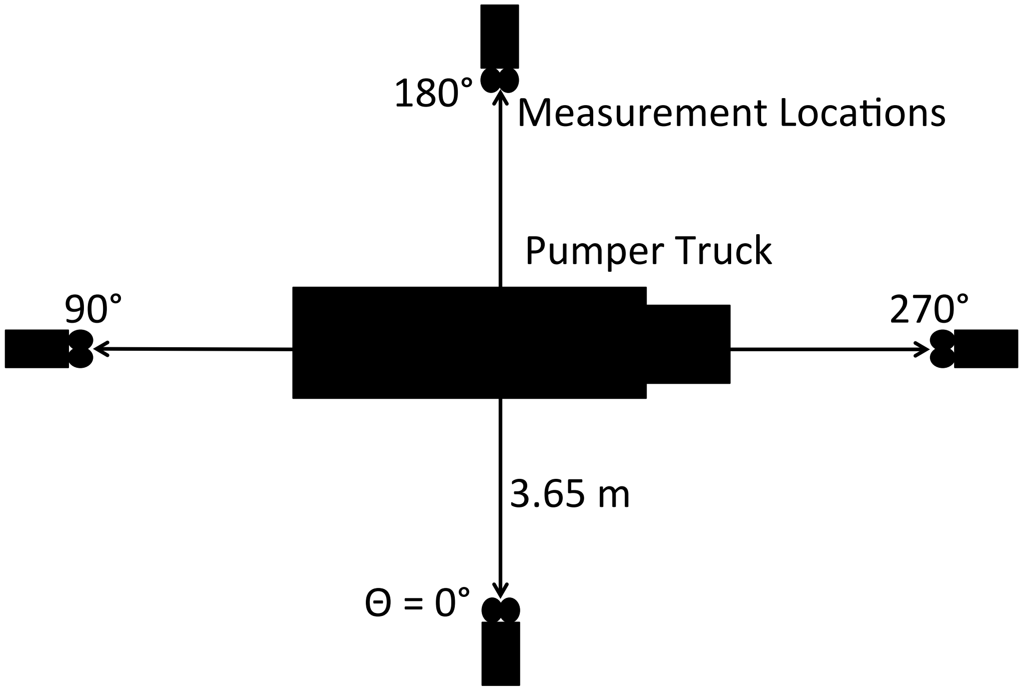


Figure 2.2: Top view of the recording layout with the DR007 locations and the pumper truck. The front of the truck faced $\theta = 270°$.

rescue saw (a type of circular saw), one ventilation saw, one PPV fan, a pumper truck idling, the same truck with the main pump engaged and running water, and the same truck with the pump and an additional on-board, gasoline-engine-powered electrical generator pumping and powering lights. In total, twelve pieces of equipment were measured.

During the recordings, the equipment was used in the manner it is typically used on the frieground. For all cases involving saws, an operator was present, holding the saw in typical cutting orientation, operating the saw at full throttle, but running with no load, not cutting anything. For all cases

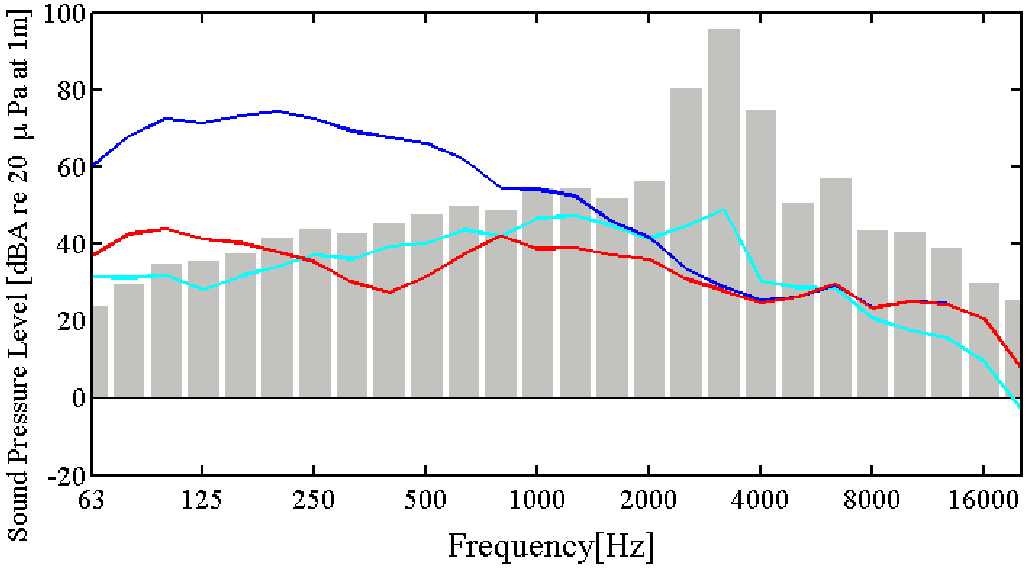


Figure 2.3: Measured ambient noise at each location. The cyan line is the noise floor at Fire Station 3. The blue line is with wind noise at the maintenance shop. The red line is without wind noise at the maintenance shop. Since the PASS device radiates most of its energy in the 2 kHz to 4 kHz band, the wind noise, which is below 1000 Hz does not effect the level comparisons in the PASS band.

using fans, the gasoline powered fans were run with their gas engines running at full throttle, which were connected to the fan by direct drive, and hence the fans were turning and blowing air at full speed. The PASS device was attached to a SCBA device and laid on the ground with the tank up putting the orientation of the PASS upwards. Zero degrees was defined for each piece of equipment and can be seen in Figure 2.4.

2.4 Analysis

The data was analyzed using 1/3-octave bands as designated in ANSI S1.11 and had A-weighting applied as designated in ANSI S1.4. [10, 16] This analysis was applied to all of the measurements at each angle. Spctrograms were also calculated for the measured PASS signals, to visualize the time-varying signal.

2.5 Results

Figures 2.5 through 2.8 show the 1/3-ocatve band analysis for all of the recorded fireground equipment at 0°, 90°, 180°, and 270°. The noise emitted by the fireground equipment is broadband, high intensity noise. The energy emitted by the PASS device is tonal and mainly in the 3150 Hz band. In this specific octave band, the level of the device is comparable to the other measured fireground equipment within about ±4 dB. In all of the other bands, the PASS device has lower sound pressure level than the equipment on the fireground.

The PASS signal is a complex signal that contains transients at various frequencies that create a repeating pattern. A spectrogram analysis was completed to show the time-frequency content of the signal. Figure 2.9 shows the full spectrogram of the signal that reveals some non-linearities of the piezo buzzer. Looking closer at the linear part of the signal, between 0 Hz and 5.5 kHz, Figure 2.10 shows the majority of the energy being is emitted between 2500 Hz and 3500 Hz. The energy in the lower frequencies, seen around

6 s to 10 s, is wind noise. Another point of interest is the fact that the 500 Hz tone, required by NFPA 1982, is not seen. These spectrograms show relative levels as they have not been calibrated or had A-weighting applied.

The overall levels of the equipment are shown in Figure 2.11 with a list of the equipment, specifications, and legend in Table 2.1. The PASS device is represented by the dark blue dots close to the 95 dBA line. This shows that there is some directionality associated with the PASS device and all other equipment as well. Also, the majority of the equipment has an overall SPL higher than that of the PASS. The highest level, Chain Saw 1, has a positive difference of 11.6 dB. Only the recordings involving the fire engine are consistently lower.

2.6 Conclusions

The PASS device recorded in this study met the minimum requirement set by NFPA 1982-2007. However, most of the equipment recorded is above that level. The loudest piece of equipment recorded, a chainsaw, was 11.6 dB above the PASS device in overall SPL. This is an SNR of −11.6 dB for listener equidistant from both sources. The piece of equipment with the lowest sound pressure level is the fire engine at 88.47 dB. This is an SNR of +10.43 dB. A larger SNR means a higher probability and a greater range of detection.

A simple equation for calculating the increase in detection range due to an increase in SNR is

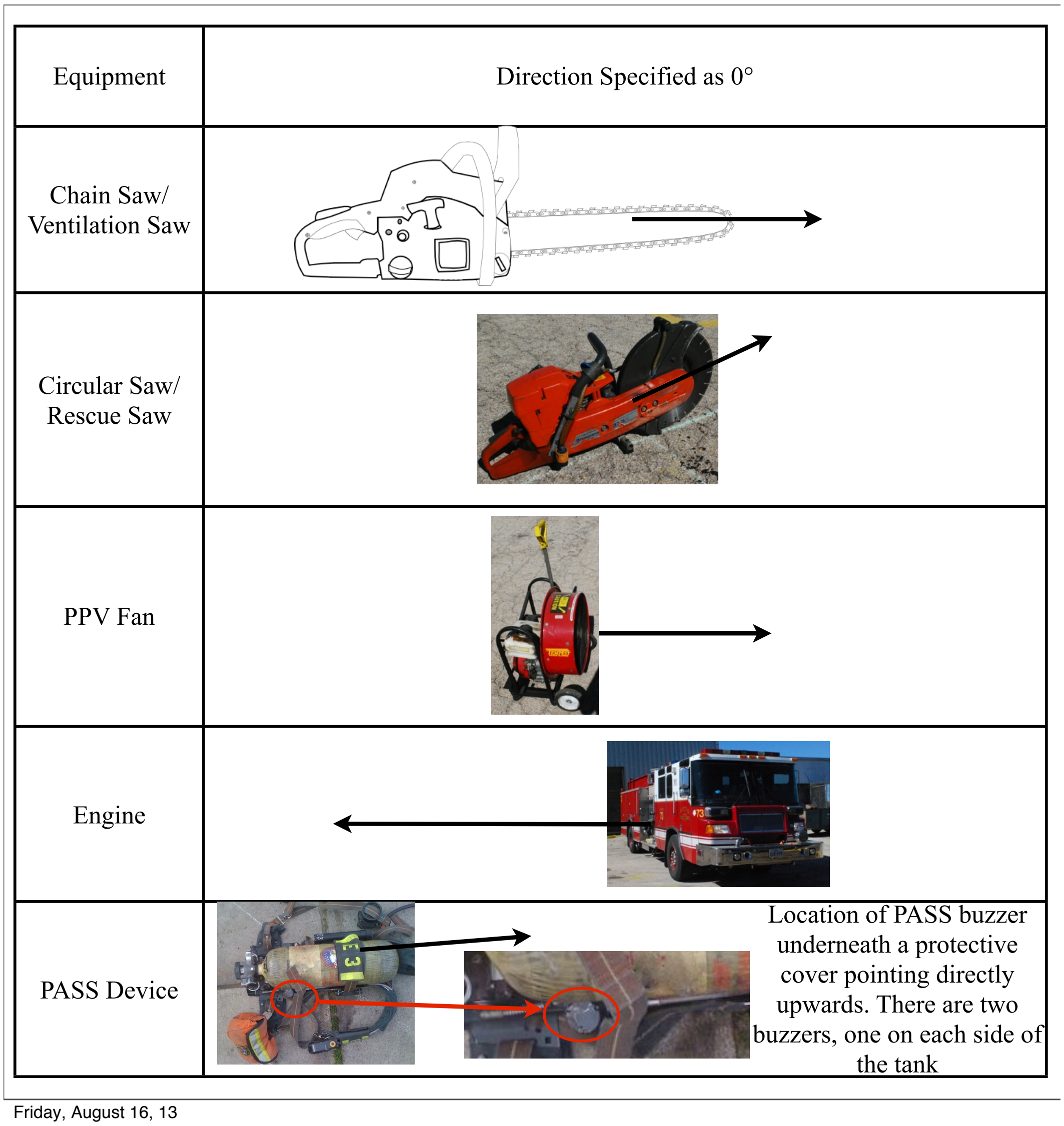
$$R = 10^{\left(\frac{\Delta \mathrm{SNR}}{20}\right)}, \tag{2.1}$$

Table 2.1: Fireground equipment recorded with over all SPL, $\theta = 0°$, dBA re 20 μPa 1 m

Equipment	Overall Levels	Specifications	Legend for Fig. 2.11
Chain Saw 1	108.5	cylinder volume: 40.8 cm^3 power: 2 kW RPMmax: 12500 rpm	●
Large PPV 2	107.72	power: 4.1 kW air volume: 13.1 m^3/s blade length: 61 cm	+ ($\theta = -45°$)
Circular Saw 1	104.9	cylinder volume 72 cm^3 power: 4.03 kW RPMmax: 13500 rpm	●
Large PPV 1	101.8	power: 4.1 kW air volume: 13.1 m^3/s blade length: 61 cm	●($\theta = -45°$)
Circular Saw 2	100.7	cylinder volume: 74.7 cm^3 power: 3.7 kW RPMmax: 9800 rpm	●
Chain Saw 2	98.8	cylinder volume: 40.8 cm^3 power: 2 kW RPMmax: 12500 rpm	+
Ventilation Saw	98.8	cylinder volume 72 cm^3 power: 4.03 kW RPMmax: 13500 rpm	+
PASS Device	96.9	attached to an SCBA	●
Small PPV	93.5	power: 2.8 kW air volume: 7.8 m^3/s blade length: 50.8 cm	●($\theta = -45°$)
Engine + Pump	90.65	pump at 125 psi	+
Engine + Pump + Generator	88.54	pump at 125 psi generator operating truck flood lights	△
Engine	86.47	Engine operating at power-take-off speed	●

where R is range in meters. As an example, if a person is standing between two pieces of equipment, an ΔSNR of +6 dB means that if they stand 2 m from the PASS device and 1 m from the noise source, the signals will have the same sound pressure level.

Another point of interest is that most of the noise on the fireground is broadband noise containing many frequencies. The PASS device is a narrow band source at 3150 Hz. In this band, the previously mentioned chainsaw is only 4 dB above the PASS device.



Equipment	Direction Specified as 0°
Chain Saw/ Ventilation Saw	
Circular Saw/ Rescue Saw	
PPV Fan	
Engine	
PASS Device	Location of PASS buzzer underneath a protective cover pointing directly upwards. There are two buzzers, one on each side of the tank

Figure 2.4: Table showing the zero degree axis defined for each piece of fire-ground equipment.

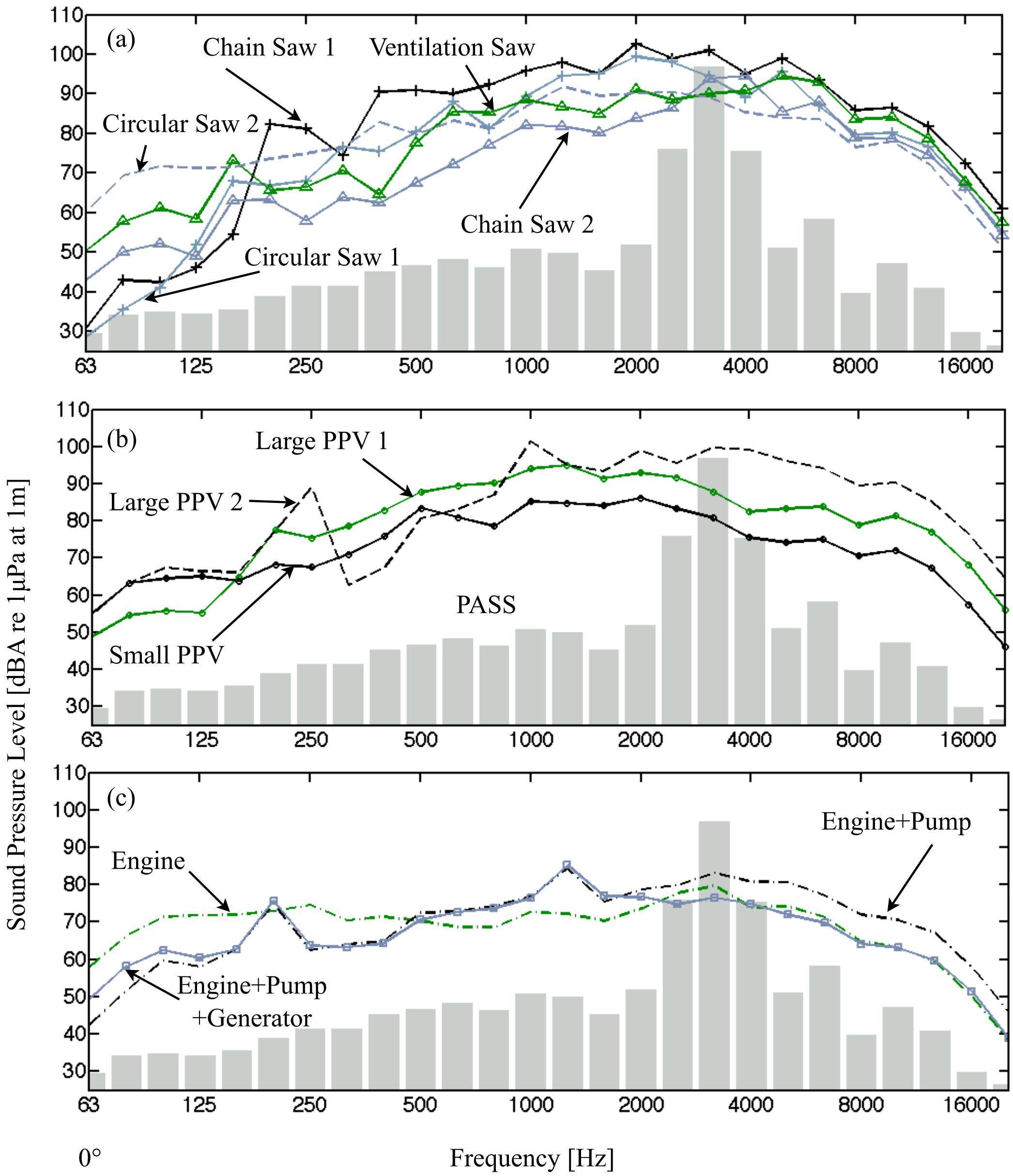


Figure 2.5: 1/3-octave band analysis of all measured fireground equipment at 0°. Figure (a) is all of the saws. Figure (b) contains all the PPV fans. Figure (c) contains all the pumper truck noises. On each plot, the grey bars represent the PASS signal.

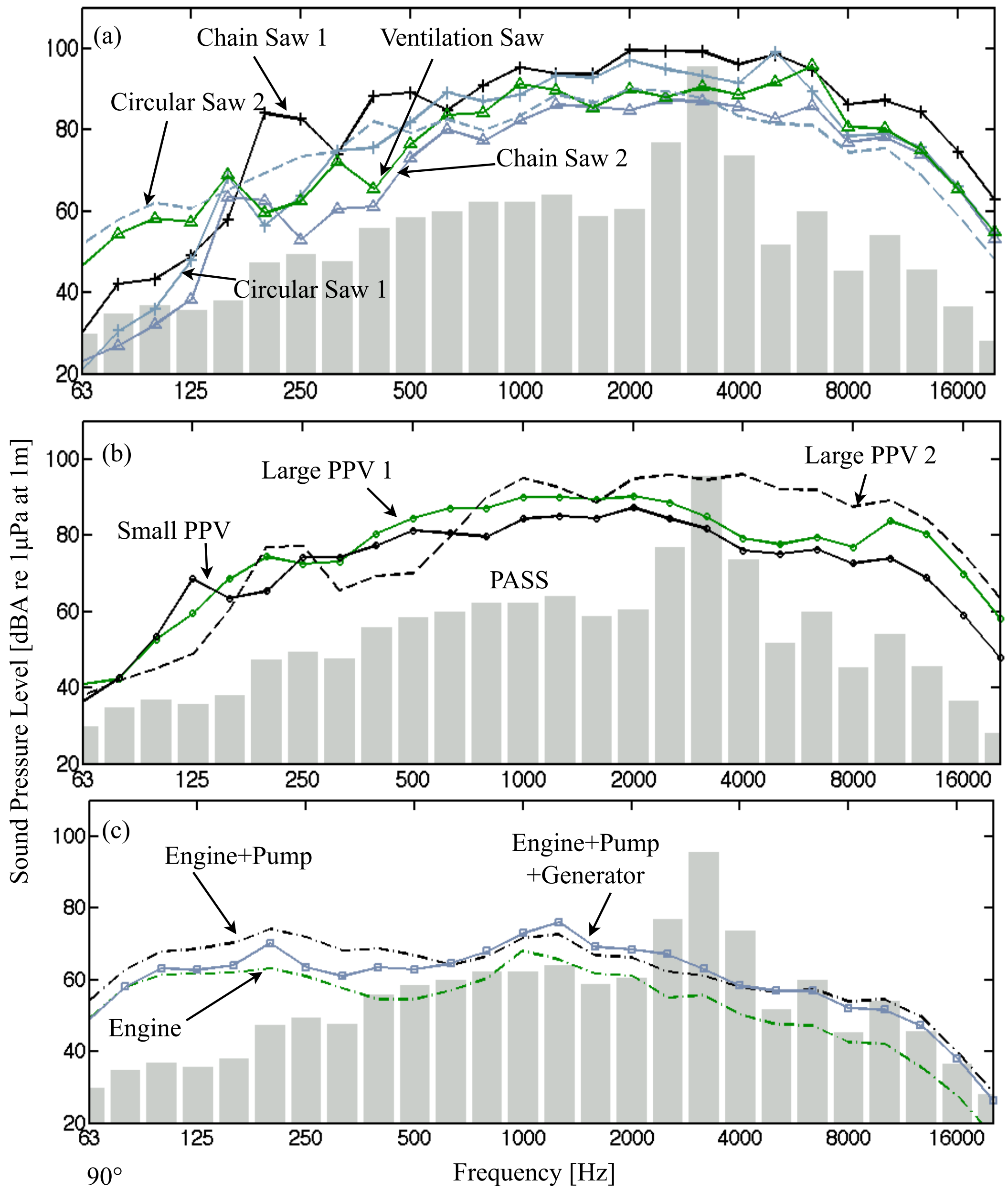


Figure 2.6: 1/3-octave band analysis of all measured fireground equipment at 90°. Figure (a) is all of the saws. Figure (b) contains all the PPV fans. Figure (c) contains all the pumper truck noises. On each plot, the grey bars represent the PASS signal.

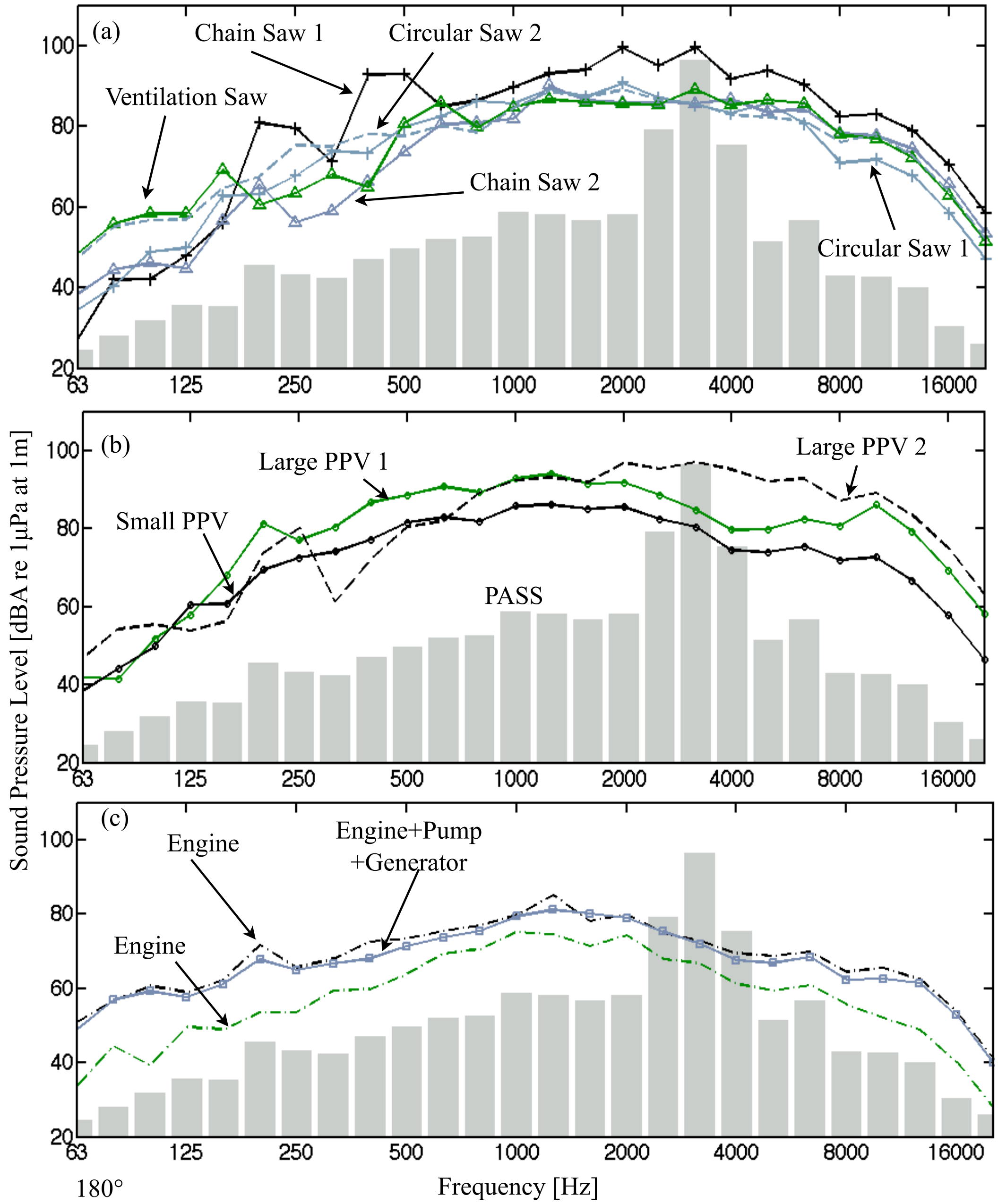


Figure 2.7: 1/3-octave band analysis of all measured fireground equipment at 180°. Figure (a) is all of the saws. Figure (b) contains all the PPV fans. Figure (c) contains all the pumper truck noises. On each plot, the grey bars represent the PASS signal.

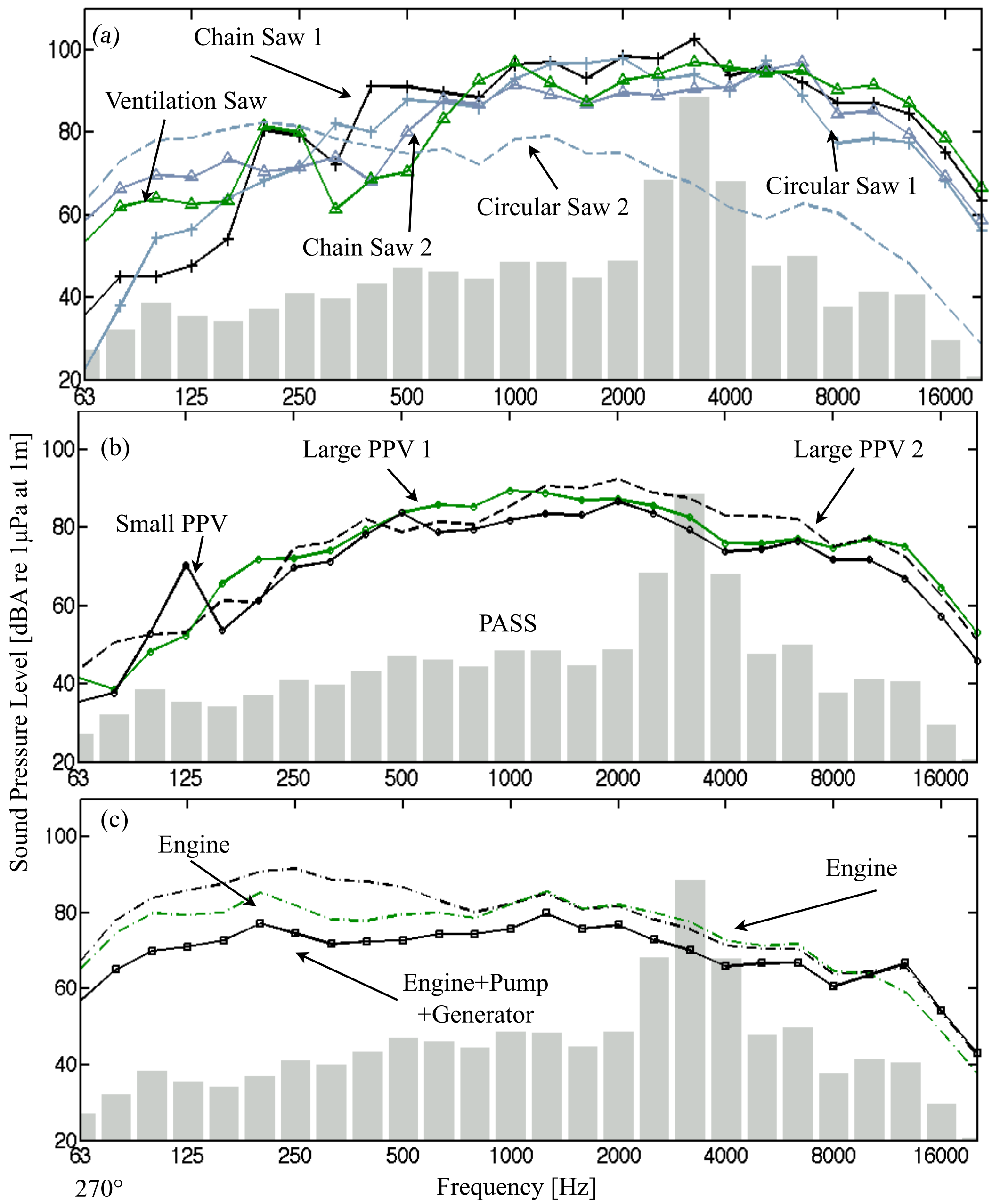


Figure 2.8: 1/3-octave band analysis of all measured fireground equipment at 270°. Figure (a) is all of the saws. Figure (b) contains all the PPV fans. Figure (c) contains all the pumper truck noises. On each plot, the grey bars represent the PASS signal.

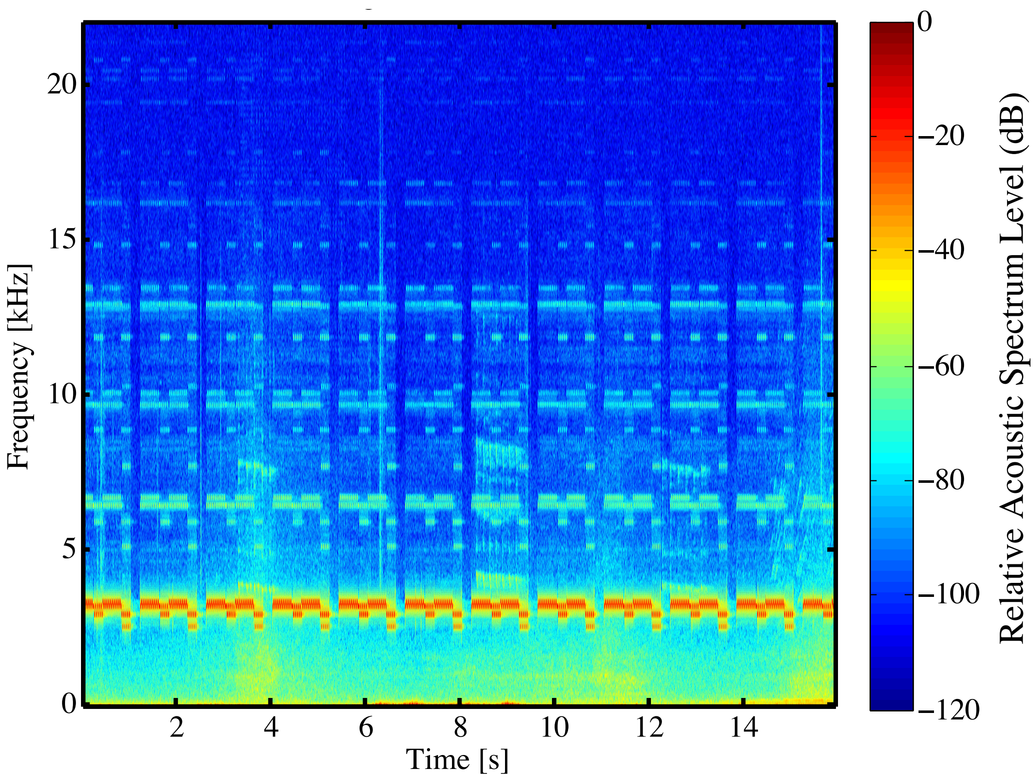


Figure 2.9: Spectrogram of a PASS alarm. The repeated signals, above 4 kHz, are non-linearities caused by the physical PASS device.

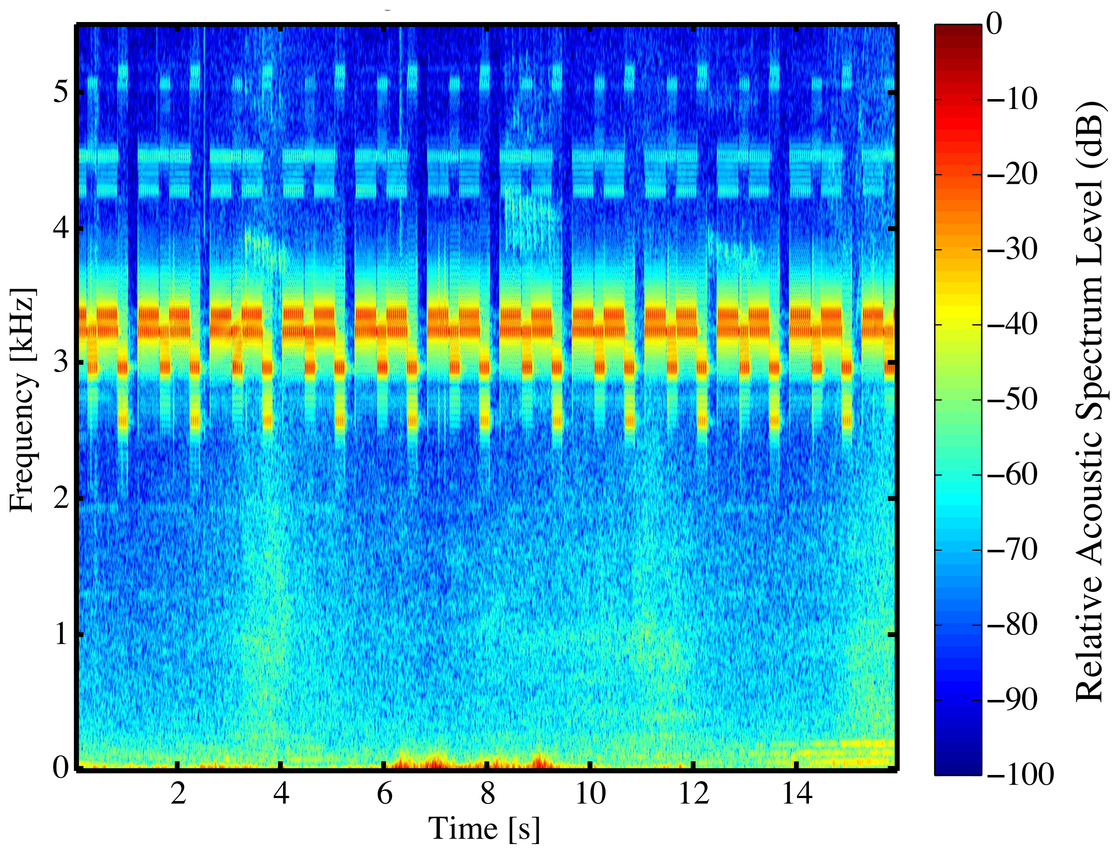


Figure 2.10: The spectrogram of the PASS device shown between 0 to 5.5 kHz.

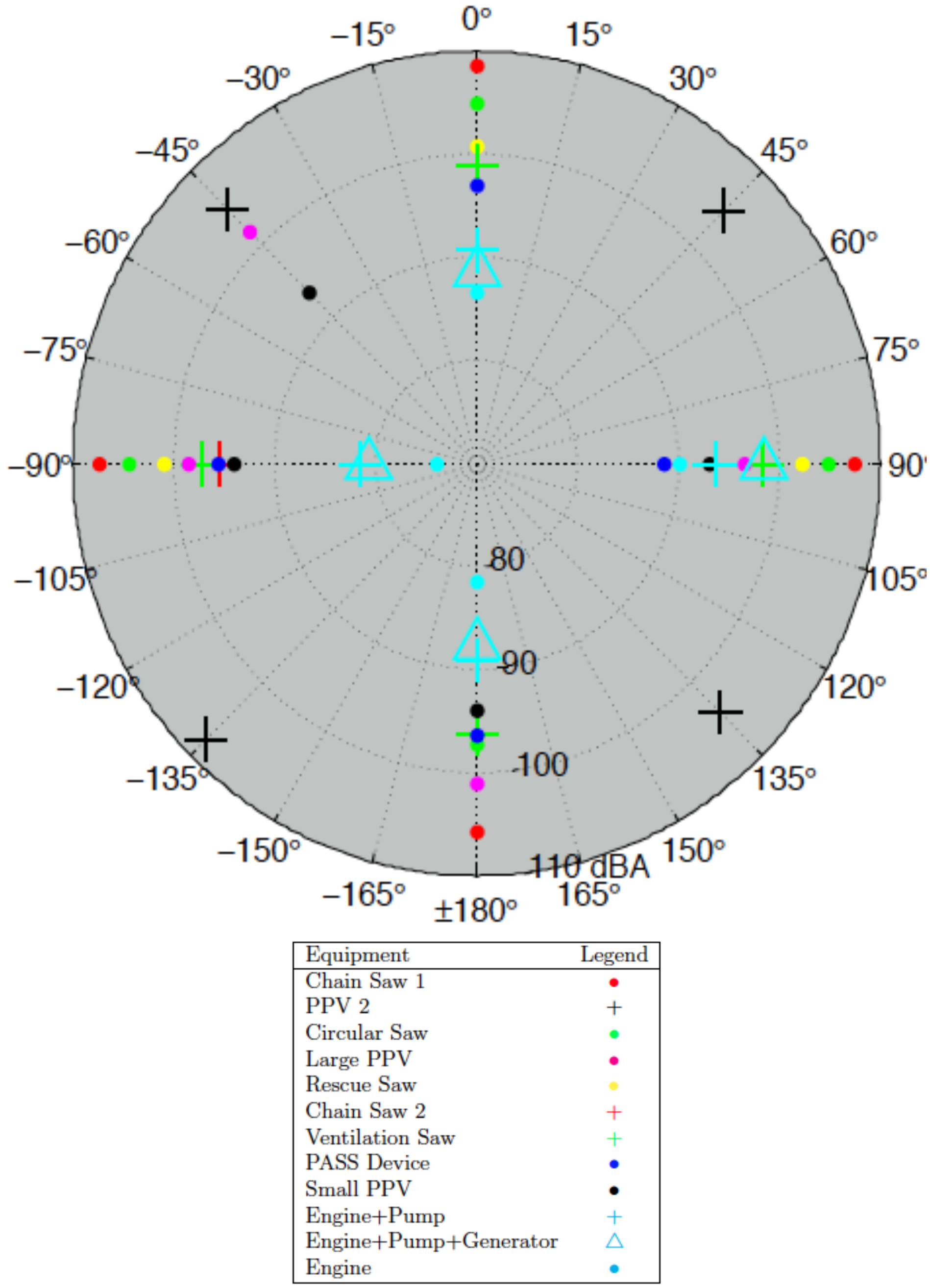


Figure 2.11: Overall levels in dBA of all equipment recorded in session one and two. The 0° is the equipment pointing at the recording devices.

Chapter 3

The Effect of Firefighting Personal Protective Equipment on Head-Related Transfer Functions

3.1 Introduction

The purpose of the PASS device is to aid in detection and localization of a downed firefighter by using an audible alarm designed to be heard by firefighters on the fireground. One must understand how a firefighter's personal protective equipment (PPE) affects the acoustic detection term (DT) in the passive sonar equation) and how the PPE effects the localization of the PASS alarm signal. The PPE studied here (provided by the Austin Fire Department) include the firefighter's coat, hood, and helmet. The PPE equipment used in this study is shown in Figure 3.1.

Detection of sound has been studied while a listener is wearing hearing protection, in the presence of hearing loss, [17] and in work environments. [18] Localization of sound has been studied thoroughly, [19, 20] including how changes in wall properties affect localization. [21] The military has investigated how wearing military-style helmets changes both detection and localization. [22, 23] To the knowledge of the author, no work has been done to understand how the combination seen in a firefighter's PPE changes human

(a) A firefighter's hood. (b) A firefighter helmet. (c) A firefighter's coat.

Figure 3.1: Pictures of firefighter PPE used in this study. The PPE gear is shown being worn by the KEMAR acoustic manikin, inside the anechoic chamber used in this research.

hearing. The current study uses a Knowels Electronics Manikin for Acoustic Research (KEMAR) to determine how PPEs worn by firefighters affect the head-related transfer function (HRTF). A HRTF is a measure of how a signal changes between the source and a person's ear drum with both phase and amplitude information.

The human head and torso affect the sound field around the listener by causing Inter-aural Time Differences (ITD) and Inter-aural Level differences (ILD). ILDs are caused by sound being blocked by the head and torso. This causes a level difference between the left and right ear. ITDs are caused by the sound diffracting around the anatomy of the head and following different length paths to each of the listener's ears. The diffraction and difference in arrival time causes a phase difference in the received signal. At lower frequencies, the effects of ITDs are predominately used for localization. At higher frequencies, the ILDs are dominant. These help a person localize in the horizontal plane. The diffraction caused by the pinna, the visible part of the ear, helps in front-back localization and in azimuth. Both of these phenomena are frequency and source position dependent. [7]

It is possible to measure HRTFs by inserting microphones into the ear canals of actual humans, but, to avoid the associated logistical and regulatory difficulties of doing human testing, acoustic manikins are commonly used. In this study a KEMAR manikin was used. A KEMAR is a head and torso manikin with microphones located where the tympanic membrane would be located in a typical human. The manikin simulates the effects of the head, torso, and especially the pinna. The KEMAR's pinna are made of a material that is acoustically matched to a human's pinna. The interested reader is directed to Reference [24] for additional discussion about HRTFs.

3.2 Description of Measurements

The measurements reported here were obtained in a fully anechoic chamber at The University of Texas at Austin. The equipment was placed on an acoustically transparent wire mesh floor within the chamber. The height of the KEMAR ears were placed to simulate a 1.8 meter tall person. The KEMAR was placed 1.8 meters away from an m-Audio AV-40 speaker that was directed towards the middle of the KEMAR's forehead. This can be seen in Figure 3.2. The KEMAR was attached to a motorized turntable that rotated 360° at 2° increments.

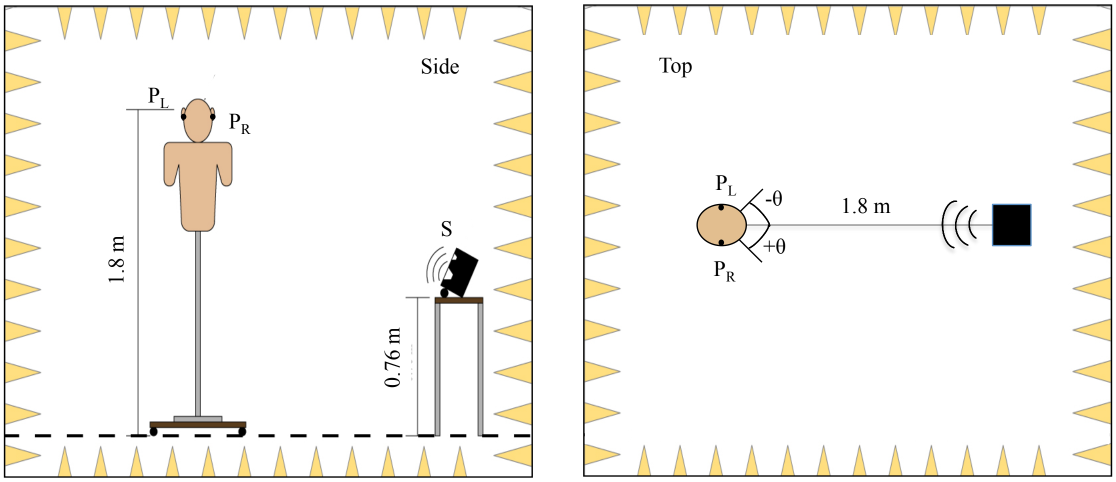


Figure 3.2: Schematic diagrams of the KEMAR, the experimental geometry and the acoustic apparatus are shown. A side view is shown on the left, and a top view is shown on the right. P_L and P_R refers to the left and right received pressure. The source signal S is shown schematically at the loudspeaker. θ is the rotation angle of the KEMAR from the center line. A negative rotation angle is a counter-clockwise rotation.

The KEMAR in-ear microphones were G.R.A.S. Type 40AG 1/2" microphones connected to G.R.A.S. Type 26AC 1/4" preamplifiers with right-angle adapters and a G.R.A.S. Type 12AR power module. A National Instruments PCI-5105 data acquisition (DAQ) card installed into a PC running LabVIEW was used to record the in-ear microphone signals and to automate the experiment. The program also controlled a Lin Engineering 4118 stepper motor with a R256 controller to rotate the turntable in the desired angular increments. A HP 3314A function generator, triggered by LabVIEW, generated the excitation signals sent to the loudspeakers (periodic chirps ranging from 500 Hz to 4 kHz).

At each angular position, the speaker produced 25 periodic chirps which were received by the microphones in the ears and recorded by a DAQ card. These signals were sent to the PC where they were linearly averaged in the frequency domain, and the HRTFs were calculated in the frequency domain using Fast Fourier Transforms with 2.1 Hz resolution bandwidth. This was done using

$$P_i(f) = \mathrm{FFT}[p_i(t)], \tag{3.1}$$

where i is either left L or right R, $p_i(t)$ is the time domain acoustic pressure output of each microphone, and

$$S(f) = \mathrm{FFT}[s(t)], \tag{3.2}$$

where $s(t)$ is the time domain signal directed to the loudspeaker, and

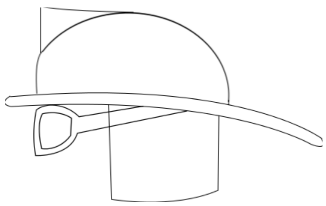
$$\mathrm{HRTF} = 20\log_{10}\left[\frac{P_i(f)}{X(f)}\right], \tag{3.3}$$

where $X(f)$ is either $S(f)$ or the P from the opposite ear.

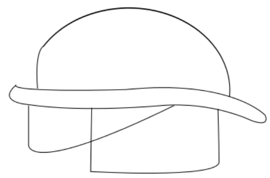
This procedure was applied to study elements of the PPE ensemble mentioned above both separately and combined. Initial work indicated that the helmet had the greatest impact on measured HRTFs. Therefore, 11 different helmets were acquired and tested. This helmet-focused study was intended to provide a more detailed understanding of the effect of firefighting helmets on human hearing.

There are two major styles of firefighter helmets in use in the United States. The first style is referred to as traditional and the second as modern. The basic structure of these helmets is the same. There is a hard shell that has a brim of varying size that ends above the ears. There is eye protection in the form of either a face shield or goggles, and an insulated fabric earlap that extends below the brim to the shoulder, covering the ears. The major difference between the two styles is that the traditional helmet will have a large rear brim and a smaller front brim, and the modern style will have a slightly larger front brim than the traditional and smaller rear brim than front. The European style helmets are different than the US styles. These helmets look more like motorcycle helmets with no brim and the shell extends over the ears. One European style helmet was tested. A representation of each style of helmet can be seen in Figure 3.3.

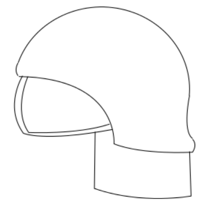
The anechoic environment was used to provide a baseline environment, free from any acoustic multipaths. This simulated either an outdoor environment, or a very large indoor space away from walls. In other words, acoustic energy was only incident upon KEMAR directly from the source. At the opposite end of the spectrum, measurements were also conducted in the reverberation chamber at UT Austin. This environment is highly reverberant, and hence provides a diffuse acoustic field, in which energy from the source bounces off the walls and floors and arrives at the KEMAR from all directions.



(a) Traditional style firefighter helmet with a larger brim in the back and goggles for eye protection.



(b) A modern style firefighter helmet with a smaller back brim and larger front brim. The eye protection is a built-in face shield, which was deployed during testing.



(c) European style firefighter helmet with no brim and layers of built-in face shields. The outer layer is is clear plastic and covers most of the face. The inner layer just provides eye protection. Both shields were deployed during testing.

Figure 3.3: The three styles of firefighter helmet used in this study. All helmets used in this study had earlaps. An earlap is the insulated heavy cloth flap that covers the ears and neck to provide protection from heat and flame.

Finally, an intermediately reverberant environment was also used, that of a typical office space, with a tile floor and hard walls, but with an acoustic tile ceiling and office furniture.

3.3 Results

The results below represent the measurements taken in the anechoic chamber, reverberant chamber, and typical office. The head-related transfer functions are calculated either to show the left receiver compared to the right receiver, $\frac{P_{\mathrm{L}}}{P_{\mathrm{R}}}$, or the right receiver compared to the original signal sent to the source, $\frac{P_{\mathrm{R}}}{S}$.

3.3.1 Anechoic Chamber

The head-related transfer functions, composed of the left received signal divided by the right received signal, $\frac{P_{\mathrm{L}}}{P_{\mathrm{R}}}$, as a function of frequency and angle, are shown in Figure 3.4. In general, when the received level is higher in the left ear, the dB value of this HRTF is positive (warm colors in Fig. 3.4). When the received level is higher in the right ear, the dB value of this HRTF is negative (cooler colors in Fig. 3.4). The angle is such that at 0° the KEMAR is directly facing the speaker; clockwise in the top view is the direction of positive rotation, and counter clockwise is negative. Figure 3.4 shows a comparison of the measured HRTFs for the bare KEMAR and the KEMAR wearing all the PPE gear (the coat, hood, and modern helmet with earlap and face shield down). The HRTFs for the individual pieces of equipment can be seen in Appendix C. These show that the helmet has the greatest effect.

These results show a significant difference between gear and no gear. In the bare case, at all frequencies, there is a smooth transition from cool colors to warm colors, as the rotation angle crosses 0° or 180°. This means that the ear nearest the sound source received a higher level than the ear facing away from the sound source (as expected) and the level smoothly equalizes as the head is turned to face directly at the sound source.

When the PPE gear is present (Fig. 3.4 right frame) significant structure in the transfer function is seen, as a result of diffraction from the helmet brim. Above 750 Hz, there is no longer a smooth transition from cool colors to warm colors as the head is turned relative to the sound source. Instead the

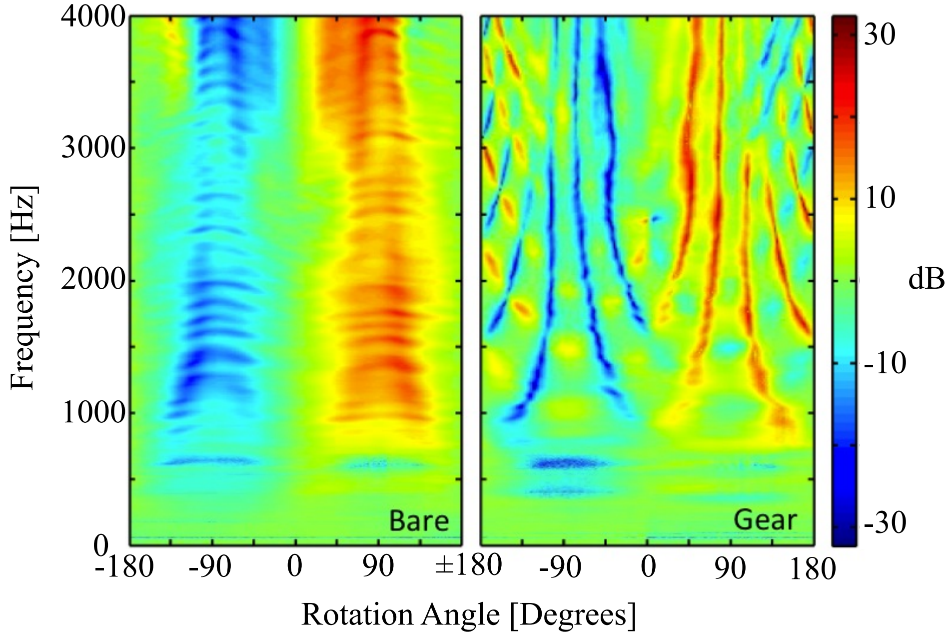


Figure 3.4: HRTF ($\frac{P_\mathrm{L}}{P_\mathrm{R}}$) comparison of the bare KEMAR (left) versus the KEMAR wearing a coat, hood, and helmet (right). Warm colors indicate a positive HRTF and cold colors a negative HRTF.

level oscillates, which is similar to what would happen if the sound source were rapidly moving. It is possible that this could cause difficulty in localization, but listening tests are required to asses the human response associated with this physical acoustics result.

Although the results in Figure 3.4 show this effect over a wide frequency range, it is also useful to look at slices taken from Figure 3.4 at single frequencies. Figure 3.5 shows HRTF frequencies 500 Hz, 1 kHz, 2.5 kHz, and 4 kHz. In the bare case, when the source is on the left side of the KEMAR head, P_L will sense a higher pressure than P_R due to the shadow created by the

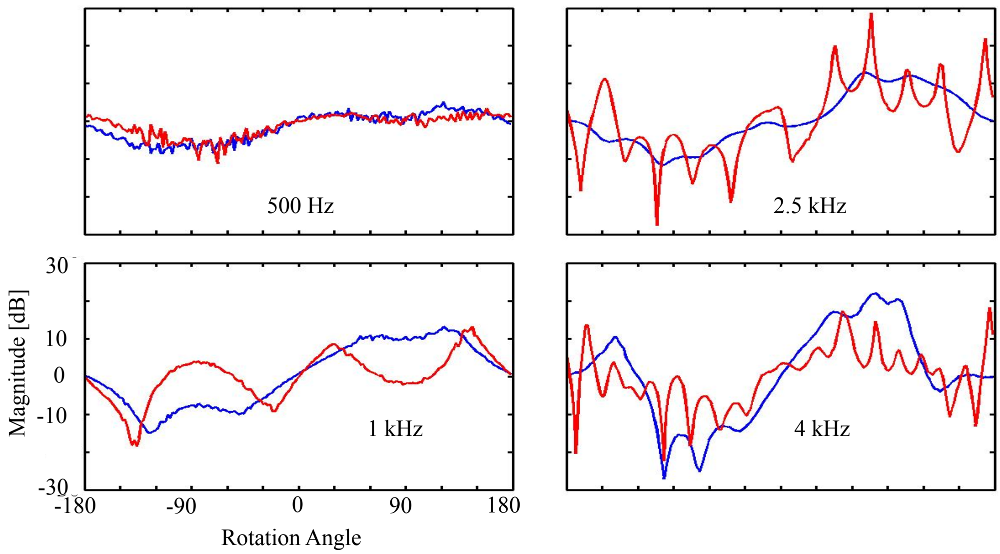


Figure 3.5: Slices taken from Fig. 3.4 at four different frequencies. The blue line is the HRTF of the KEMAR without gear and the red line is the HRTF of the KEMAR with gear. All plots have the same axes as the 1 kHz plot.

head, and the HRTF will be positive. The transition from negative angles to positive angles is smooth and the HRTF magnitude monotonically increases, crossing the 0 dB level twice, at 0° and 180°. This is true for both gear and no gear cases at 500 Hz. As the frequency increases, this transition is no longer smooth or monotonic. The level fluctuates above and below 0 dB more than twice as the head is turned. The number of 0 dB crossings increases with frequency. This could cause localization difficulty since one of the normal cues for localization is disrupted.

Finally, transfer functions between the source signal and the received level at each receiver were computed and $\frac{P_{\mathrm{R}}}{S}$ can be seen in Figure 3.6. From this data, the absolute level at each ear was calculated, then averaged over frequency and angle. It was found that this average receive level was about 3 dB less when wearing all of the tested gear as compared to the bare KEMAR. In other words, on average, the PPE reduces the received level by about 3 dB compared to the no gear case, averaged across frequency and angle. The results for the left ear, $\frac{P_L}{S}$, are not shown, but are nearly identical to the data shown in Figure 3.6, except reversed left-to-right.

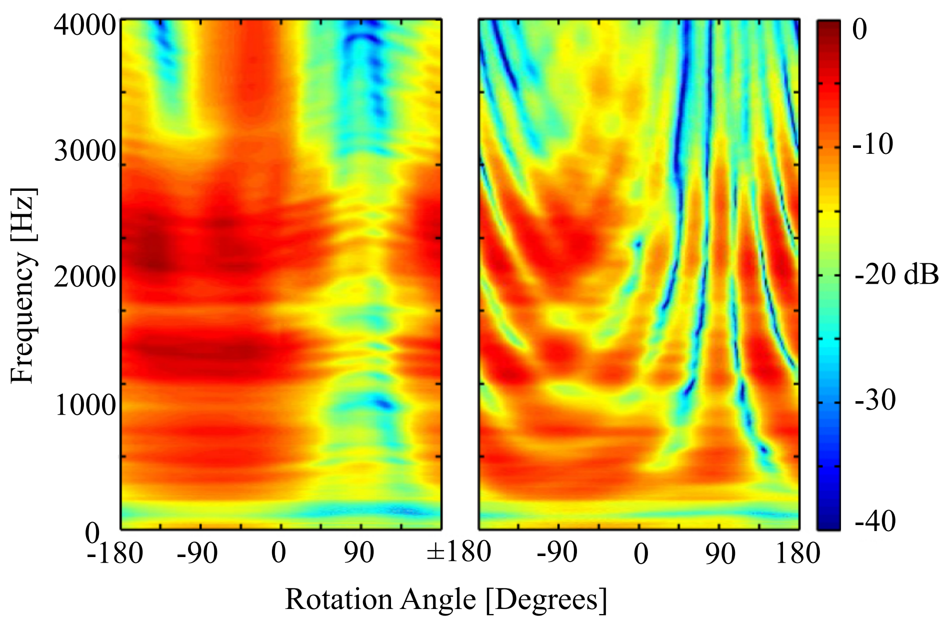


Figure 3.6: HRTF of right receiver over source, $\frac{P_R}{S}$, HRTF comparison of KEMAR without gear (on left) and KEMAR with gear (on right). Warm colors indicate a higher magnitude than cooler.

3.3.2 Reverberation Chamber and Office

The physical acoustics measurements that were made in the anechoic chamber (as described in Section 3.3.1) were repeated in a reverberation chamber and a typical office. The results are compared in Figures 3.7 and 3.8. These results show that as reverberation energy in the room increases, the effects of the gear decreases. This is expected as reverberation distributes the incoming energy more evenly. This does not mean that in a more reverberation chamber better localization is expected. As reverberant energy increases, localization becomes more challenging. Adding the PPE on top of this challenging environment does not make the already difficult job of localization in the reverberant chamber any worse.

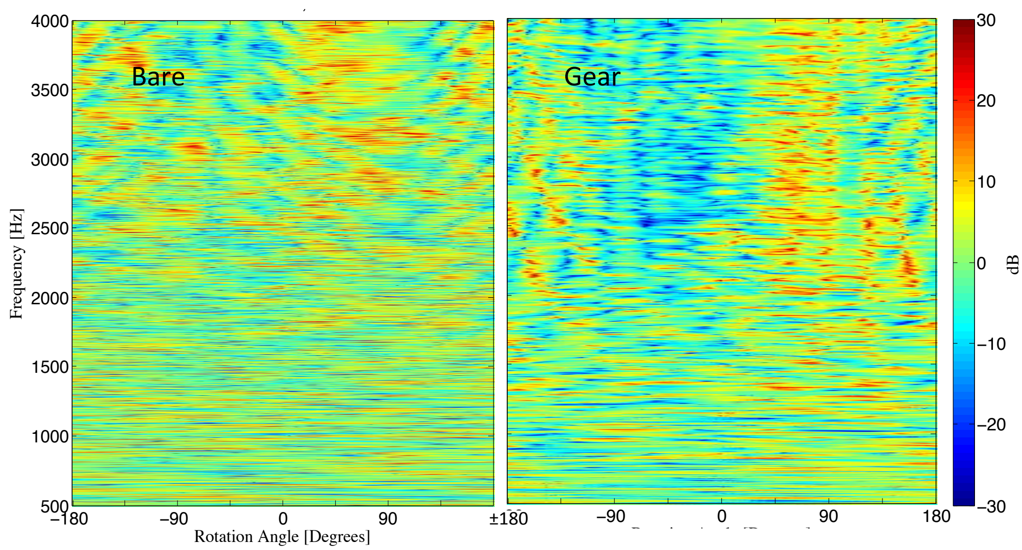


Figure 3.7: HRTF of KEMAR bare, left, and wearing gear, right, in a room. Warm colors indicate a higher magnitude than cooler. The effects of the firefighting PPE are still visible, but more reverberant energy has smoothed the peaks and valleys.

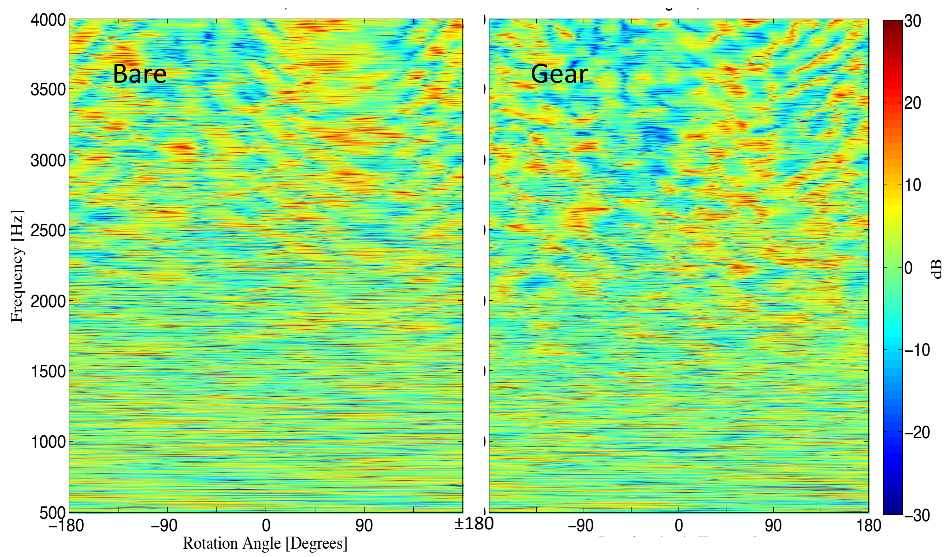


Figure 3.8: HRTF of KEMAR bare, left, and wearing gear, right, in the reverberation chamber. Warm colors indicate a higher magnitude than cooler. The effects of the PPE are not noticeable under the reverberant field.

3.3.3 Helmet Study

By measuring HRTFs for the various pieces of gear separately, it was found that the helmet was the primary cause of the differences seen in Figures 3.4 and 3.5. The separate HRTFs of each piece of gear can be seen in Appendix C. There are many different helmet designs in use in the fire service today, with different shapes, sizes and geometries. Eleven different helmets with a variety of features were acquired from the most commonly used manufacturers. Five of the helmets were traditional style, six were modern, and one was a European helmet. Three of the five traditional helmets and one of the modern style used goggles as eye protection. The others used a version of a face shield. The European helmet had retractable face shield and a retractable eye shield. Both were fully deployed.

HRTFs, such as shown in Figures 3.4 and 3.5 were measured for all eleven helmets and can be seen in Appendix C. Showing all of the results in colormap format, as in Fig. 3.4, or even at single frequencies, as in Fig. 3.5 may show a qualitative picture of the results, but a quantitative measurement was needed. A single quantitative metric was found to describe the fluctuations seen in the HRTFs. This metric was calculated using

$$D(\theta, f) = 20\log_{10}\frac{P(\theta, f)_{\mathrm{R,Bare}}}{P(\theta, f)_{\mathrm{R,Helmet}}}. \tag{3.4}$$

This has been adapted from Gyorgy, et al. [25] Then, the D was summed across angle and averaged across all frequencies of interest. The final metric is the following:

$$D_{\mathrm{rms}} = \frac{1}{2\pi N}\sum_{f_i}\sqrt{\sum_{\theta_i} D(\theta, f_i)^2}, \tag{3.5}$$

where N is the number of discrete frequencies that were calculated in the FFT. This process can be seen in Appendix E. The calculated D_{rms} for each helmet can be seen in Figure 3.9. In addition to the D_{rms}, coherence was calculated between the bare case and the helmets using the following:

$$C_{xy}(f) = \frac{\|P_{xy}(f)\|^2}{P_{xx}(f)P_{yy}(f)} \tag{3.6}$$

where $P_{xy}(f)$ is the cross spectral density of the HRTFs and the $P_{xx}(f)$ and $P_{yy}(f)$ are the power spectral densities of the HRTFs. Coherence ranges between 0 and 1, 0 being completely different and 1 being perfectly matched. D_{rms} and coherence shows that the effects of each helmet vary. The first two helmets are clearly closer to the bare case and the last helmet is farther from the bare case. In general, a larger value of D_{rms} indicates a greater change compared to the bare case, however, this metric can miss important details as is the case for helmet 12.

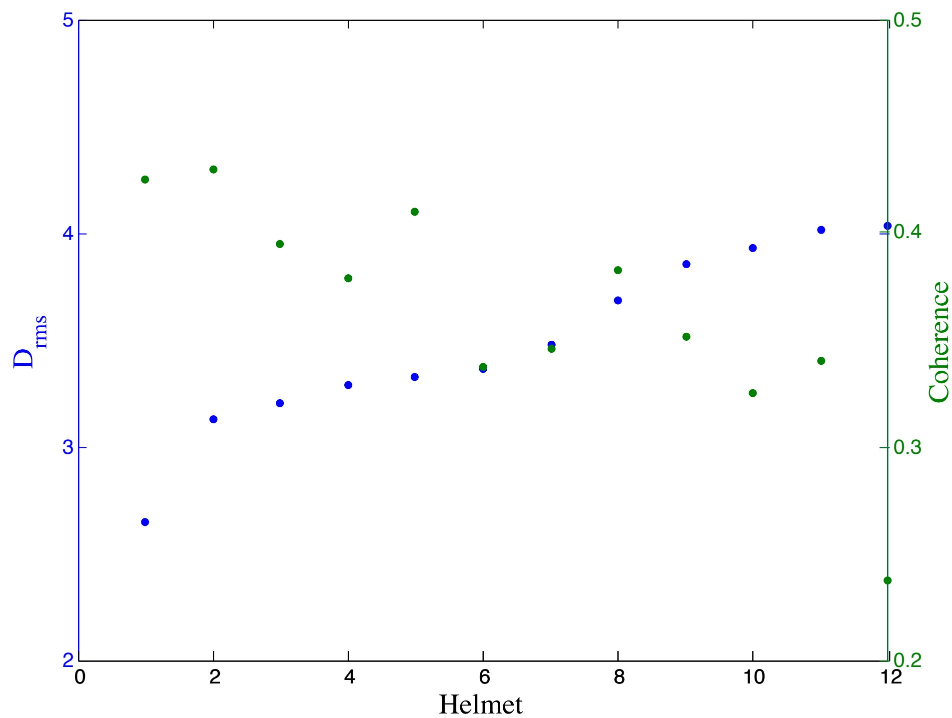


Figure 3.9: The calculated D_{rms} and coherence for each helmet.

A very unusual HRTF is shown in Figure 3.10 for helmet 12, a european style helmet. This shows the HRTF at 1000 Hz for all rotation angles. The HRTF for a bare case is shown in blue. Note the slope of the curve is positive crossing zero degrees for the bare case, but is negative for helmet 12. This could possibly cause the wearer to make a left-right error when wearing helmet 12, as sound coming physically from the right side was received louder in the left ear, potentially a very confusing situation. This reinforces the idea that some type of helmet rating would require human hearing tests using all of the different helmets, which is beyond the scope of this work. The physical acoustic effects alone are not sufficient.

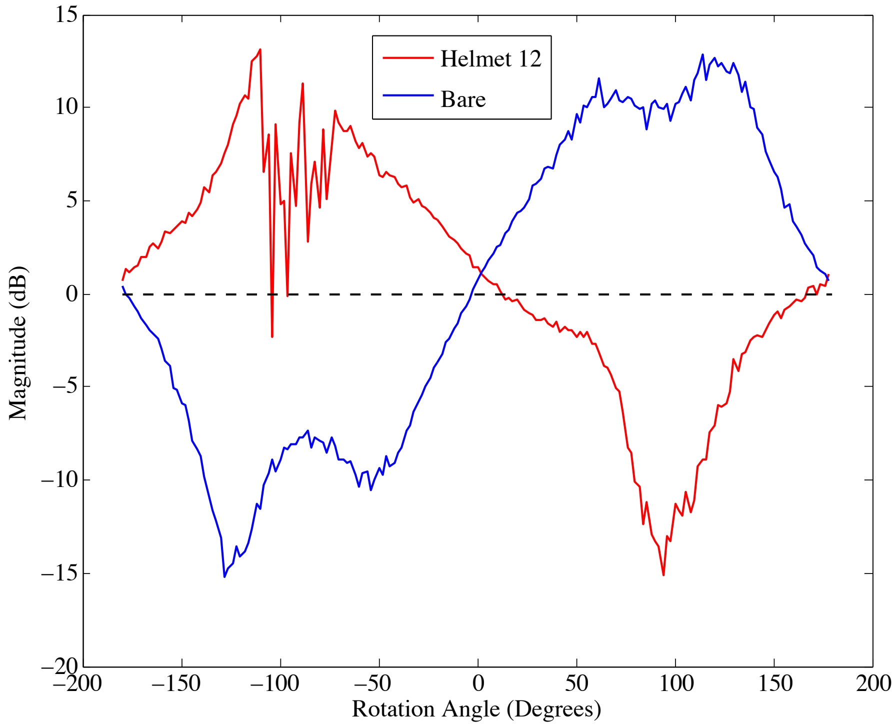


Figure 3.10: HRTF of helmet 12 at 1 kHz.

3.4 Conclusion

The use of firefighter personal protective equipment, although necessary, alters signals that reach the ears of the firefighters. On average, the PPE (with modern style helmet, Figure 3.6) lowers the received level by 3 dB, which can reduce the detection range, and adds significant structure that can potentially cause localization errors. These effects are reduced as the reverberation energy increases in the room, as the incident energy on the firefighter is coming from multiple angles at the same time.

The most significant changes occur because of the helmet. These changes are seen in all helmets tested. This is not the proper forum to rate the acoustic performance of particular helmets, other than to say all helmets cause some significant effects. One possible remedy would be to train people wearing the helmets to turn their heads and to move back and forth during localization, in an attempt to average out the observed effects. This is already done in some fire departments, but emphasizing this, and providing knowledge of why it is necessary would be useful. The use of the single number metric, D_{rms}, was shown as a means for measuring performance, but it was also shown to be insensitive to some important features of the individual HRTF curves, such as a left-right localization cue reversal.

Although the observed physical acoustics effects on received level at the KEMAR ears are significant and previously unknown (to the knowledge of the author), the effect on human hearing must be measured in psychoacoustic testing in order to assess the true impact as described in Chapter 4.

Chapter 4

Effect of Firefighter Personal Protective Equipment on Human Hearing: an Audiology Study

4.1 Introduction

Although the results from the KEMAR experiment show how the personal protective equipment (PPE) changes the physical sound field that reaches the ears, the experiment did not show how these changes affect the human reaction to and perception of the sound.

The human auditory system has a complex physiology that applies filters and integration to the sound traveling through the ear. The ear is broken up into three main sections – the outer ear, middle ear and inner ear. The outer ear contains the pinna and the auditory canal, or meatus. The middle ear consists of the eardrum, or tympanic membrane, and the ossicles. The outer and middle ear are shaped such that they amplify the frequencies between 1 and 3 kHz. This amplification has been characterized and is reproduced in frequency measurements by using and A, B, or C-filter. The inner ear consists of the cochlea. [7]

The cochlea is spiral shaped and filled with a nearly incompressible fluid and two membranes, the basilar membrane and the Reissner's membrane. The vibration applied by the stapes to the oval window creates a pressure difference in the fluid which in turn sets up a traveling wave along the basilar membrane. Movement of the basilar membrane causes the hair follicles to vibrate and excite the auditory nerve which communicates with the brain. [7] One of the characteristics of human hearing that results from this physiology is the hearing threshold, also called the auditory threshold. It is the minimum acoustic pressure level that is detected by an individual, which is frequency and direction dependent, and also varies from person to person, and can vary with the age of an individual.

There are two main ways to study the auditory threshold of subjects. The first is called the method of constant stream line (MCS), [26] where the subject is presented with a signal at many levels multiple times randomly. The subject's task is to indicate when they hear a signal. From this data, a psychometric function is calculated, and, from that function, an auditory threshold is determined.

The second experiment used to find auditory threshold of a subject is the method of limits (MOL). [26] A MOL study can be conducted three different ways. The "descending" version of this experiment is where the level of the signal is decreased at a fixed step size until the subject reports that they do not hear the signal. A second version is "ascending," where the level is increased until the subject hears the signal. The adaptive version is where the signal starts at an easily heard level and is decreased until the subject can not hear the signal. Then, the signal is increased incrementally until the subject hears it. Then decreased again. The levels at which the direction is changed are called turnarounds. The different lowest levels at which the subject hears the signal are averaged to calculate the auditory threshold. The rules of an MOL study refer to the amount of times a subject hears the signal before the level is changed: one-down-one-up, two-down-one-up, three-down-one-up, etc. Also, the length of the study is defined based on either number of trials or number of turnarounds.

This study used an adaptive style method of limits study with one-up-one-down rules and a minimum set number of five turnarounds. The purpose of the study is to determine the differences in auditory thresholds caused by the personal protective equipment worn by firefighters.

4.2 Description of Experiment

A MOL experiment was chosen because of the number of conditions and signals. Five different signals were presented to subjects via a KRK Rokit 5 RPG2 powered loud speaker. The signal levels were set using a Grason Stadler, Inc (GSI) 61 Clinical Audiometer. This apparatus can be seen in Figure 4.1. This study was conducted in concordance with the UT Human Subjects and Institutional Review Board protocol # 2012-09-0023.

The signals presented to the subject were chosen based on the physical acoustic measurements detailed in Chapter 3. Limitations of the equipment in production of pure tones necessitated some flexibility in the choice in frequencies. Based on the information in Figure 4.2, four frequencies were chosen: one where the signals were similar, one where the bare signal was the lowest, and two close to the nulls seen in the upper frequency range. The signals chosen were 500 Hz, 1 kHz, 3 kHz, 4 kHz, and a recorded PASS signal. The procedure and equipment used in this study provided a threshold measurement resolution of 5 dB.

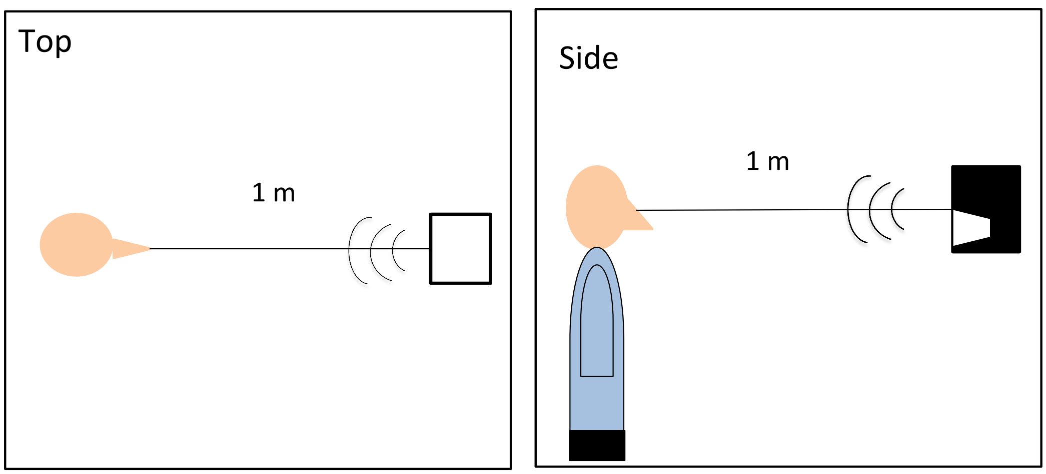


Figure 4.1: Subject setup during the MOL experiment.

Recruitment of subjects was done using a flyer and announcements in classes. The project was presented to subjects age 19 to 49 with normal hearing. The recruitment flyer can be seen in Appendix D. Ten subjects were used for this experiment. Each subject was placed in an audiology booth 1 m away from the center of the speaker that was adjusted to fit the subject's height. The subjects were screened for hearing loss before starting the tests. The subject was asked to indicate, by pressing a button, when they heard a

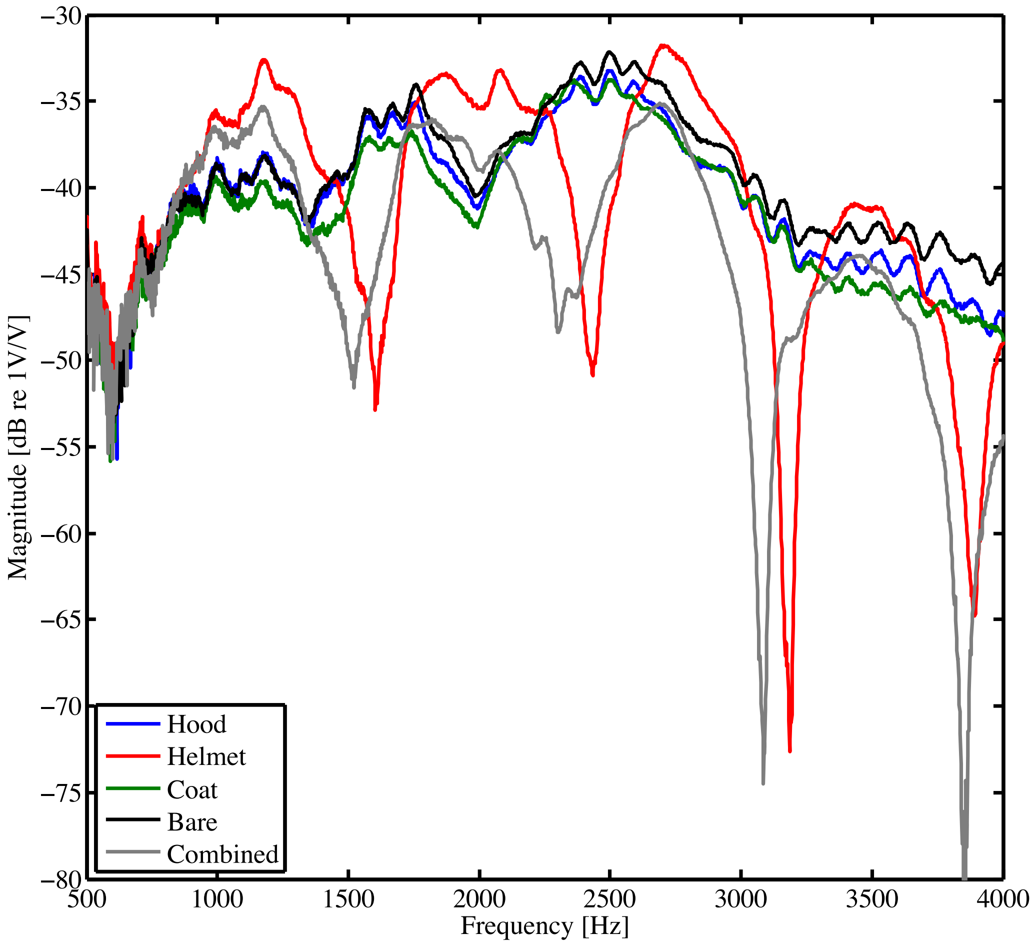


Figure 4.2: Results depicting the effects of the PPE measured by the KEMAR at 0° that led to the chosen frequencies.

signal. After the hearing screening, the first case was conducted without any firefighting gear, or "bare." Each of the five signals were presented to the subject and the auditory threshold recorded. The middle conditions, the subject wearing just the helmet and the subject wearing the helmet, hood, and coat, were conducted the same way with varying order in the signal presentation. The last case was the same as the first one (bare) to ensure repeatability.

The results were averaged for each signal type in each case to find the auditory threshold. Once the auditory thresholds were measured for each case across all subjects, the differences were computed between the bare case and the case with the helmet and all the gear, separately.

4.3 Results

The results are presented in Figure 4.3, for the differences between the helmet and bare, and in Figure 4.4, for the differences between all the gear versus bare. The results shown are averaged across all subjects and the error bars show the range of the results across all subjects. A positive difference means that the sound needed to be louder than the bare case for the subject to detect. These results show a distinct difference in the auditory threshold in the higher frequencies and for the PASS signal that was presented. In the lower frequencies (500 Hz and 1 kHz) there is no significant difference in the auditory threshold. The differences found in the 3 kHz, 4 kHz, and PASS signal were all similar and range from 5 dB to 15 dB depending on the subject.

For the PASS signal, it is interesting to note that when wearing the

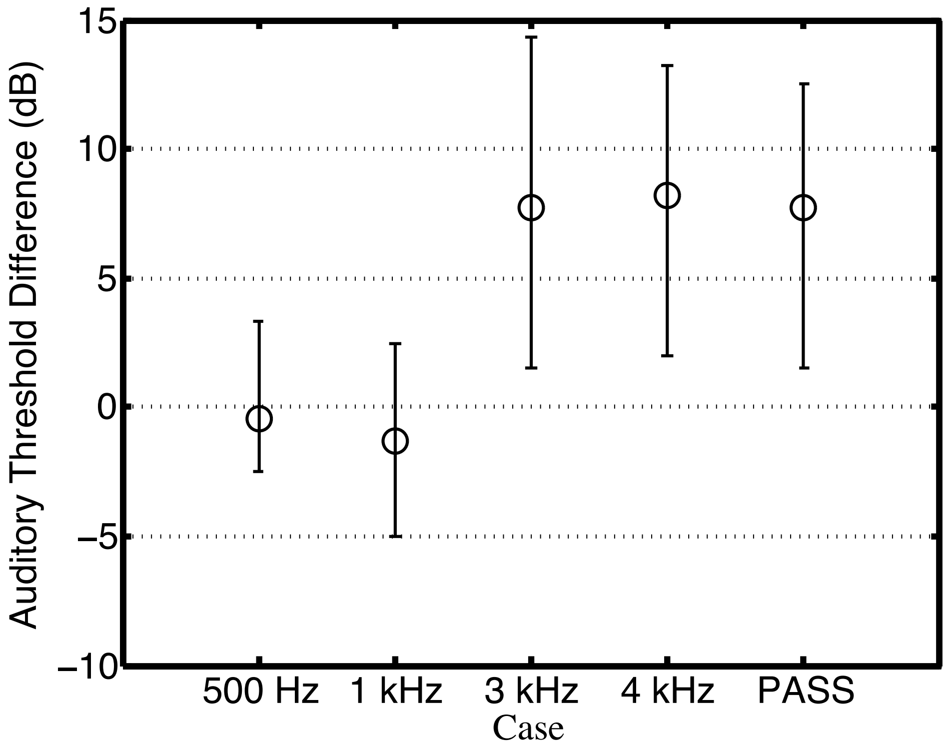


Figure 4.3: Auditory threshold differences (dB) between wearing the helmet versus the bare case. Open circles represent the mean over all subjects. The error bars represent the range over all subjects. Positive difference indicates increased acoustic pressure level required for detection.

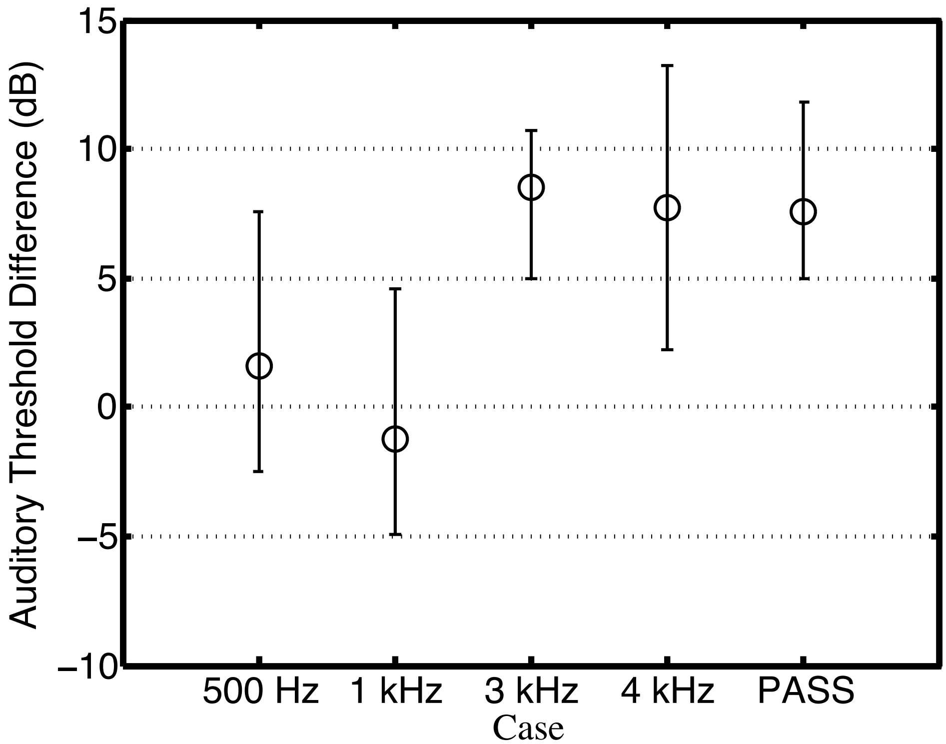


Figure 4.4: Auditory threshold differences (dB) between wearing the coat, hood, and helmet versus the bare case. Open circles represent the mean over all subjects. The error bars represent the range over all subjects. Positive difference indicates increased acoustic pressure level required for detection.

helmet alone (Figure 4.3), the variation in auditory threshold among subjects is greater tan when wearing all of the gear (Figure 4.4). It appears that the effect of the helmet (acoustic diffraction from the brim) is diminished by the rest of the PPE gear.

4.4 Conclusion

The results of the MOL experiment show increased auditory threshold due to wearing the firefighter PPE. Such a change in auditory threshold is consistent with the physical acoustic effects reported in Chapter 3. The increase is observed where expected at 3 and 4 kHz. The increase is also observed in the PASS signal, which has the majority of energy at 3150 Hz. This suggests that the PASS signal should be louder to compensate for this increase in auditory threshold.

The broad range of results in the helmet case (differences from 2 dB to 13 dB, Figure 4.3) suggest that errors inherent to the experiment were more pronounced in this case. The errors typically present in a MOL audiology experiment conducted with a loudspeaker include variability in the subject's stance. As seen in the physical acoustics test, the angle of the head relative to the signal source changes the level received by the subject. Although the subject is instructed to look at the speaker, there are still moments when the subject moves. Small changes in stance and head angle can cause large changes in received acoustic level, as seen in Chapter 3.

Chapter 5

Conclusions

The acoustics of the fireground were investigated using the formalism of the sonar equation. The ultimate goal of this work is to provide a scientific basis for the design of an optimum alarm signal for the Personal Alert Safety System (PASS) used by firefighters. In this thesis, the background noise NL, source level SL, and detection threshold DT were the focus. A PASS device that conformed to NFPA 1982-2007 was used as the source in this work, and represents the SL term in the sonar equation. Detection threshold was defined to be the auditory threshold of the common firefighter. The DT was investigated in the presence of firefighter PPE.

In Chapter 2, the most-commonly used pieces of firefighter equipment were investigated for overall SPL, 1/3-octave band SPL, and directionality. This equipment included chainsaws, circular saws, positive pressure ventilation (PPV) fans, fire engines, pumps, and a PASS device integrated into a SCBA. It was found that most of the equipment used on the fireground exhibited higher overall source levels than the PASS device. The sounds emitted by the pumper truck that was investigated in this work (engine alone; engine plus pump; engine, generator, and pump) did not exceed the source level of the

PASS device. One of the chainsaws studied here exhibited the highest source level of the study, which was 11.6 dB greater than the source level of the PASS device. The overall SPL study also showed that the PASS device had some inherent directionality due to the mounting on the SCBA, exhibiting ± 3 dB in the azimuthal plane.

The 1/3-octave band analysis showed that the majority of the energy emitted by the PASS device was in the 3150 Hz band. In this band, the PASS device is comparable to most of the equipment, but the loudest device, one of the chainsaws, had a source level 4 dB greater than that of the PASS device.

In Chapter 3, the effects of firefighter PPE on the physical acoustics of human hearing were investigated. This part of the study utilized an acoustic manikin KEMAR to measure the signal received at the location of the tympanic membrane inside the KEMAR ear canal both bare and while wearing a firefighter coat, hood, and helmet. It was shown that the PPE reduced the overall level of the received signal by 3 dB, but the reduction was more significant at higher frequencies. In addition, it was found that the helmet caused significant changes to head related transfer functions, eliminating the smooth transition from left to right that normally occurs with the bare head. Diffraction around the brim of the helmet caused significant frequency-dependent changes in the HRTF compared to a bare head, which could confound localization.

The HRTF measurements were conducted in an anechoic environment, and repeated in a typical office and a reverberation chamber to simulate a range of possible acoustic environments. As expected, increased reverberation tempered the effects of the PPE on HRTFs, but it also effected the structure in the HRTFs measured for the bare cases, emphasizing the difficulty of acoustic localization in reverberant environments, even when unhampered by PPE.

Since the helmet was found to have the greatest effect, and since several different types of helmets are commonly used in the fire service, a study was conducted with 12 common helmet types. These helmets fit into three categories: traditional, modern, and one European style helmet. A single number metric was derived for each helmet that showed a range of variations from the bare case. The European helmet, which had the most protection covering the ears, exhibited the greatest difference. The traditional and modern style helmets showed similar ranges in results.

The physical acoustic effects reported in Chapter 3 motivated a study of how the helmet effected human perception using psychoacoustic testing on human subjects. The results from this experiment show that at 500 Hz and 1 kHz there is not a significant increase in auditory threshold. However, at 3 kHz, 4 kHz, and with the PASS signal, there is an increase in auditory threshold, both while wearing just the helmet and all of the gear. To restate this important results in other words, wearing just a firefighting helmet, and wearing all the PPE gear (helmet, coat, and hood) both increase the level of a just-detectable PASS signal in the human hearing tests reported here, by from about 5 dB to 10 dB relative to no gear.

5.1 Recomendations

Perhaps the simplest suggestion that can be made following these results is that the PASS device should be louder. If based on the results in Chapter 2, the PASS device should be 12 dB louder in order to be easily detectable above the loudest sounds on the fireground. The results from the audiology study show that increasing the signal amplitude by 7 dB would overcome the effects of the PPE. So, this author's recommendation is to increase the overall amplitude of the signal by 7 dB at the start of the alarm. Then, increase the amplitude over a set period of time by another 8 dB. This equals an overall increase of 15 dB and puts the level of the signal at 120 dB.

Another recommendation is to have some sort of auditory component to helmet and hood standards. This addendum to the standard is not a way to evaluate the helmets and hoods but to report the amount of transmission loss associated with the each piece equipment.

5.2 Future Work

This study reported on SL, NL, and DT components of the sonar equation. Additional research is underway under the same grant that supported this research, to study acoustic propagation on the fireground, which will impact the transmission loss (TL) term of the sonar equation. Knowledge of TL will allow future use of the sonar equation to completely analyze and optimize the PASS signal. Only a limited set of fireground sounds were studied here. It would be useful to eventually measure the SL and NL of additional sound found on the fireground.

Appendices

Appendix A

Calibration of the Tascam DR007

The DR007 was calibrated using the substitution calibration method in an anechoic chamber. The anechoic chamber provided a field environment and allowed for absolute calibration of acoustic equipment, free from the confounding effects of multipath reception. The reference microphone and DR007 were located on a microphone stand 1.72 m above the wire mesh of the anechoic chamber. The source was located 2.34 m away from the microphone. This apparatus can be seen in Figure A.1.

Twenty linear chirps, five seconds each, from 20 Hz to 20 kHz were defined by a laptop computer and sent to a M-Audio Studiophile AV 40 speaker using a NI USB-4431 DAQ. First, a G.R.A.S. type 46BE calibrated microphone, serving as the reference microphone, recorded the chirp using the DAQ and PC. Then, the DR007 recorder was put in the same location as the reference microphone and recorded the same chirps. This is detailed in Figure A.2.

Calibration was performed as follows. The signals from the reference and DR007 microphones were converted into the frequency domain using FFTs, A-weighting was applied, 1/3-octave band levels were calculated. Band levels calculated this way were averaged from the 20 sweeps previously de-

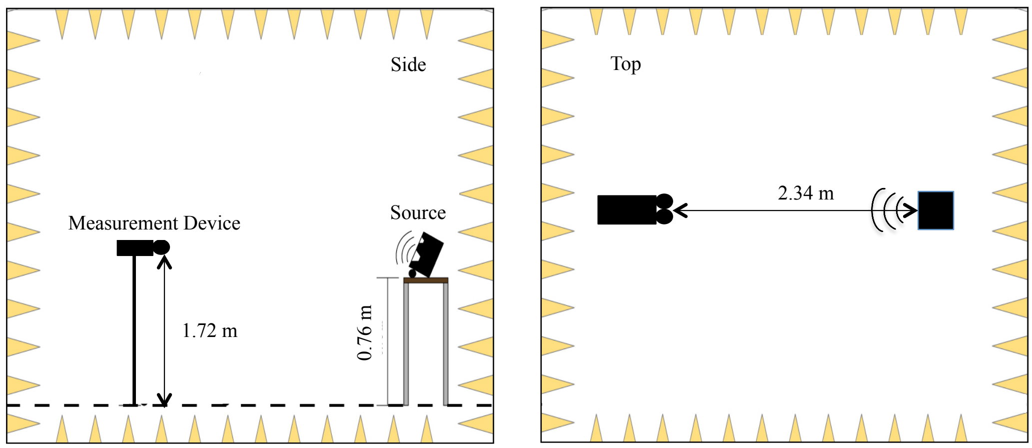


Figure A.1: The calibration apparatus in the anechoic chamber.

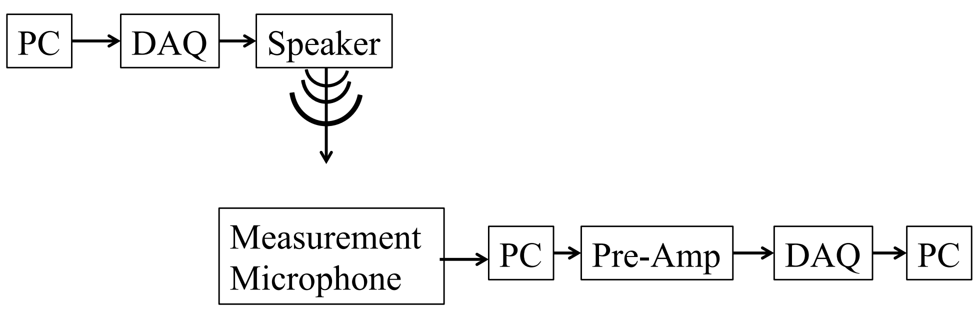


Figure A.2: The path of the signal in the calibration.

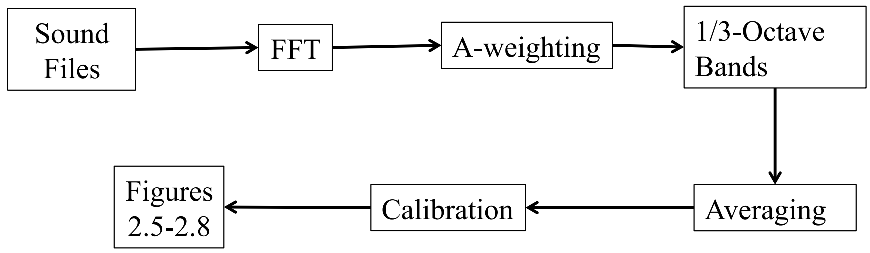


Figure A.3: The analysis approach for 1/3-octave band application.

scribed. The difference between the 1/3-octave band levels of the reference and the DR007 was calculated. This difference became the calibration function. The calibration function was then applied to all subsequent A-weighted 1/3-octave analysis recorded by the DR007 and subsequently shown in Figure A.3, and the corresponding m-file is in Appendix E. The 1/3-octave band analysis and A-weighting was applied as applied in ANSI S1.11 and ANSI S1.4, repectavely.

Appendix B

HRTFs ($\frac{P_L}{P_R}$) for the hood, coat, and helmet seperately

The HRTFs of the bare KEMAR and the KEMAR with all of the gear are presented in Chapter 3. Here is presented the HRTFs of KEMAR wearing the different pieces of the PPE separately: coat, hood, and helmet.

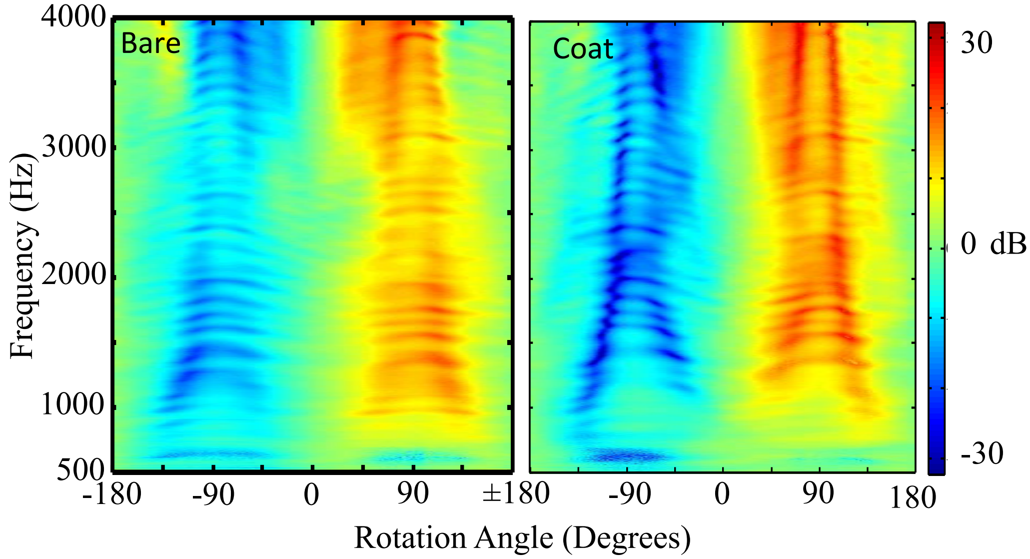


Figure B.1: HRTF of the coat.

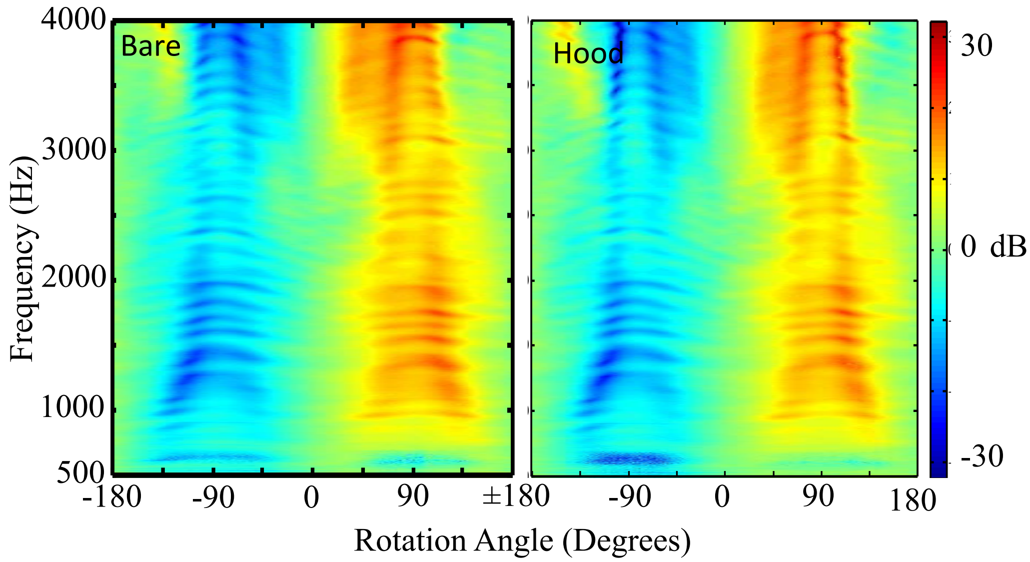


Figure B.2: HRTF of the hood.

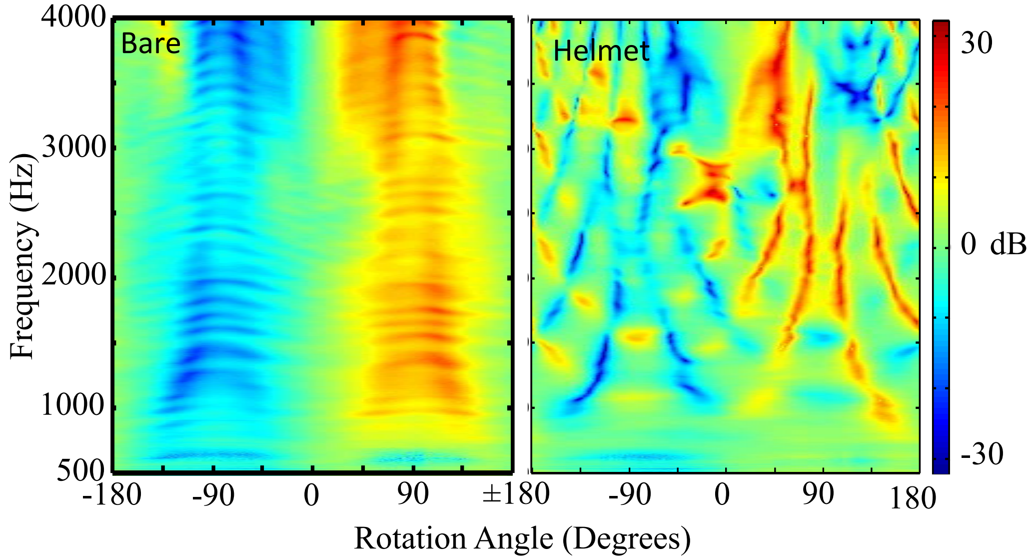


Figure B.3: HRTF of the helmet.

Appendix C

HRTFs ($\frac{P_L}{P_R}$) for all Helmets

There are many different helmet designs in use in the fire service today, with different shapes, sizes and geometries. Eleven different helmets with a variety of features were acquired from the most commonly used manufacturers. Five of the helmets were traditional style, six were modern, and one was a European helmet. Three of the five traditional helmets and one of the modern style used goggles as eye protection. The others used a version of a face shield. The European helmet had retractable face shield and a retractable eye shield. Both were fully deployed. Presented here are the HRTFs ($\frac{P_L}{P_R}$) for these helmets.

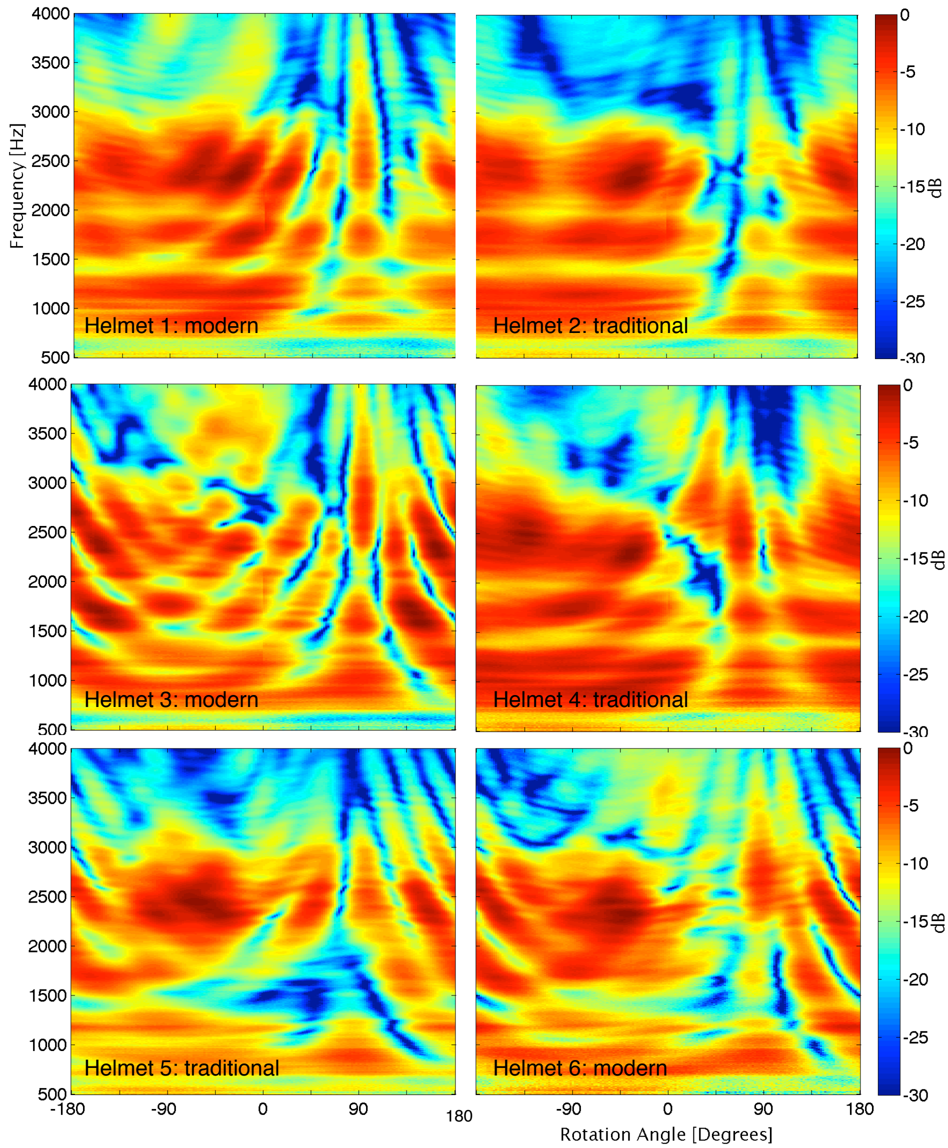


Figure C.1: The Head Related Transfer Function for all tested helmets.

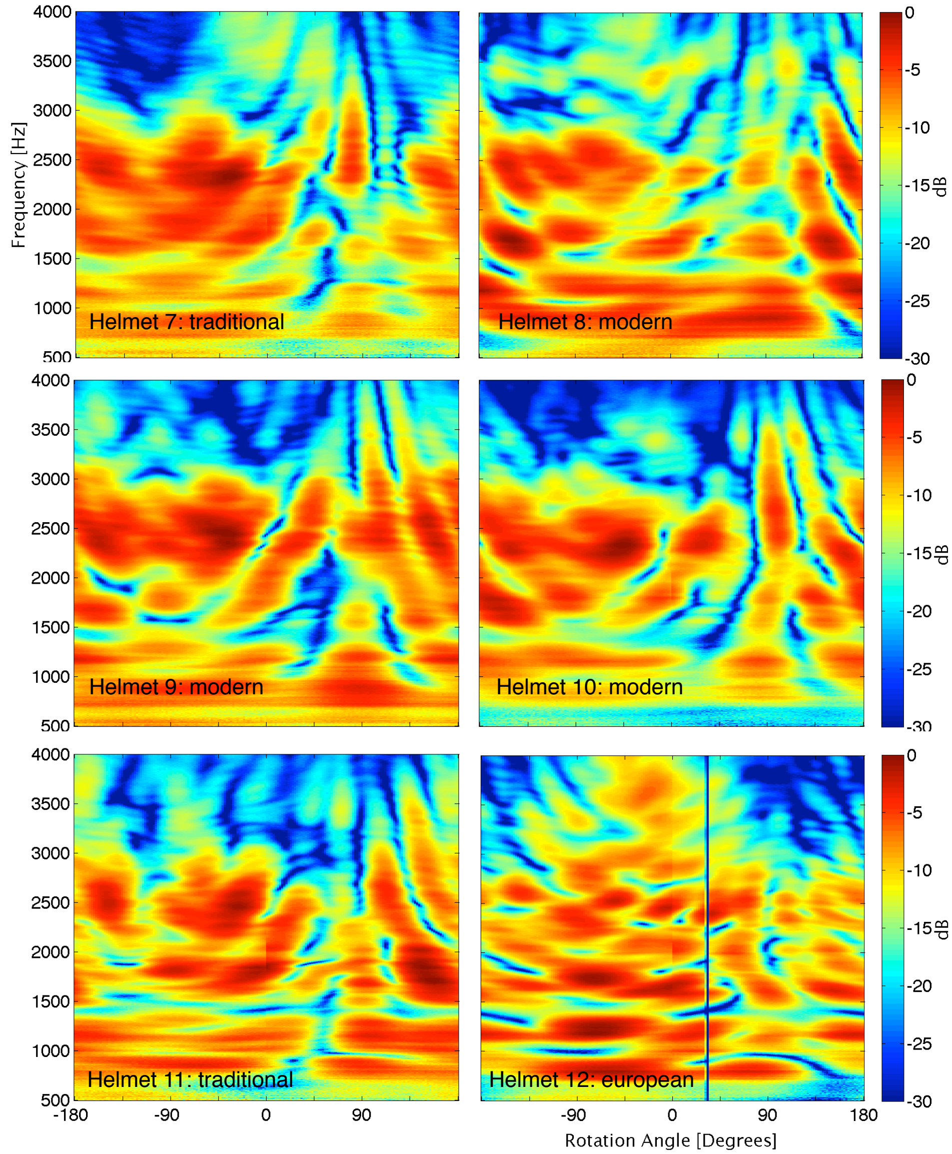


Figure C.2: The Head Related Transfer Function for all tested helmets.

Appendix D

Audiology Study Recruitment Flyer

The following flyer was poster around the UT Austin ETC building to recruit student to be involved in the audiology study conducted in Chapter 4.

If you are between the ages of 19 and 49
years and have normal hearing…

Be part of a study –

The Effect of Firefighter Safety Gear on Hearing

Participants will receive a free hearing screening
and will be paid $15/hour for one 1-hour session

If interested, please contact via email:
jsuits@utexas.edu

Fire safety gear
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Appendix E

m-files to calculate 1/3-octave bands

The matlab code that calculated the D_{rms} for the helmets.

```
close all
clear all
clc

cd ../KEMAR/Prep
Names=dir('X*');
cd ../../MATLAB
L=length(Names);
[datb,freq,theta,ind1,ind2,dtheta]=KEMARBare; %retrieves the HRTF,
%PR/S, for the bare case
pref=20e-6;
datblin=10.^(datb./20).*pref; %prms of the bare case all frequencies
for i=1:L
     figure(i);
    [testname, datdb, theta,ind1,ind2,dtheta]=KEMAR_analysis_V4...
    ...(Names(i).name,i,A); %retrieves the HRTF PR/S for the helmets
```

```
    Helmet(i).name=testname;
    datl = 10.^(datdb./20).*pref; %prms of the helmets
    HRTFD(:,:,i)=20.*log10(datblin./datl);

N=length(datdb);
%%
cd ../KEMAR/Prep
    for n=1:1902
        HRTFDf(n,:,i)=sqrt(trapz(theta(1:180),(HRTFD(n,:,i)).^2));
    end
        HRTFDs(i)=sum(HRTFDf(:,:,i))./(N*2*pi);
        figure(i);
        name=['Results/' Helmet(i).name];
        set(gcf,'PaperPositionMode','auto');
        set(gcf, 'PaperOrientation', 'landscape');
        set(gcf, 'PaperSize',[8.5 11]);
        set(gcf,'PaperType','uslegal');
        saveas(gcf,name,'png')
cd ../../MATLAB
end
```

The MatLab code that calculated the 1/3-octave band noise levels with calibration.

```
function [P1,F1,SPL]=AnalysisSpectA(flname,cnum,G,n)
%flname is the name of the file to be analyzed
%cnum is the channel number
%G is the gain set on the Tascam: 0 to 90
% close all
clc
text('Interpreter','latex','FontName','TimesNewRoman','FontSize',12)
bw=30;
cd ../Calibration/Calibration3/Results
C=csvread('TF5a.txt'); %Calibration File where the calibration values
%are saved as 1/3-octave band dB levels
cd ../../../MATLAB
J=0.49.*G; %Calculates the addition of gain based on the DR007 value
R=10*log10(12.*0.3048);  %Accounts for the spherical spreading
%caused by range

if n==1
cd ../FT/1/Tascam
[sig,Fs,nbits] = wavread(flname);
cd ../../../MATLAB
else
cd ../FT/2/Tascam
[sig,Fs,nbits] = wavread(flname);
```

```
cd ../../../MATLAB
end
sigin = sig(:,cnum);
%% A-weighting
[A,B]=adsgn(Fs);
SigA=filtfilt(A,B,sigin);
sigin=SigA;

%% Fourier Transform
F3A=figure;
Sig=sigin(:,:);
L=length(Sig);
NFFT = 2^nextpow2(L); % Next power of 2 from length of y
Y = fft(Sig,NFFT)/L;
f = Fs/2*linspace(0,1,NFFT/2+1);
plot(f,2*abs(Y(1:NFFT/2+1)))
axis([0 8000 0 max(2*abs(Y(1:NFFT/2+1)))])
xlabel('Frequency[Hz]')
title('Fourier Transform of the A-weighted Signal')

%% 1/3-Octave Band Analysis
[P,Freq]=ThirdOctave(sigin,Fs);
P1=P+R-J+C;
```

```
F1=bankdisp(P1,Freq);
hold all
set(gcf,'OuterPosition',[50 100 1200 500]);
set(gcf,'PaperPositionMode','auto');
set(gcf, 'PaperOrientation', 'landscape');
set(gcf, 'PaperSize',[8.5 14]);
set(gcf,'PaperType','uslegal');
title('A-weighted 1/3-Octave Bands, ref 1m 20 \mu m')

pref=20E-6;
SPL = 10.*log10(sum(10.^(P1./10)));
```

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Vita

Joelle Suits graduated from Pine Creek High School in 2006. In the fall of 2007, she began attending the University of Colorado at Colorado Springs (UCCS) pursuing a degree in Mechanical Engineering. Over the next four years she joined the American Society of Mechanical Engineers and minored in Aerospace Engineering.

At the end of her Junior year, she started a job as an undergraduate research assistant in the Exploration and Space Technologies Lab. While there, she researched using Tunable Diode Laser Absorption Spectroscopy to measure temperatures of a gas in-situ with minimal interferance.

Joelle graduated from UCCS in May of 2011, and in fall started at the University of Texas at Austin (UT). There, she pursued a Masters degree in Mechanical Engineering focusing on Acoustical Engineering. Her research focus was the noise sources present on a fireground, and the effect of firefighter's personal protective equipment on human hearing. While there, she joined the Acoustical Society of America.

Upon graduation in August of 2013, she will continue her research in acoustics on the fireground at UT. She is interested in using her degree for acoustic consulting.

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