Evaluation and Enhancement of Fire Fighter PASS Effectiveness

Final Report

A DHS/Assistance to Firefighter Grants (AFG) Funded Study

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EXECUTIVE SUMMARY

The Personal Alert Safety System (PASS) has become an indispensable part of the fire fighter personal protective equipment ensemble. PASS devices have been credited in many fireground accidents with leading rescuers to fire fighters in danger.

While the virtues of PASS technology are clearly evident, it has evolved with minimal scientific basis and there is ample room for improvement. Despite more than 3 decades of implementation, there still have been an unacceptable number of fire fighter line-of-duty injuries and deaths associated with fire fighters not being found and rescued as quickly as possible. Although the applicable PASS standard and associated technologies have evolved since the inception of PASS, there has not been systematic research on the overall characteristics of the PASS device and acoustical characterization of the fireground environment in which the PASS device is expected to operate.

This study has sought to develop a systematic approach to evaluating the acoustical properties of the PASS device with a goal of improving the device, its use within fire fighter PPE, and training to improve overall use of PASS. The study identified a well-developed framework for the use of sonar technology for detection and localization in the ocean environment and adapted it to the fireground environment. The sonar formalism is based upon recognition that the ability to detect and localize an acoustic signal depends on the signal characteristics of the source, the presence of confounding sounds in the environment, distortion of the signal during transmission in the environment, and the characteristics of the listener. Interestingly, this fundamental acoustics approach had not been used in prior characterization and evolution of PASS. A major contribution of this work has been adapting the sonar framework to fireground acoustics to better organize existing work and provide a roadmap for future work.

For this study, we used three fundamentally different types of research activities to exercise the sonar equation formalism and examine the use of PASS. These research activities were physical acoustics testing, audiology lab testing, and field testing with fire service partners.

Physical Acoustics

This component of the project measured the acoustical properties of a variety of firefighting equipment. The frequency dependent sound pressure level (SPL) was measured in a directional manner. These SPL values were compared with the PASS SPL and were often found to be larger than PASS SPL. For particular sources (including the PASS device) there were directions with significantly lower SPL due to shadowing effects, which is recognized as an important detail for training fire fighters.

Sound transmission and distortion were measured and simulated for the high temperature conditions typically found in structure fires. Results indicate the room acoustical modes changed as the fire evolved. Particular frequencies in the PASS spectrum were significantly attenuated with the temperature evolution in the structure. Knowledge of the acoustic distortion could have implications for development of machine based PASS detection technologies.

Sound transmission was measured using an acoustic mannequin (KEMAR) wearing standard types of fire fighter PPE. A 3 decibel drop was measured for conditions in which the mannequin had a hood and helmet, and included a cross-section review of the basic equipment designs. A metric was developed to evaluate the effect of helmets on distortion of the incident spatial pattern of the acoustic signal. There was a wide range in the extent of distortion associated with different helmet types relative to the bare mannequin head case.

Physical acoustics measurements were also made on the building materials (e.g., gypsum board) as a function of thermal degradation, as might occur as a result of a fire. No significant changes were found in the acoustic properties.

Audiology Testing

Human subject testing was conducted in laboratory conditions. In these tests, normal-hearing subjects listened to sounds while being either bare headed or wearing fire fighter PPE (i.e., jacket, hood, and helmet). The human subject testing showed that the detection threshold increased by approximately 7 dB when the subjects were wearing the fire fighter PPE.

Field Testing with Fire Service Partners

Field tests were conducted to evaluate the effects of external noise on the time to detect and localize the PASS signal. These tests were conducted with three fire service partner organizations (Austin Fire Department, Oklahoma City Fire Department, and Glendale Fire Department).

Four separate testing configurations were conducted. The tests were conducted in three different types of structures (small office layout, large office layout, warehouse layout). The tests found a crawling speed during the quiet search evolutions of approximately 1 foot/second. The tests showed that the presence of noise not only increased the average amount of time required to find the PASS signal, but also increased the standard deviation in this time. This suggests that a simple multiplicative factor cannot be used to estimate the time to find a PASS signal under noisy conditions, but must include the possibility of significantly different hearing acuity of the particular fire fighters engaged in the search.

FOREWORD

Fire fighters are often exposed to hostile environments of heat and smoke, and this includes the possibility of becoming disoriented or trapped in a structure. When this occurs, it is crucial that there is a reliable means to alert other fire ground personnel to their need for assistance.

Personal Alert Safety System (PASS) devices are used by fire fighters to alert aid using audible signal technology, and the operate by emitting an alarm signal if the lack of motion exceeds a specific time period. However, despite its widespread use throughout the fire service and on-going enhancements in recent years, certain problems still exist with audible PASS technology such as the use of multiple different PASS alarms being used in the field. This project is directly applicable to the requirements addressed by NFPA 1982, *Standard on Personal Alert Safety Systems (PASS)*.

This project seeks to establish a scientific basis for a single PASS alarm signal for use throughout the U.S fire service, and additionally address possible technological enhancements such as receiver enhancements and addressable non-audible frequencies. The goal of this project is to improve the safety of distressed firefighters engaged in structural firefighting operations and to aid in rescue activities, by establishing a credible and scientific basis for determining the optimum PASS signal performance characteristics and to evaluate technological enhancements for this technology.

The research program has been conducted under the auspices of the Fire Protection Research Foundation with guidance from a Project Technical Panel, and in collaboration with the University of Texas – Austin. Project deliverables addressed in this report include a detailed literature search, digital portfolio of fire ground noise, analysis of existing PASS alarm sounds, models of sound transmissions applicable to PASS, evaluation of fire fighter response to PASS signals, recommendations for an optimum PASS signal, and recommendations for practical and readily implemented alternative technologies.

The Fire Protection Research Foundation expresses gratitude to members of the project Technical Panel for their guidance throughout the project, and all others who contributed to this research effort. Special thanks are expressed to the U.S. Department of Homeland Security (AFG Fire Prevention & Safety Grants) for funding this project.

The content, opinions and conclusions contained in this report are solely those of the authors.

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1. Introduction

When firefighters are overcome by the heat or smoke of a fire and become disoriented or trapped in a structure, it is crucial that there is a reliable means to alert other fire ground personnel to their need for assistance. Personal Alert Safety System (PASS) devices are designed to alert aid using audible signal technology. Normal operation is for the PASS devices to activate a 95-decibel multiple-frequency alarm signal if the lack of motion exceeds a specific time period.

However, despite its widespread use throughout the fire service and on-going enhancements in recent years, certain problems still exist with audible PASS technology. Foremost among these problems is that nationally recognized standards currently allow a range of performance for the PASS alarm signal, and this has resulted in multiple different PASS alarms being used in the field.

This project seeks to establish a scientific basis for a single PASS alarm signal for use throughout the U.S fire service, and additionally address possible technological enhancements such as receiver enhancements and addressable non-audible frequencies.

The goal of this project is to improve the safety of distressed firefighters engaged in structural firefighting operations and to aid in rescue activities, by establishing a credible and scientific basis for determining the optimum PASS signal performance characteristics and to evaluate technological enhancements for this technology. The specific objectives for meeting this goal are to:

a) Provide science-based guidance to PASS device manufacturers, firefighters, researchers, and standards developing organizations for the optimization of PASS alarm sounds;

b) Investigate the feasibility of technological enhancements to PASS devices that can be implemented within five years; and

c) Produce a methodology by which to optimize audible alarms that can be applied to a wide range of research areas.

This project is directly applicable to the requirements addressed by NFPA 1982, *Standard on Personal Alert Safety Systems (PASS)*. This project is also applicable to NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program*.

The research program has been conducted under the auspices of the Fire Protection Research Foundation with guidance from a Project Technical Panel, and in collaboration with the University of Texas – Austin. Project deliverables addressed in this report include a detailed literature search, digital portfolio of fire ground noise, analysis of existing PASS alarm sounds, models of sound transmissions applicable to PASS, evaluation of fire fighter response to PASS signals, recommendations for an optimum PASS signal, and recommendations for practical and readily implemented alternative technologies.

2. Literature Review

2.1 Introduction

When firefighters are overcome by the heat or smoke of a fire and become disoriented or trapped in a structure, it is crucial that there is a reliable means to alert other fire ground personnel to their need for assistance. Personal Alert Safety System (PASS) devices are designed to alert aid using audible signal technology. Normal operation is for the PASS devices to activate a 95-decibel multiple-frequency alarm signal if the lack of motion exceeds a specific time period.

However, despite its widespread use throughout the fire service and on-going enhancements in recent years, certain problems still exist with audible PASS technology. Foremost among these problems is that nationally recognized standards currently allow a range of performance for the PASS alarm signal, and this has resulted in multiple different PASS alarms being used in the field. This project seeks to establish a scientific basis for a single PASS alarm signal for use throughout the U.S fire service, and additionally address possible technological enhancements such as receiver enhancements and addressable non-audible frequencies.

2.1.1 Definition of PASS

The acronym PASS stands for Personal Alert Safety System. PASS is defined as “A device that continually senses for lack of movement of the wearer and automatically activates the alarm signal, indicating the wearer is in need of assistance; can also be manually activated to trigger the alarm signal” (NFPA 1982, section 3.3.14, 2013).

Traditional PASS devices function through the use of audible notification signals. In the field, PASS can be a stand-alone device worn on part of a firefighter’s protective clothing, or it can be integrated with several items of protective clothing or equipment. PASS devices are often integrated with SCBA (self-contained breathing apparatus), though this is not a requirement (Teele 2008).

2.1.2 Inherent Dangers of Fire Fighting

Firefighting is a dangerous profession. In 2012, U.S. fire departments responded to an estimated 1,375,000 fires. These reported fires caused 2,855 civilian deaths, 16,500 civilian injuries, $12.4 billion in direct property damage, 64 on-duty firefighter fatalities, and 69,400 on-duty firefighter injuries (Michael J. Karter, Fire Loss in the United States During 2012, 2013) (Fahy, LeBlanc and Molis 2014) (Michael J. Karter and Molis, Firefighter Injuries in the United States, 2014). In calculations of the total cost of fire, these losses translate into a combined total of $329 billion in 2011 (John R. Hall 2014).

Based on 2012 data compiled in an NFPA profile report of the U.S. fire service, there are 30,100 fire departments in the U.S. with roughly 1.13 million firefighters. Just under three-fourths (69%) of the 1.13 million firefighters are volunteers, and most of those are in departments that protect fewer than 25,000 and more than half are located in small, rural departments that protect fewer than 2,500 people. Only 8.7 percent (or one in 12) fire departments are all-career, but 49 percent (or about 5 of every 10) U.S. residents are protected by such a department. Approximately 60 percent of fire departments also handle emergency medical service (EMS) activities (Michael J. Karter, Fire Loss in the United States During 2012, 2013).

2.1.3 Audible PASS Technology Usage

PASS is widely used within the fire service, but not all firefighters are equipped with PASS. An estimated half (48%) of fire departments do not have enough PASS devices to equip all emergency responders on a shift (U.S. Fire Administration 2006). These numbers indicate on one hand the widespread usage of this technology, and on the other hand the potential for many firefighters to still receive this technology.

For communities with populations of 50,000 or more, at most 5% of departments have insufficient PASS devices to equip all emergency responders on a shift. This rises to one in five for communities with 10,000 to 24,999 population, one-third for communities with 5,000 to 9,999 population, over half for communities with 2,500 to 4,999 population, and three-fifths in the departments protecting communities with less than 2,500 population.

Today in the U.S. marketplace there are approximately a dozen manufacturers of audible PASS devices for firefighters. Some of these units are stand alone, but others are integrated into other firefighting personal protective equipment. It is relatively common for audible PASS devices to be integrated with SCBA (NIST 2011).

2.2 Background on PASS Technology Experience

2.2.1 Need for Enhanced PASS Technology

In lieu of more sophisticated location/tracking systems that are currently under development but not yet reliable enough for mandated use within the fire service, PASS devices are the only equipment required by NFPA 1500 to aid in locating and rescuing downed firefighters (NFPA 2013). There are questions about whether the frequencies and sound pressure levels of current PASS device alarms meet their intended purpose and if they can be improved:

- Can the alarm be clearly heard over ambient fire ground noise and when firefighters are wearing their full turnout ensemble, including hoods and breathing apparatus?
- Is the content of the alarm signal optimized for localizing the source (locating the firefighter in distress) as expediently as possible?
- Is the alarm capable of penetrating complex structure geometries to provide a useful signal at the distances necessary for standard firefighting operations?
- Given the characteristics of the piezoelectric sound emitters currently used in PASS devices, is it possible to enhance the ability of firefighters to hear/identify specific frequencies?

No rigorous research has been done to determine optimal PASS alarm characteristics and the development of reliable location/tracking systems for the fire service is still many years away. If the proposed research is conducted and improvements in PASS alarm signals implemented, the impact on the safety of firefighters will be significant.

This project will have a short and long term positive impact on improving fire fighter safety. PASS is a mainstream safety device and improvement in its operability is beneficial to the many fire fighters that use this technology. The establishment of a scientifically based optimum audible signal will directly benefit fire fighters by better enabling immediate rescue and by minimizing hearing impairments. This project is innovative because it uses a well-established scientific basis to definitively clarify the optimum PASS audible signal.

This project directly responds to the issue of “PASS Failure Analysis”, which was a top priority research topic from the “National Fire Service Research Agenda Symposium” hosted by the National Fallen Firefighters Foundation in 2005 and in 2011, the issue of “Determination of Optimal Personal Alert Safety Systems (PASS) Alarm Sound Frequencies and Patterns” has also been raised for further study. This established a recognized agenda for the nation’s fire service for the development of fire fighter safety projects, and research as proposed herein has not been yet occurred to address this issue.

2.2.2 Case Study Events Involving PASS Devices

The literature is full of multiple examples of real-world situations were audible PASS technology was directly involved. One source of these examples can be found on an interactive web portal called “FireFighterNearMiss.com” (2011). Although not providing data in a manner that readily allows comprehensive data analysis, the case studies provided are informative and establish a higher level understanding of the dangers faced regularly by firefighters. A search of the “FireFighterNearMiss.com” database for incidents involving PASS reveals 160 events involving the activation of the PASS audible signal and its relation to a “near miss” event (2011).

During this most recent decade the NIOSH Firefighter Fatality Investigation and Prevention Program has actively been investigating and reporting on pertinent firefighter line-of-duty-deaths (LODDs). Aside from the saves credited to audible PASS technology, their reports have also provided clarity of actual events where PASS has not operated as expected. A review of several of these fire investigation reports exemplifies that audible PASS technology is not perfect, and on-going efforts are required for continued improvements and enhancements.

Further, these incidents symbolize the extremely dangerous environments faced regularly by firefighters, and when a situation turns bad the need to locate a downed firefighter must be immediate. Several exemplary incidents are offered as real-world examples and are summarized in Table 2.2, Selected Fire Events Involving PASS.

The information in Table 2.2 is based on information extracted from reports summarized through the NIOSH Fire Fighter Fatality Investigation and Prevention Program. It illustrates the diversity of fire ground incidents involving structural firefighting where PASS technology has a role. These events occur regularly in a wide range of geographic locations and with a spectrum of fire ground conditions.

The purpose of this summary is to demonstrate the seriousness of the situations where PASS technology is needed as well as the diversity of these events. The incidents cited here are based on NIOSH reports on fire fighter line of duty deaths or near death events, and are the most serious applicable events. This should not be misinterpreted as being statistically representative of the overall functionality of PASS technology, which is a well-established and has a high effectiveness rate.

Table 2.2: Selected Fire Events involving PASS (NIOSH/CDC 2014)

Date	Location	Description	NIOSH Report
Apr 2013	Maryland	Volunteer Fire Fighter Found Unresponsive With His Facepiece Off Dies Eight Days Later	F2013-13
Feb 2013	Texas	Two Career Lieutenants Killed and Two Career Fire Fighters Injured Following a Flashover at an Assembly Hall Fire	F2013-04
Jan 2013	New York	Volunteer Captain Dies After Floor Collapse Traps Him in Basement	F2013-02
Nov 2012	Illinois	Career Captain Sustains Injuries at a 2-1/2 Story Apartment Fire then Dies at Hospital	F2012-28
Sep 2012	Texas	Captain Dies from Hyperthermia and Exertional Heatstroke While Performing Advanced Survival Training	F2012-27
July 2012	Virginia	Volunteer Fire Fighter Dies After Being Ejected From Front Seat of Engine	F2012-23
Apr 2012	Pennsylvania	Career Lieutenant and Fire Fighter Killed and Two Fire Fighters Injured by Wall Collapse at a Large Commercial Structure Fire	F2012-13
Mar 2012	Wisconsin	Volunteer Lieutenant Killed and Two Fire Fighters Injured Following Bowstring Roof Collapse at Theatre Fire	F2012-08
Jan 2012	Hawaii	Fire Apparatus Operator Suffers Sudden Cardiac Death During Physical Fitness Training	F2012-03
Dec 2011	Massachusetts	Career Fire Fighter Dies during Fire-Fighting Operations at a Multi-family Residential Structure Fire	F2011-31
Dec 2011	Massachusetts	Career Fire Fighter Dies and Another is Injured Following Structure Collapse at a Triple Decker Residential Fire	F2011-30
June 2011	California	Career Lieutenant and Fire Fighter/Paramedic Die in a Hillside Residential House Fire	F2011-13
Feb 2011	California	Career Fire Fighter/Paramedic Dies from Injuries Following an Unexpected Ceiling Collapse	F2011-05
May 2010	Kansas	Career fire fighter dies while conducting a search in a residential house fire	F2010-13
Apr 2009	Texas	Career probationary fire fighter and captain die as a result of rapid fire progression in a wind-driven residential structure fire	F2009-11
Mar 2008	Pennsylvania	Volunteer fire lieutenant killed while fighting a basement fire	F2008-08
Mar 2008	North Carolina	Two career fire fighters die and captain is burned when trapped during fire suppression operations at a millwork facility	F2008-07
Aug 2007	Texas	A volunteer mutual aid captain and fire fighter die in a remodeled residential structure fire	F2007-29
Apr 2007	Virginia	Career fire fighter dies in wind driven residential structure fire	F2007-12
Oct 2006	Maryland	Career fire fighter dies in residential row house structure fire	F2006-28
Aug 2006	New York	Floor collapse at commercial structure fire claims the lives of one career lieutenant and one career fire fighter	F2006-27
May 2006	Colorado	Career Lieutenant dies in residential structure fire	F2006-19
Feb 2005	Texas	Career fire captain dies when trapped by partial roof collapse in a vacant house fire	F2005-09
Jan 2005	Michigan	Career captain dies after running out of air at a residential structure fire	F2005-05
Dec 2004	Texas	One probationary career firefighter dies and four career firefighters are injured at a two - alarm residential structure fire	F2005-02
Dec 2003	New York	Career fire fighter dies of carbon monoxide poisoning after becoming lost while searching for the seat of a fire in warehouse	F2004-04

May 2002	Missouri	Two career fire fighters die in four-alarm fire at two-story brick structure	F2002-20
Jun 2001	New York	Hardware store explosion claims the lives of three career fire fighters	F2001-23
Feb 2000	Texas	Restaurant fire claims the life of two career fire fighters	F2000-13
Dec 1999	Iowa	Structure fire claims the lives of three career fire fighters and three children	F2000-04
Dec 1998	Georgia	Roof collapse in arson church fire claims the life of volunteer fire fighter	99-F04
Aug 1998	Mississippi	Commercial building fire claims the lives of two volunteer fire fighters	98-F21
Feb 1998	Ohio	Single-family dwelling fire claims the lives of two volunteer fire fighters	98-F06
Feb 1997	Kentucky	Floor collapse in a single family dwelling fire claims the life of one fire fighter and injures another	97-04
Mar 1996	Virginia	Sudden roof collapse of a burning auto parts store claims the lives of two fire fighters	96-17

2.3 Literature Review

Data and information related to the scope of this project has been collected from the literature in support of this study. This is described in greater detail in the following sections and has been categorized into the following five basic groups:

I. Nationally Recognized Consensus Standards
II. Fire Fighter Hearing And Response Characteristics
III. Fireground Environment
IV. Audio-Based Pass Technology
V. Alternative Locator/Tracking Technology

2.3.1 Nationally Recognized Consensus Standards

Today, PASS is addressed in detail by NFPA 1982, Standard on Personal Alert Safety Systems (PASS). This nationally recognized consensus standard specifies the minimum requirements for the design, performance, testing, and certification for Personal Alert Safety Systems (PASS) for emergency services personnel, including (but not limited to) stand-alone PASS and integrated PASS.

At this time, the latest available edition of NFPA 1982 is the 2013 edition. The document is presently in the F2017 revision cycle, and is scheduled to generate a new edition in 2018, depending on the adjudication of any controversial revisions. The following are the dates of issuance of each of the editions of NFPA 1982: 1st in 1983; 2nd in 1988; 3rd in 1993; 4th in 1998; 5th in 2007, and 6th in 2013, and 7th tentative in 2018.

Section 7.1 of NFPA 1982 (2013 edition) provides the specific parameters to which the PASS audible pre-alarm signal and PASS Alarm signal is required to perform. For example, this requires that the alarm signal shall have a sound pressure level not less than 95 dBA at 3 m for an uninterrupted duration of not less than 1 hour. Further, the alarm signal shall consist of three primary frequencies, Type 1 Chirp shall begin with a frequency of 4.000 kHz ± 0.02 kHz and shall sweep to a frequency of 2.000 kHz ± 0.01 kHz; Type 2 Chirp starts at a lower frequency of 2.0 kHz ± 0.1 kHz to an upper frequency of 4.0 kHz ± 0.1 kHz; The Type-3 chirp shall begin with a frequency of 2.000 kHz ± 0.01 kHz and shall sweep to a frequency of 4.000KHz ± 0.02 kHz; and shall have these frequencies sounded sequentially rather than simultaneously.

These operational requirements provide latitude for the actual signal, resulting in different audible signals depending on the PASS device manufacturer (NFPA 1982, section 6.4.3.9, 2013).

The requirements of section 7.1 of NFPA 1982 (2013 edition) are central to this research study. As such, these requirements are summarized here, for convenience, in Table 3.1(a), Basic PASS Signal Requirements from NFPA 1982, 2013 Edition.

Table 3.1(a): Basic PASS Signal Requirements from NFPA 1982, 2013 Edition

7.1 Sound Pressure Levels.

7.1.1 PASS Pre-Alarm Signal.

7.1.1.1 PASS shall be tested for the sound pressure level of the audible primary pre-alarm signal as specified in Section 8.2, Sound Pressure Level Tests. The sound pressure level of the Type 1 tone pair shall be between 80 dBA and 95 dBA. The sound pressure level of the Type 2 tone pair shall be between 86 dBA and 104 dBA and shall be at least 6 dB greater than the Type 1 tone pair. The sound pressure level of the Type 3 tone pair shall be between 100 dBA and 110 dBA and shall be at least 6 dB greater than the Type 2 tone pair.

7.1.1.2* PASS shall be tested for primary pre-alarm signal frequency as specified in Section 8.14, Signal Frequency Test, shall have at least an audible signal, and shall have the primary pre-alarm as specified in 6.4.2.8.

7.1.2 PASS Alarm Signal.

7.1.2.1 PASS shall be tested for the sound pressure level of the alarm signal as specified in Section 8.2, Sound Pressure Level Tests, and shall not have the alarm signal, once activated, be deactivated by the motion detector; shall have the alarm signal sound pressure level not be less than 95 dBA for an uninterrupted duration of not less than 1 hour, and shall have PASS function properly as specified in 6.4.3.

7.1.2.2 PASS shall be tested for frequency content as specified in Section 8.14 and shall have the alarm signal as specified in 6.4.3.9.

The key parameters included in these requirements, and how they have changed with the evolution of NFPA 1982, are summarized in Table 3.1(b), Evolution of Basic PASS Signal Requirements in NFPA 1982.

Table 3.1(b): Evolution of Basic PASS Signal Requirements in NFPA 1982

Document Edition:		1983	1988	1993	1998	2007	2013
Document Section:		2.3	3.3	3.3 & 4.1	5.1	7.1	7.1 & 6.4
Pre-Alarm	Activation Sound Pressure Level		70 dBA to 85 dBA	70 dBA to 85 dBA	60 dBA to 95 dBA	80 dBA to 95 dBA	80 dBA to 95 dBA
	Activation Sound Duration		0 sec	0 sec	0 sec	0 sec	0 sec
	Initial Sound Pressure Level				> 100 dBA	100 dBA to 110 dBA	86 dBA to 104 dBA
	Initial Sound Duration				@ 6-10 sec	@ 6-10 sec	0 sec
	Operating Sound Pressure Level	30-50% of alarm dBA	70 dBA to 85 dBA	70 dBA to 85 dBA	> 100 dBA	100 dBA to 110 dBA	100 dBA to 110 dBA
	Operating Sound Duration	Total 4-10 sec	Total 7 -15 sec	Total 7 -10 sec	additional 3 – 5 sec, @ max 13 sec	additional 3 – 5 sec, @ max 13 sec	Total 10 sec +3/−0 sec
	# of Frequencies				2 minimum	2 minimum	
	Frequency Range		> 1000 Hz & < 4000 Hz	> 1000 Hz & < 4000 Hz	> 1000 Hz & < 4000 Hz	> 1000 Hz & < 4000 Hz	> 1000 Hz & < 4000 Hz
Alarm	Pressure Level	> 95 dBA	> 95 dBA	> 95 dBA	> 95 dBA	> 95 dBA	> 95 dBA
	Duration	1 hour	1 hour	1 hour	1 hour	1 hour	1 hour
	# of Frequencies	3 minimum	3 minimum	3 minimum	3 minimum	3 minimum	3
	Frequency Range	> 1000 Hz & < 4000 Hz	> 1000 Hz & < 4000 Hz	> 1000 Hz & < 4000 Hz	> 1000 Hz & < 4000 Hz	1 @ 500 Hz ±20 Hz; 2 @ > 1000 Hz & < 4000 Hz	1 @4.000 kHz ± 0.02 - 2.000 kHz ± 0.01 kHz; 2@2.0 kHz ± 0.1 kHz - 4.0 kHz ± 0.1 kHz; 3@2.000 kHz ± 0.01 kHz - 4.000KHz ± 0.02 kHz

The revision-cycle documentation for each of the five editions of NFPA 1982 in Table 3.1(b) illustrates the extensive debate and consideration given by the fire service technical community to the on-going evolution of these requirements. However, the initial scientific basis for these requirements is not obvious in the literature, and much of the evolving enhancements appear to be based on extensive empirical field experience. This has served the implementation of this technology well and addressed noteworthy milestone issues, such as the automatic activation of all PASS alarms, the integration of PASS alarms with SCBA equipment, and a test method to assure proper operation in high temperature environments.

Twenty-seven NFPA standards are adopted by the U.S. Department of Homeland Security and are designated as DHS National Standards. Of the NFPA standards addressing PPE, this includes the 2007 edition of NFPA 1982, *Standard on Personal Alert Safety Systems (PASS)*. In the last several years the federal government has significantly leveraged compliance with these documents by requiring their consideration as a prerequisite for Fire Grant funding sought by fire departments for supplemental equipment and personnel (U.S. DHS 2014).

Additional applicable reports, articles and other information in the literature from the perspective of standards, regulations and policy, include the following:

- "Memorandum of Understanding (MOU) between the National Institute for Occupational Safety and Health (NIOSH) National Personal Protective Technology Laboratory (NPPTL), Fire Fighter Fatality Investigation and Prevention Program (FFFIPP) and the National Fire Protection Association (NFPA), Fire Protection Research Foundation (FPRF)," FPRF, Quincy MA, 20/Sep/2010.
- NFPA 1500, Standard on Fire Department Occupational Safety and Health Program, NFPA, Quincy MA, 2013
- NFPA 1982, *Standard on Personal Alert Safety Systems (PASS) for Fire Fighters*, NFPA, Quincy MA, 1983
- NFPA 1982, *Standard on Personal Alert Safety Systems (PASS) for Fire Fighters*, NFPA, Quincy MA, 1988
- NFPA 1982, *Standard on Personal Alert Safety Systems (PASS) for Fire Fighters*, NFPA, Quincy MA, 1993
- NFPA 1982, *Standard on Personal Alert Safety Systems (PASS)*, NFPA, Quincy MA, 1998
- NFPA 1982, *Standard on Personal Alert Safety Systems (PASS),* NFPA, Quincy MA, 2007
- NFPA 1982, *Standard on Personal Alert Safety Systems (PASS*), NFPA, Quincy MA, 2013
- "Report of the National Fire Service Research Agenda Symposium", National Fallen Firefighters Foundation, Emmitsburg MD, 1-3/Jun/2005, Website: www.fire.nist.gov/bfrlpubs/fire08/art035.html, cited: 14/Jan/2011, pg. 31
- "Report of the 2nd National Fire Service Research Agenda Symposium", National Fallen Firefighters Foundation, Emmitsburg, MD, 20-22 May 2011, cited: 31 July 2014
- U.S. DHS, "Science & Technology Standards", U.S. Department of Homeland Security, Washington DC, website: http://www.dhs.gov/standards, cited; 31 July 2014

2.3.2 Fire Fighter Hearing and Response Characteristics

An appreciable body of work can be found that generally addresses human perception and response to alarm sounds. Often, these studies attempt to determine the optimal tones for alarm notification for various populations.

In general, the literature in this area does not address the complexity of sound transmission and perception in the fire ground where the listeners are bunkered in protective gear. For example, one particular study discusses alarm signals most effective in notifying sleeping populations, and as such this is only indirectly related to PASS audibility on the fireground (Bruck et al. 2006).

Some of these reports address how individuals react to alarms. As an example with other populations, one study found that signals most able to communicate a sense of urgency have a fundamental frequency of 800 Hz with harmonics of 1600, 2400, 3200 and 4000 Hz (Edworthy 1998). Another study provides guidelines for good alarm sounds and suggests that the richness of the harmonic content of the tone is a requirement for a go alarm sound (Edworthy and Hellier 2000).

Additional applicable reports, articles and other information in the literature from the perspective of fire fighter hearing and response characteristics include the following:

- Adams, D.R., “Distress Alert Signals From Personal Alert Safety Systems Devices Do Not Trigger Physiological Responses”, USFA EFO Paper, Aug 2001
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2.3.5 Alternative Locator/Tracking Technology

In the last several years there has been considerable effort to enable advanced firefighter locator technology. Despite using comparative concepts and addressing similar purpose, advanced locator technology has some important distinctions from traditional audible PASS technology. For example, audible PASS technology is currently in widespread use as a simple, technologically mature, and relatively dependable last-resort mechanism for locating firefighters needing immediate assistance.

Advanced locator technology is in its infancy and has yet to overcome significant technological hurdles that are preventing its field application. In the meantime, existing PASS technology is the established backbone of locating firefighters needing immediate rescue. If and when advanced locator technology overcomes its technological challenges, the established use of audible PASS devices is not expected to be replaced but rather supplemented.

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2.4 Review of Building Construction and Fire Ground Audibility

Technical issues involving audibility on the fire ground are directly related to the materials of construction and furnishing that are found in these settings. Complicating our understanding of fire ground conditions is that the unwanted fires of yesterday are not the same as today. The fire ground environment is a relatively diverse in terms of materials, geometries, configurations, quantities, etc, but nevertheless, certain baseline characteristics are available that help clarify technical issues relating to fire ground audibility.

2.4.1 Evolution of Fire Ground Hazards

An important consideration of interest is the evolving nature of today’s environments typically encountered by fire fighters. In recent decades there has been a noteworthy shift in the environments encountered by structural fire fighters. For example, a recent study on the structural stability of engineered lumber in fire conditions indicates the modern fire environment has changed, with shorter time to flashover and faster fire propagation (UL 2008).

Experienced fire fighters often indicate that today’s fires are different from what they were fighting three or four decades ago. Structure fires involving modern building construction and furnishings produce significantly higher heat release rates than legacy buildings and their furnishings of earlier years, exposing firefighters to more rapid heat development and intense thermal conditions (NFPA, SCBA Facepiece Lenses may undergo thermal degradation when exposed to intense heat, 2012).

On-going research has confirmed this observation, such as a recent study on Fire Behavior in Legacy and Contemporary Residential Construction (Kerber 2010). Among its important findings, this study provides a side-by-side comparison demonstration between two similar room fires using effectively the same fuel load but different furnishings: one room with modern furnishings and another with legacy furnishings (approximate 40 year-old vintage). Ignited at the same time the modern room reaches flashover in 3 and ½ minutes, while the legacy room takes 29 and ½ minutes.

The impact on faster, more-powerful fires on fire ground tactics and strategy is meaningful. Fire fighters are being faced with shorter escape times, and shorter time to collapse with certain construction types such as engineered lumber. Further exacerbating the challenging fire environment are changes in how fire fighters are protected. Today's better equipment is allowing fire fighters to be exposed to greater hazards for longer periods of time. The Personal Protective Equipment (PPE) used by today's fire fighters has evolved to provide enhanced overall thermal protection with fire fighters remaining in adverse conditions for longer time periods, and they are less likely to be able to detect changing thermal conditions.

In summary, structure fires involving modern building construction and furnishings produce significantly higher heat release rates than legacy buildings and their furnishings of earlier years. These faster more intense fires are exposing fire fighters to more rapid heat development and intense thermal conditions. This should be a consideration when addressing the performance characteristics of PASS alarm signals.

2.4.2 Materials of Construction

The perspective of materials involved on an unwanted building fire generally fall into two basic groupings: building construction, and interior finish and furnishings. The materials used in building construction are the components necessary for structural integrity, compartmentation, and other functional building purposes. Interior finish and furnishings involve the transitory materials that are independent of the structure and building construction, such as carpeting, furniture, and other contents. Both are important, and both can considerably contribute to the fuel load of an unwanted fire.

A building is defined as a structure, usually enclosed by walls and a roof, constructed to provide support or shelter for an intended occupancy (ASCE/SEI 7, 2010). Each portion of a building that is separated from other portions by a fire wall is considered to be a separate building (NFPA 5000, *Section A-3.3.69,* 2012).

Building construction methodology is often different in each country and is dependent on certain influencing factors such as weather, seasonal conditions, seismic activity, societal culture, etc. Classifications have evolved based on the materials used for structural elements and the degree of fire resistance these elements offer. In the United States, construction is generally classified according to the following sub-types: (Willse, Fire Protection Handbook, 2008)

- Type I, formerly referred to as fire-resistive construction;
- Type II, formerly referred to as noncombustible construction;
- Type III, formerly referred to as exterior protected combustible or ordinary construction;
- Type IV, formerly referred to as heavy-timber construction; and
- Type V, formerly referred to as wood-frame construction.

The model building code community in the United States has evolved recognizing that the building components are either noncombustible or combustible. They address the key types of building components, as well as other supporting features such as interior partitions, exterior walls, floor/ceiling assemblies, roof framing systems and coverings, vapor barriers, and other building features (NFPA 220

2012). The three key types of building components are based on fire resistance of the basic elements of a building and are: (Modern Construction Considerations for Company Operations 2010)

- Exterior wall;
- Primary structural frame; and
- Floor.

2.4.3 Interior Finish and Furnishings

The interior finish of a building is considered to be the exposed surfaces of walls, ceilings, and floors within buildings (NFPA 101®, Section 3.3.92, 2012). Interior finish is not intended to apply to concealed surfaces within spaces, such as those that are inaccessible (NFPA 5000, Section A-3.3.221.2, 2012). The materials and assemblies that form the exposed interior surfaces of a building, that is, the walls, ceilings, floors, and certain other fixed surfaces, are considered interior finish.

Specific examples of interior finishes other than simply walls, ceilings and floors are the interior finish of columns, fixed or movable walls, fixed partitions, and movable partitions. Some examples of the materials used for interior finish include wood, plaster, wallboard, ceramic tiles, acoustical tile, wall and ceiling coverings, plastics, and insulating materials (Hirschler, Fire Protection Handbook, 2008). Interior finish is most likely to represent the majority of the internal building surfaces encountered by structural fire fighters. Thus these materials and assemblies are particularly important when considering the interaction with the PASS alarm signal used by fire fighters within a structure.

The term “furnishings” is sometimes used interchangeably with “contents”. Furnishings are considered any movable objects in a building that normally are secured or otherwise put in place for functional reasons, excluding (1) parts of the internal structure of the building, and (2) any items meeting the definition of interior finish (NFPA 101®, Section 3.3.50, 2012). Thus, furnishings do not include materials or assemblies that in some cases might be secured in place for functional reasons, which would instead be considered interior finish.

All of these materials used for interior finish and furnishings have unique characteristics that directly affect the acoustical properties within that space, and consequently, the functionality of a fire fighter’s PASS alarm signal. Ultimately, the performance of a PASS signal depends on multiple factors. Some of these factors are directly related to the acoustical challenges of the environment being protected, separate and apart from other factors such as the electronics of the communications system itself.

A useful parallel for this discussion are built-in building communication systems that are designed to transmit some manner of communications with the buildings occupants. Examples are public address systems or fire alarm systems. They often are focused on the transmission of voice messages, and thus focus on addressing the performance characteristics of both audibility and speech intelligibility.

In such built-in building communication systems, both audibility and speech intelligibility are necessary to provide proper instructions to the occupants of a building. Audibility is a key performance characteristic with any acoustic signal. It is generally measured in A-weighted decibels (dBA) and is defined as the state or quality of being perceptible by the human ear (Grant, Intelligibility of Fire Alarm and Emergency Communication Systems, 2008).

Speech intelligibility is a performance characteristic important for voice communications, and is the state or quality of being understood by a human, and more specifically, as the percentage of speech units understood by a listener in a communications system. Speech intelligibility is not a physical quantity like feet, meters, Volts, Amperes, or decibels, but instead is a benchmark of the degree to which we understand spoken language (Jacob and Tyson, SUPDET 2008, 2008).

From the perspective of the interior finish and furnishing of a building, the factors that relate to a listener transmission path can generally be grouped into three general areas: signal--to-noise ratio; decay; and distortion. (Jacob, presentation at NFPA WSCE in Anaheim CA, 2001) These are illustrated in Fig. 4.3, Factors Related to a Listeners Transmission Path.

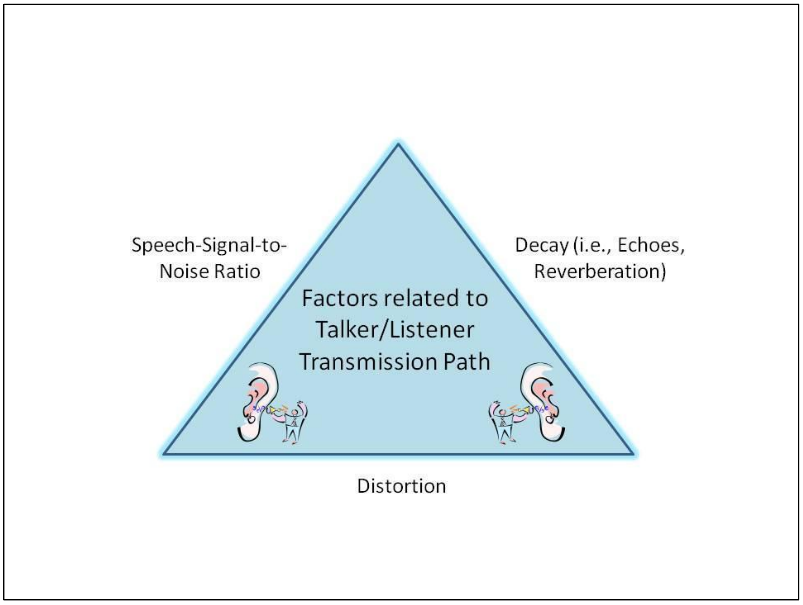

Fig. 4.3, Factors Related to a Listeners Transmission Path

The signal-to-noise ratio is the effect of masking or obscuring the audible signal due to noise. Humans can tolerate significant background noise, unlike artificial systems. Distortion is a form of noise that masks the original signal resulting from electrical or electro-acoustical components in the transmission system. Finally, and perhaps most important in relation to PASS alarm signals, decay includes sound reflections, such as echoes or reverberations. This is magnified by hard surface interior finish materials that have reflective qualities (Watkins, The British Society of Audiology, 2004).

In summary, the materials of construction and materials and assemblies used for interior finish and furnishings all have unique features that contribute to the complex transmission of the acoustic signal. Of particular interest are the materials and assemblies used for interior finish because they most likely represent a majority of the interior surfaces, and consequently are most likely to be interacting with the PASS alarm signal used by fire fighters within a structure.

This discussion of interior finish and furnishing is based on normal conditions prior to experiencing a fire requiring the operations of structural fire fighters. Obviously, physical conditions can change significantly during an unwanted fire and involve appreciable changes in temperature and pressure, as well as introducing significant other factors into the fire ground environment such as products of combustion and moisture from firefighting hoses. These can all have significant effect on certain acoustical properties of the materials of construction, and materials and assemblies used for interior finish and furnishings.

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3. Sonar Equation Formalism

3.1 Introduction

The PASS system can be described as a passive sonar problem. In a passive sonar problem, there is a receiver whose job is to detect, identify, and localize the target signal in the midst of noise signal deterioration. This maps directly to the PASS system, as it is the searching firefighter’s job to detect, identify, and localize the target signal. To fully understand and optimize the process, the source signal, background noise, transmission loss through the medium, and receiver need to be understood. This information is used in the sonar equation

$$DT=SL+DI-TL-NL \qquad \text{Eq. 3.1}$$

where DT is the detection threshold of the receiver; DI is the directivity index of the source; SL is the source level; TL is the transmission loss through the medium; and NL is the background noise level.

Different aspects of underwater sonar map to these terms. The DT and the DI are based on the sensitivity and self-noise of the receiver, usually a ship. The NL can be shipping noise, bubbles, fish schools, rain, etc. TL comes from the temperature gradient in the ocean and interaction with the surface and the ocean floor. The interested reader can find more information in Urick (1996). A simple sketch of these elements can be seen in Fig. 3.1.

Analogous to these aspects in the underwater scenario are parts of the PASS scenario. The source is the PASS alarm, and the receiver is a firefighter. The noise on the fireground comes from other equipment used to fight the fire, the fire itself, radio chatter, other alarm sounds, etc. The DI is applied to both the directivity of the PASS and the receiver. DT is the auditory properties of the firefighter while wearing the firefighter personal protective equipment (PPE). A sketch illustrating this can be seen in Fig. 3.2.

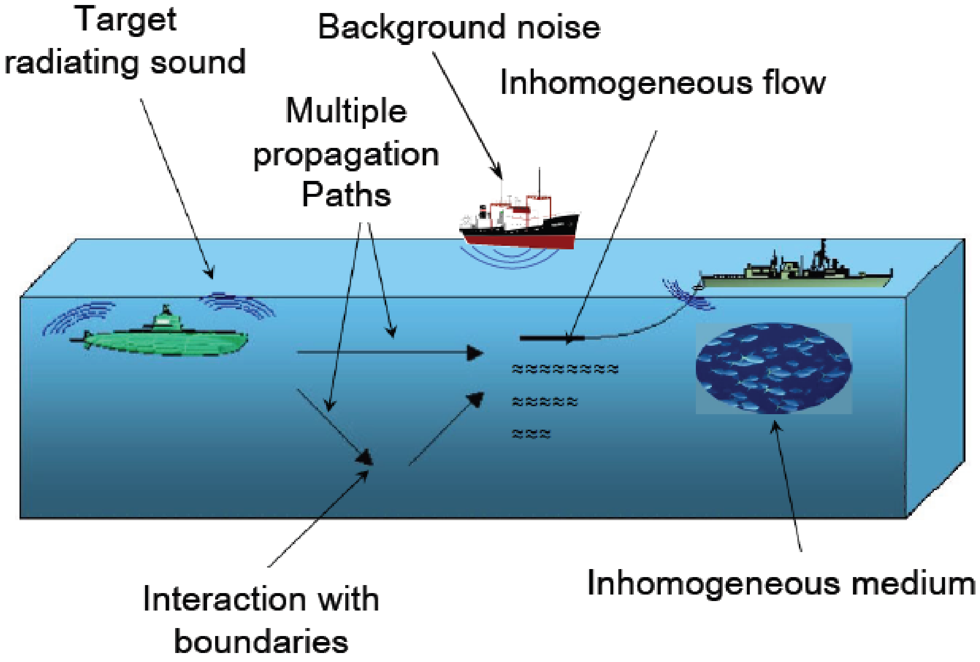

Fig. 3.1: A cartoon representation of the passive sonar environment in underwater acoustics.

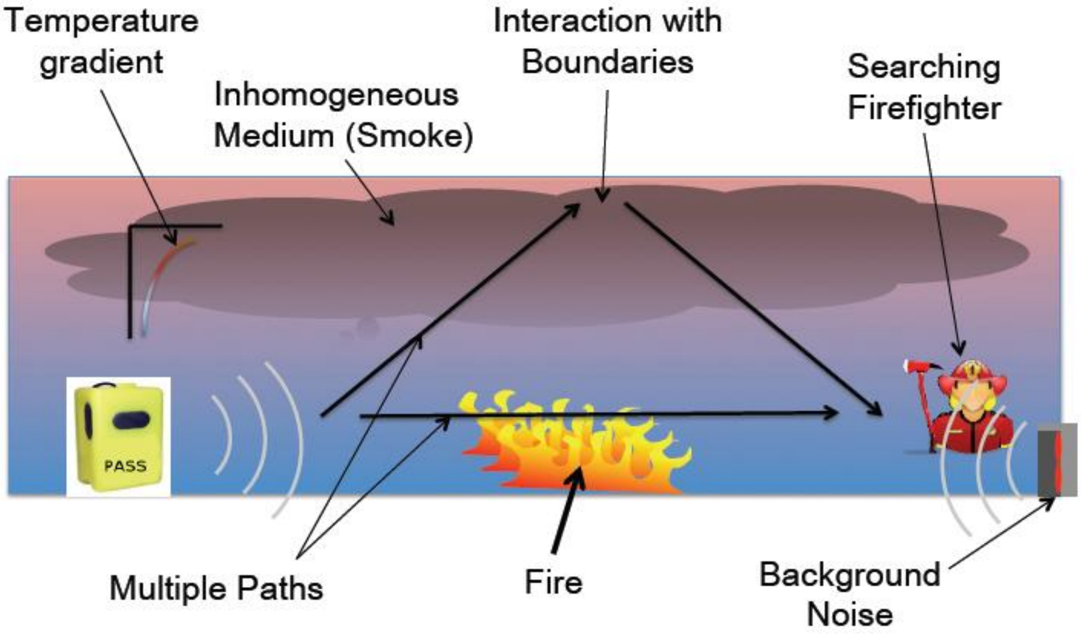

Fig. 3.2: A cartoon representation of the passive sonar environment in fireground acoustics.

Using the passive sonar equation as reference, this study has branched out to begin to understand each of these terms on the fireground. To measure NL, several of the louder pieces of firefighting equipment have been measured for sound pressure level and frequency content. TL was studied using models and full-scale experiments. SL was studied by recording a functioning PASS SCBA device compliant with the 2007 standard. DI was studied in relation to both source and receiver. The source directivity was briefly studied when the levels were recorded. The receiver directivity was studied by measuring head-related transfer function (HRTF) differences when an acoustic manikin was wearing firefighter PPE. DT was measured by looking at how firefighter PPE changed auditory thresholds. As an attempt to put a portion of these into an experiment, four field tests were conducted at three different fire departments across the nation. These tests combined the results of the SL, NL, basic TL, and the DT of the passive sonar equation.

3.2 Implications on Future Technological Enhancements

The sonar equation formalism was developed to facilitate the analysis, design and optimization of sonar systems, hence implementing the formalism is the first step toward any future technological enhancement of PASS. An example of how it is used if given here. When optimizing a sonar system, one typically wants to increase the detection range of the system while minimizing the false alarms. This is done within the sonar equation by manipulating the different terms of the equation. Manipulating the source level is one way to do this. A quick way of calculating how increasing the source level changes the detection range *R* is

$$\Delta R = 10^{\frac{SNR}{20}} \qquad \text{Eq. 3.2}$$

where SNR is the signal-to-noise ratio which is calculated from the sonar equation. With this equation, an increase of 6 dB in SL would double the detection range.

4. Portfolio of Fire Ground Noise

4.1 Introduction

Noise sources used in firefighting have been studied before. Neitzel measured the over all levels of construction tools in relation to hearing loss (2005). Reischl et. al. studied noise sources involved in getting to an incident (Reischl, Bair and Reischl 2010). Haywood studied the noise exposure firefighters experience at the firehouse (2004). These studies have focused on the conditions that result in noise induced hearing loss. For this project a more in depth study of the noise sources in operation during fire suppression operations is needed. To this end, twelve pieces of fireground equipment have been – three chainsaws, two circular saws, three positive pressure ventilation (PPV) fans, a pumper truck idling, the same truck with the pump running, and the same truck with the pump and an on-board generator running. Along with these recordings, a 2007 compliant PASS device was measured to include SL. These recordings were analyzed to provide both sound pressure level (SPL) and frequency content of the equipment.

The equipment was recorded from four different angles – 0°, 90°, 180°, and 270° – using a Tascam DR007 hand held recorder. The equipment was placed at a designate point 12 ft. (3.65 m) away from the equipment. The equipment was rotated to measure data from different angles. If an operator was necessary, they were present in each recording. These methods were adapted from ANSI S12.15, ANSI S12.18, and ANSI S12.23. This setup can be seen in Fig. 4.1.1.

From the recordings, the sound pressure level (SPL) was calculated as both an overall level and as 1/3-octave band levels[1] as designated in ANSI S1.11 and had A-weighting applied as designated in ANSI S1.4. The octave band levels are designed to give a more in depth look at the frequency and level content of sounds. The recordings used available hard flat-open surfaces, parking lots, to make the recordings. Spherical spreading was used to scale the recordings back to 1 m.

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[1] 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 these 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.

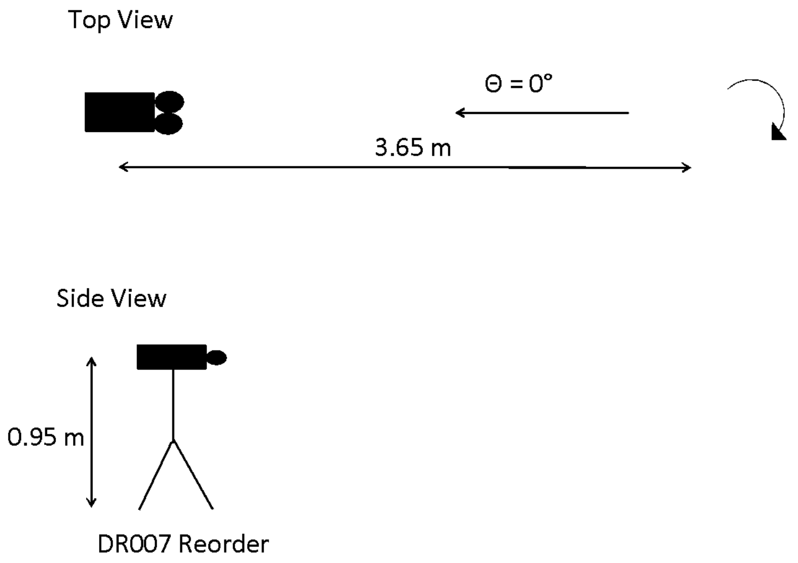


Fig. 4.1.1: Position of recording equipment and fireground equipment when sound was recorded.

4.2 Source and Background Noise Characteristics

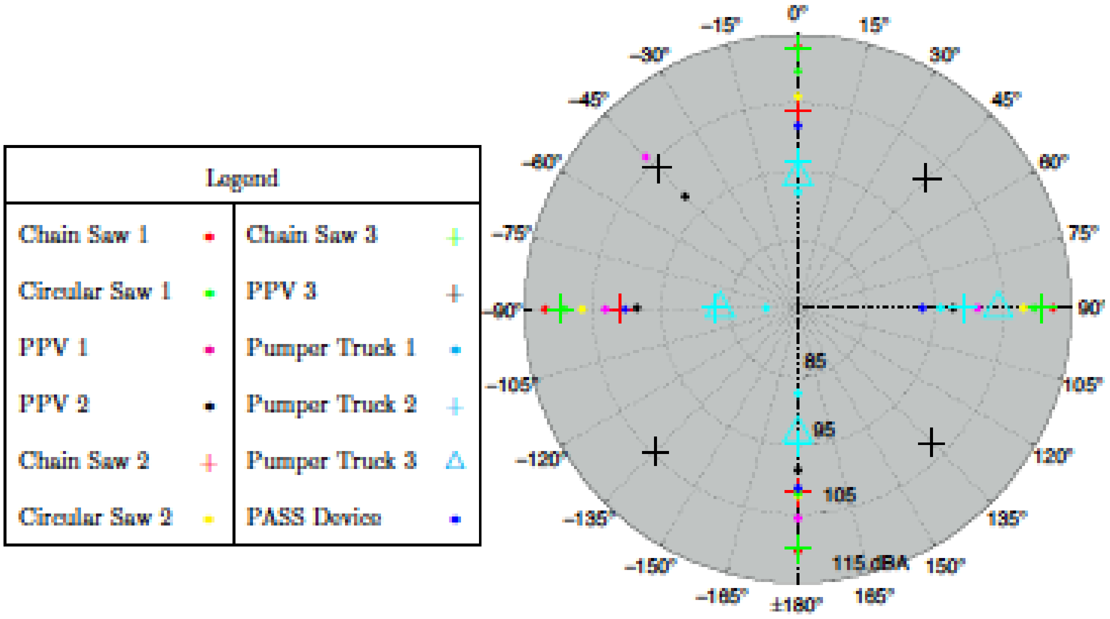


Fig. 4.2.1: The overall levels in dBA re 20 μPa at 1 m. The dark blue dots represent the PASS device. Pumper Truck 1 is the pumper truck by itself. Pumper Truck 2 is the pumper truck with the pump running. Pumper Truck 3 is the pumper truck with the generator and pump running.

Fig. 4.2.1 shows the overall SPL calculated for all the equipment that was recorded. The overall levels show that the majority of the equipment is louder than the PASS device. Chain Saw 1 is 11.6 dB above the PASS device at 0°. PPV 1 is 4.8 dB above the PASS. However, the pumper truck is lower than the other equipment. At 0°, the pumper truck, without the generator or pump, is 9.5 dB below the PASS signal.

Another interesting point is that all the equipment has some portion of directivity. The pumper truck had the most directivity of 17.8 dB between 90° and 270° in the configuration with pump and generator running. Chain Saw 1 had a difference of 2.8 dB between 0° and 180°. Directivity is important to note as directivity in either a noise source or the target signal creates situations where the position of the receiver to these sound sources causes differences in the signal-to-noise ratio. Some positions will allow the receiver to detect the signal at a greater distance than other positions.

The PASS recorded here was recorded on a flat hard surface and not on a dummy. The SCBA tank was facing up and the straps were out to the side. This position is one that would not be seen normally on the fireground. However, in this position the directivity is significant. To investigate this directivity further, a PASS/SCBA was recorded in The University of Texas anechoic chamber.

The SCBA was placed in the anechoic chamber on a large circular sheet which indicated the angle that the PASS was oriented. A fiber board floor was placed in the chamber making it semi-anechoic so that the measurements were more comparable to the outdoor measurements. Due to the limitations of the anechoic chamber, the PASS was not placed on a full sized dummy. The SCBA was lying with the tank up and the straps out to the side. The first measurements were conducted in ten degree increments rotating the SCBA by hand. After analysis, the measurements were conducted again increasing the resolution in areas of interest, where the directivity of the device was more prominent. The results are in Fig. 4.2.2.

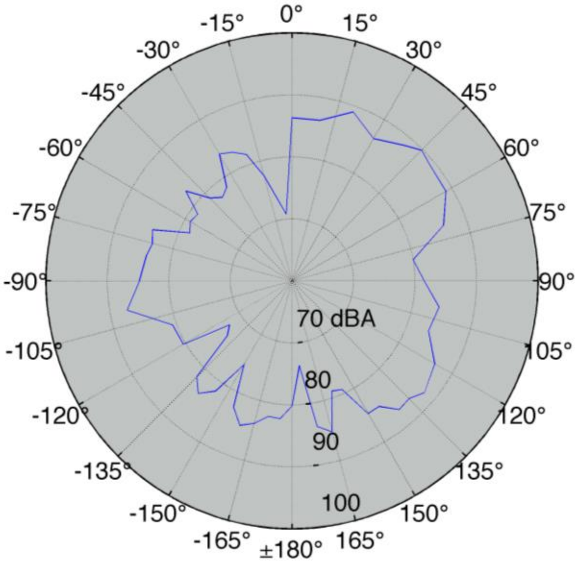


Fig. 4.2.2: The measured directivity of the PASS/SCBA device in the anechoic chamber. 0° is the direction of the bottom of the tank.

This represents the directivity of one PASS device in a laboratory environment. However, in this environment, the PASS/SCBA is highly directive and it can be noted that it will be seen in other orientations of the PASS.

4.3 Frequency Dependence

Fig. 4.3.1 shows the calculated 1/3-octave levels of all the equipment in dBA at 0°. This is a representative angle of all the measured angles. The overall levels of the equipment may change, but the frequency pattern is consistent through the angles. This shows that the noise on the fire scene is broadband, high intensity noise. In contrast, the PASS signal is tonal. The majority of the energy in the PASS signal is in the 3150 Hz octave band. In this band, the signal is comparable to the noise on the fireground. All angles can be seen in Appendix A.

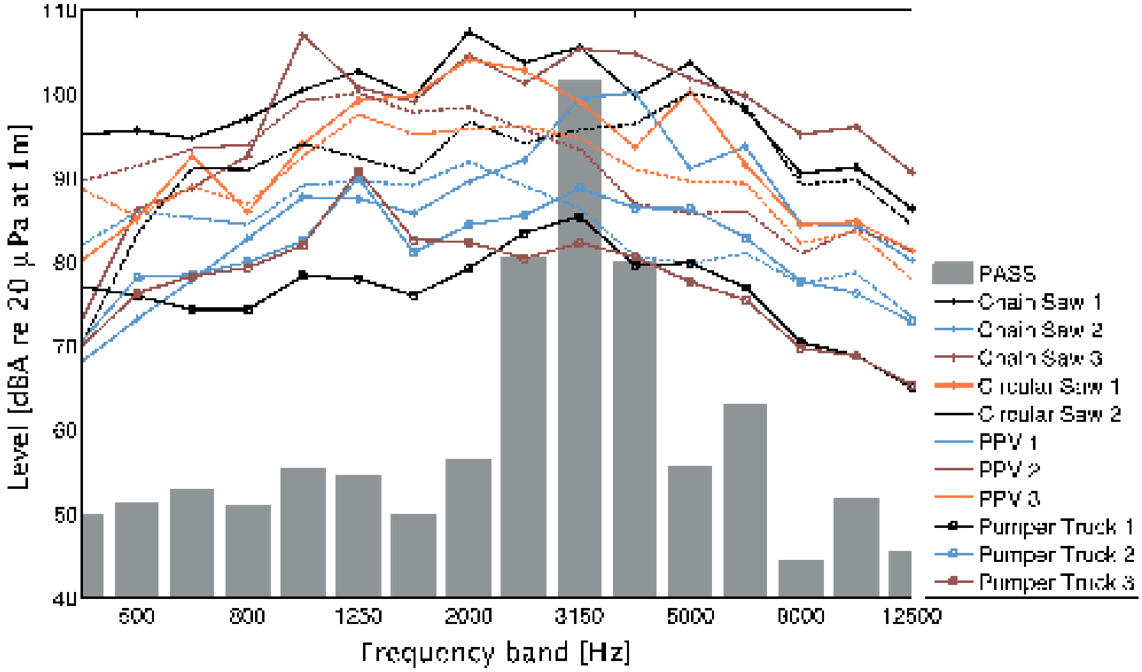


Fig. 4.3.1: 1/3-octave band level of all measured equipment at the 0° angle in dBA re 20 µPa at 1 m. The gray bars represent the PASS device.

NFPA 1982-2007 loosely defined the frequencies of the PASS alarm, leaving room for many different signals to be used in the fire service. The PASS signal analyzed here is one of the PASS alarms that were coherent to that standard. In the 2013 edition, the committee changed the standard for the signal so that all the signals would sound the same. Fig. 4.3.2 shows the new signal compared to the old signal in frequency. The 2013 PASS was not recorded from a PASS/SCBA device, but synthesized according to the standard. In order to compare the signals, the 2013 signal was calibrated such that both signals have the same overall SPL value. This shows a discrepancy in peak SPL. The peak SPL is higher in the 2007 signal than the 2013 signal. This analysis is assuming that the transducer produces the same total acoustic energy.

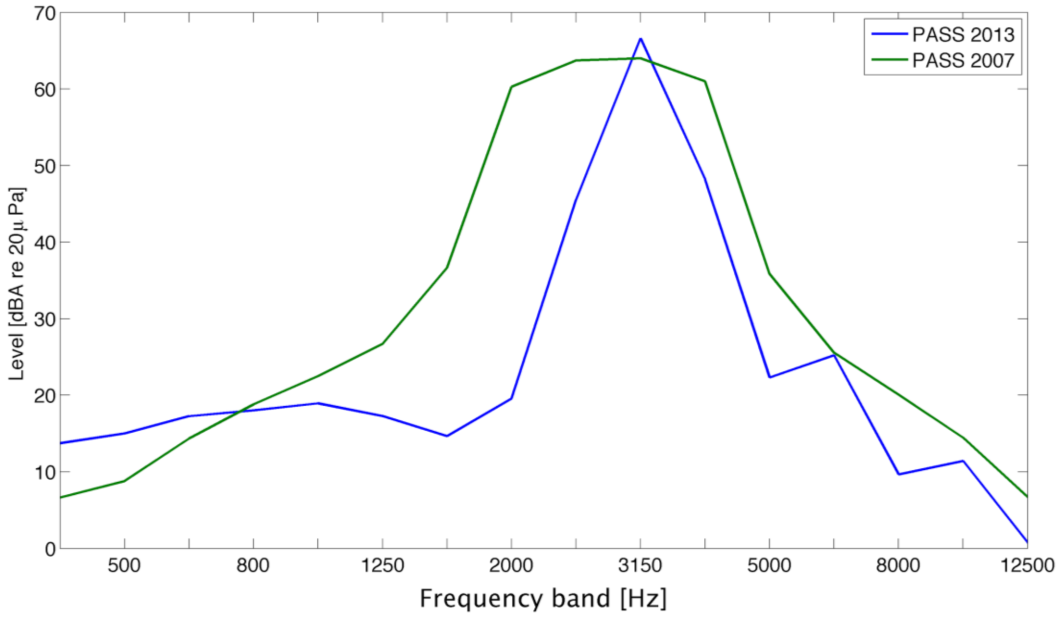


Fig. 4.3.2: 1/3-octave band analysis of the synthesized 2013 edition standard signal to the recorded 2007 edition PASS signal. The levels are normalized such that they both have the same overall SPL values.

4.4 Source Level & Noise Level Conclusions

The measurements showed that the majority of the equipment used on the fireground has a higher level than the PASS device when received at the same distance. The PASS device measured and reported in this study complied with the 2007 edition of NFPA 1982. Saws and fans, in general, had higher source levels than the PASS, and the pumper truck had the same or lower levels. As PASS levels fall below the levels of the equipment fire ground, detection, classification, and localization become more difficult for the human listener. As indicated by the sonar equation, the effect of either increasing the PASS source level or decreasing the noise of the equipment on the fireground would result in increased detection ranges for PASS.

The 2013 PASS signal is constructed from a series of sweeps and is less tonal than the 2007 signal. In general, this would improve detection, classification, and localization in the presence of stochastic transmission losses and fire ground noise.

4.5 Implications on Future Technological Enhancements

Given the potentially low signal-to-noise levels described above, the rejection of isotropic noise would improve detection ranges for a PASS signal. This could be achieved through the use of an increased receiver aperture, which would increase the directivity index DI term in the sonar equation. This could be implemented by using multiple acoustic sensors mounted on fire helmets or other parts of the PPE.

5. Modeling and Validation of Sound Transmission

5.1 Introduction

Anecdotal data from fireground operations suggest that sound transmission might be altered in complex heat loaded structural volumes. Modifications to the acoustical properties of the structure associated with fire will necessarily affect the ability to accurately recognize the PASS signal. To better understand the acoustical transmission properties of enclosures and structures that have been subjected to fire loading, a set of experimental and computational exercises were laid out to characterize this response. In this section, we will detail the cases that were studied and summarize the findings.

The use of acoustical modeling techniques will become increasingly important in characterizing fireground acoustics. Line of duty injuries and line of duty death investigations regularly include discussion of the presence and impact of PASS signals on rescue operations. With increasing use of computational fluid dynamics modeling tools to characterize the fire environments in any given accident scenario, it has become clear that modeling the acoustic field will also provide insights into how the rescue operation evolved. The following sections present experimental and computational results of thermal and acoustical properties of compartment fires.

5.2 Temperature Distribution in a Compartment Fire

A fire changes the temperature, and hence the properties of the gases inside a compartment fire. For a simplified model, the assumption can be made that the gas mixture can be treated as air. The speed of sound, density and acoustic impedance of air are dependent on the temperature according to the following set of equations.

$$c_0 = \sqrt{\gamma RT}$$
$$\rho = \frac{p}{R_{specific} T_0}$$
$$Z_0 = \rho c_o \qquad \text{Eq. 5.2}$$

T is the temperature in degrees Kelvin, $c_o$is the sound speed $\rho$is the density $R_{specific}$ is the universal gas constant divided by the molecular weight of the gas (R = 287.08 J/kg K) for air. $Z_o$is the characteristic acoustic impedance of the medium.

The change in properties associated with the fire has two effects. First, the change in the acoustic impedance causes sound to see the gas at a different temperature as a new medium, and scatter from it. The reflection coefficient for plane sound waves in given by:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad \text{Eq. 5.2.1}$$

The reflection coefficient compares the amplitude of the incident wave to that of the reflected wave. If the reflection coefficient is 1, then all the sound is reflected, and if it is 0 then none is reflected. Fig. 5.2.1 shows the reflection coefficient for sound travelling from a cold medium to hot medium. The reflection coefficient changes depending on the temperature of gas. The two highlighted points are the 800 ^{o}C mark (which is a typical temperature of the plume in a diffusion flame) and the 2200 ^{o}C mark, which is a typical flame temperature. At these temperatures, we see a significant reflection coefficient of about 0.3 to 0.5.

The other effect of the change in material properties is the creating of a temperature gradient inside the room due to the change in density. This gradient can refract the sound inside a room, and cause it to change direction. This is a similar effect to the optical mirage phenomenon where a hot surface bends light and gives the appearance of a highly reflective surface (e.g. the road on a hot day). If we assume the temperature gradient in linear, then Fig. 5.2.2 shows the ray paths with and without a fire. The top of Fig. 5.2.2 shows how ray path are straight in an isothermal room, and the bottom shows the change in the ray paths as they travel inside the temperature profile. The sound rays bend down towards the floor, changing the acoustic field inside the room.

A more realistic scenario can also be calculated using computational fluid dynamics to calculate the temperature field produced by the fire.

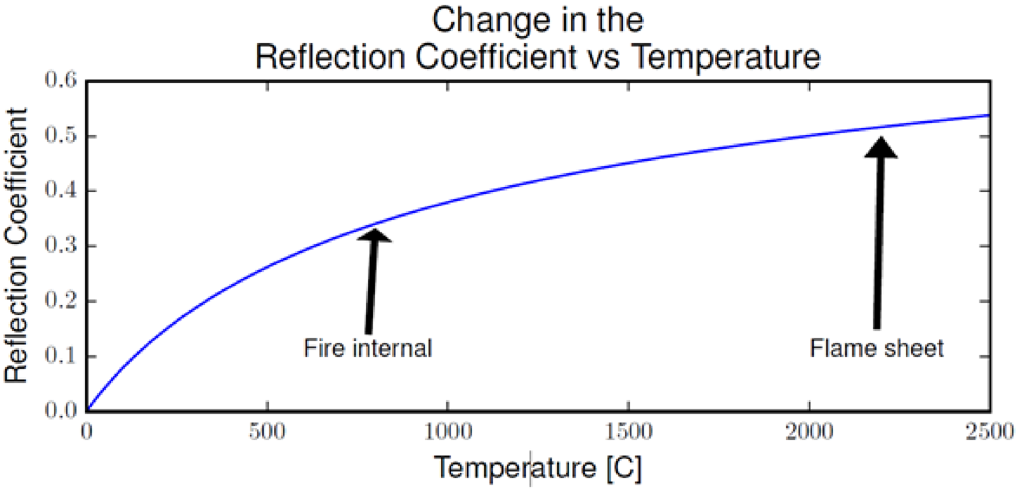


Fig. 5.2.1: Reflection of coefficient of sound travelling from cold air (25 C) to hot air.

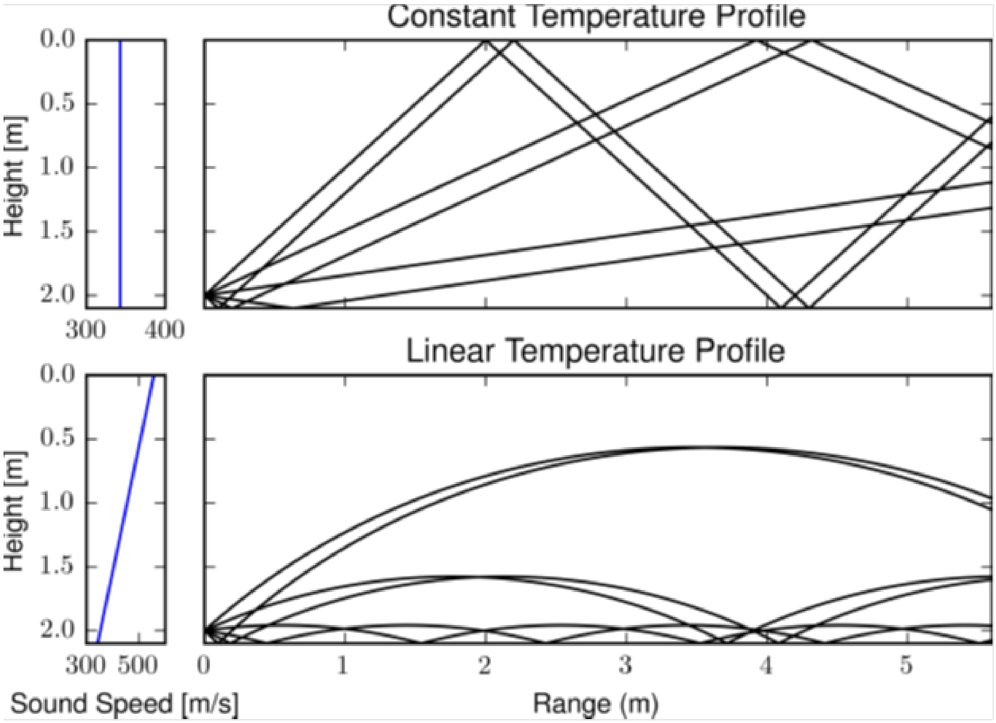


Fig. 5.2.2: Refraction of sound by a linear temperature profile

5.3 Measured Transmission Loss during a Compartment Fire

In order to understand the effect of a fire on the sound heard inside a room, we recorded the PASS alarm being played through speakers inside the University of Texas burn facility. Fig. 5.3.1 shows the setup for this experiment, and Fig. 5.3.2 shows a 3d rendering of the layout. A speaker and microphone are placed inside a burn facility, along with a propane sand burner (Fig. 5.3.3). The following recordings are samples taken from this experiment. The InRoom.mp3 file is recorded inside the burn facility, with all the equipment in place, but no fire. 0second.mp3 is recorded at the ignition point, and 10seconds.mp3 is recorded 10 seconds after ignition. Listening to these clips provides clear evidence that indeed the sound is changed by the fire.

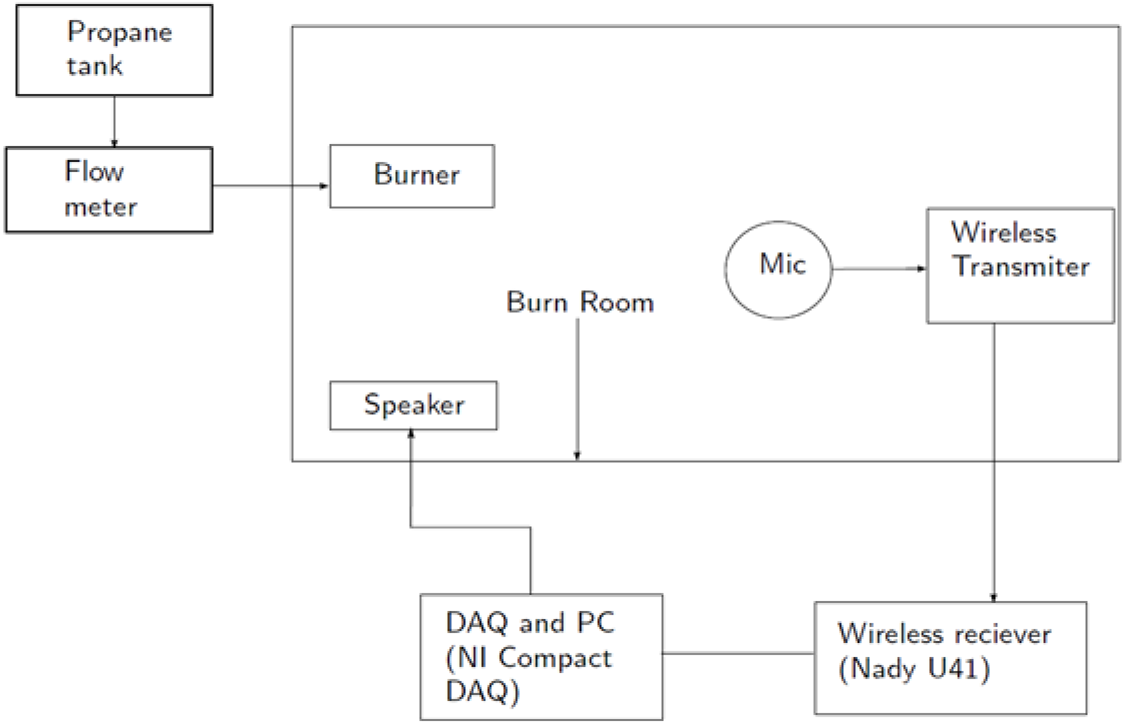


Fig. 5.3.1: Experimental Schematic

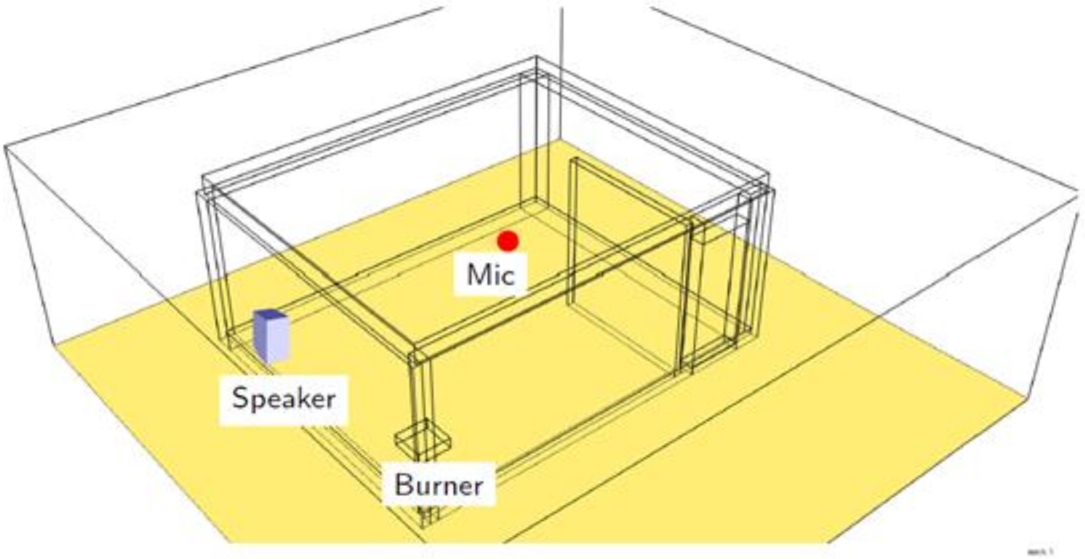


Fig. 5.3.2: Experiment Rendering

Fig. 5.3.3: Top, Burn structure. Bottom, Speaker and Burner

We can further measure this change by measuring the acoustic response of the room as the fire develops. We assume the system is linear-time-invariant and then measure the transfer function of the room, using the signal processing scheme shown in Fig. 5.3.4. A simple cartoon example of the way this processing works is given in Fig. 5.3.5. A chirp signal (frequency modulated sweep) is emitted from the speaker, and recorded by the microphone. The transmitted signal and the received signal have certain characteristic that can be compared to give the frequency response of transmission system. This is the transfer function we calculate. In this example we see the transfer function is a low pass filter with a -

3dB point at 25 Hz. We can manipulate the transfer function and convert it to a heat map. By stacking many of these heat maps we obtain the response of the room over time as the fire evolves.

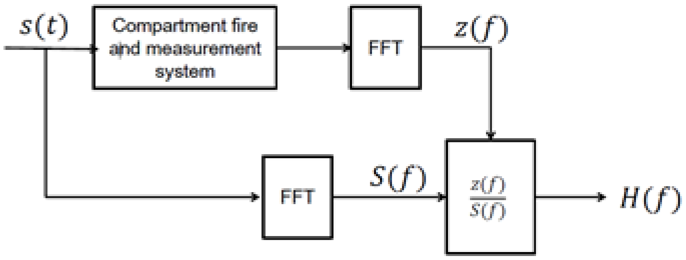


Fig. 5.3.4: Room response measurement signal processing

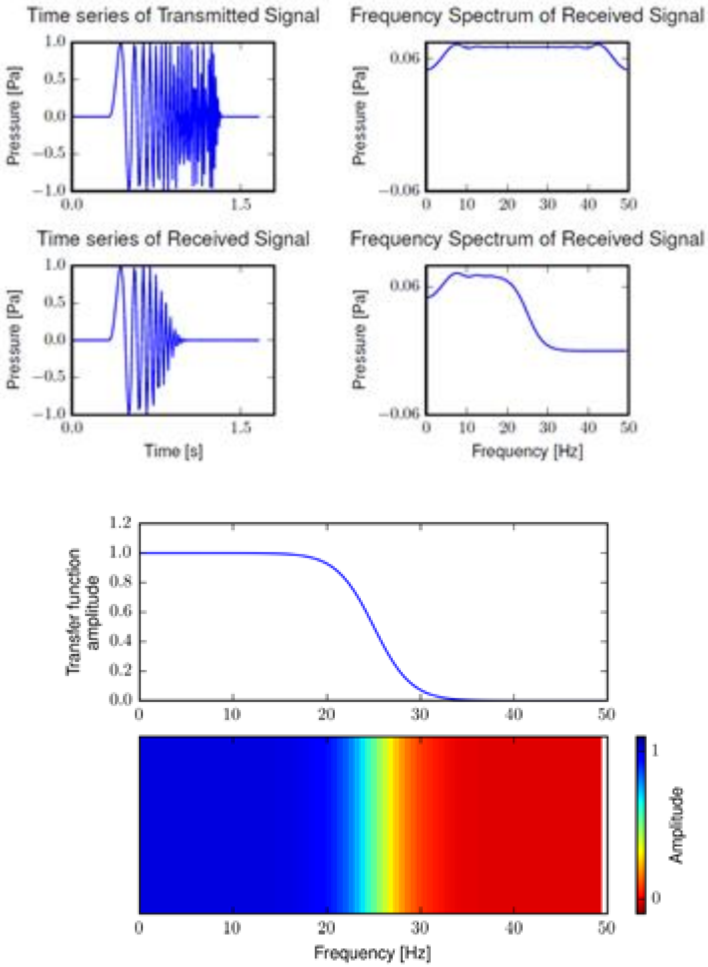


Fig. 5.3.5: Cartoon transfer function processing

Fig. 5.3.6 shows the evolution of the frequency response of the fire develops. On the x-axis we have frequency and on the y-axis real time. The experiment is started without a fire, and after a few seconds the fire is ignited. We see that the low frequency modes of the room increase in resonance frequency and the high frequency modes attenuate. This shows how the fire is changing the room conditions, and potentially changing the sound heard by a listener inside the room.

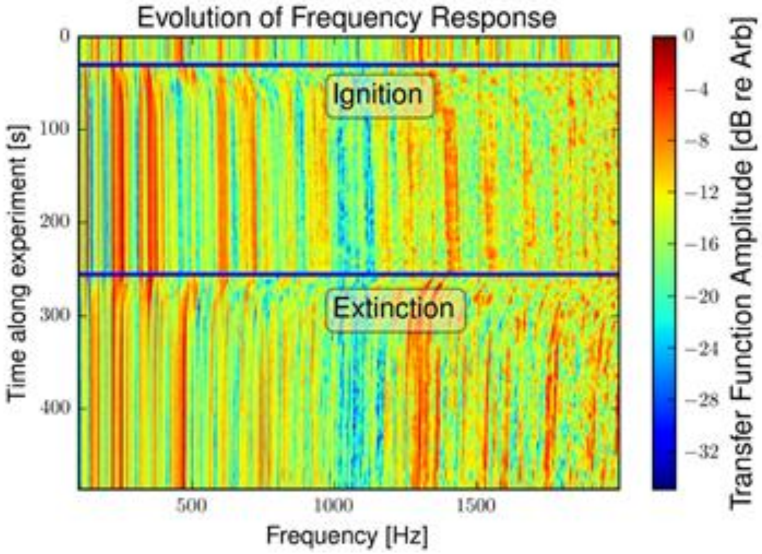


Fig. 5.3.6: Frequency Response as the fire develops

We experimentally see that there is an acoustically measurable change in the response of the room because of fire. In order to learn more about the reason for this change, we will use numerical models. For the first model we will use a reacting flow computational fluid dynamics code fire dynamics simulator (FDS), to calculate temperature and fire conditions inside our room, and then use those temperatures an inputs into a COMSOL Multiphysics finite element acoustics model to calculate the frequency response. This can then be compared to the experiment results. Fig. 5.3.6 and Fig. 5.3.7 show the results from the fire model and Fig. 5.3.8 shows the acoustic response of the room as calculated by COMSOL. The acoustic response is calculated over the 2-D slice of temperature shown in Fig. 5.3.7, rather than the full 3D geometry because of the computational complexity of the model. The 2D model requires about a week of runtime on a 16 core computer and 10s of gigabytes of ram. A full 3D model of the burn facility at the frequencies of interest was not computationally reasonable. Therefore the results in Fig. 5.3.8 are qualitatively comparable to the experimental results shown in Fig. 5.3.6. In both the experimental and the numerical result we see an increase in the lower frequency resonance modes and attenuation of the higher frequency modes. This gives us confidence in both the numerical results and the experimental results. It also shows that the change in resonance modes and the attenuation is principally a temperature inhomogeneity effect rather than a flow effect, since the finite element acoustics model did not consider flow.

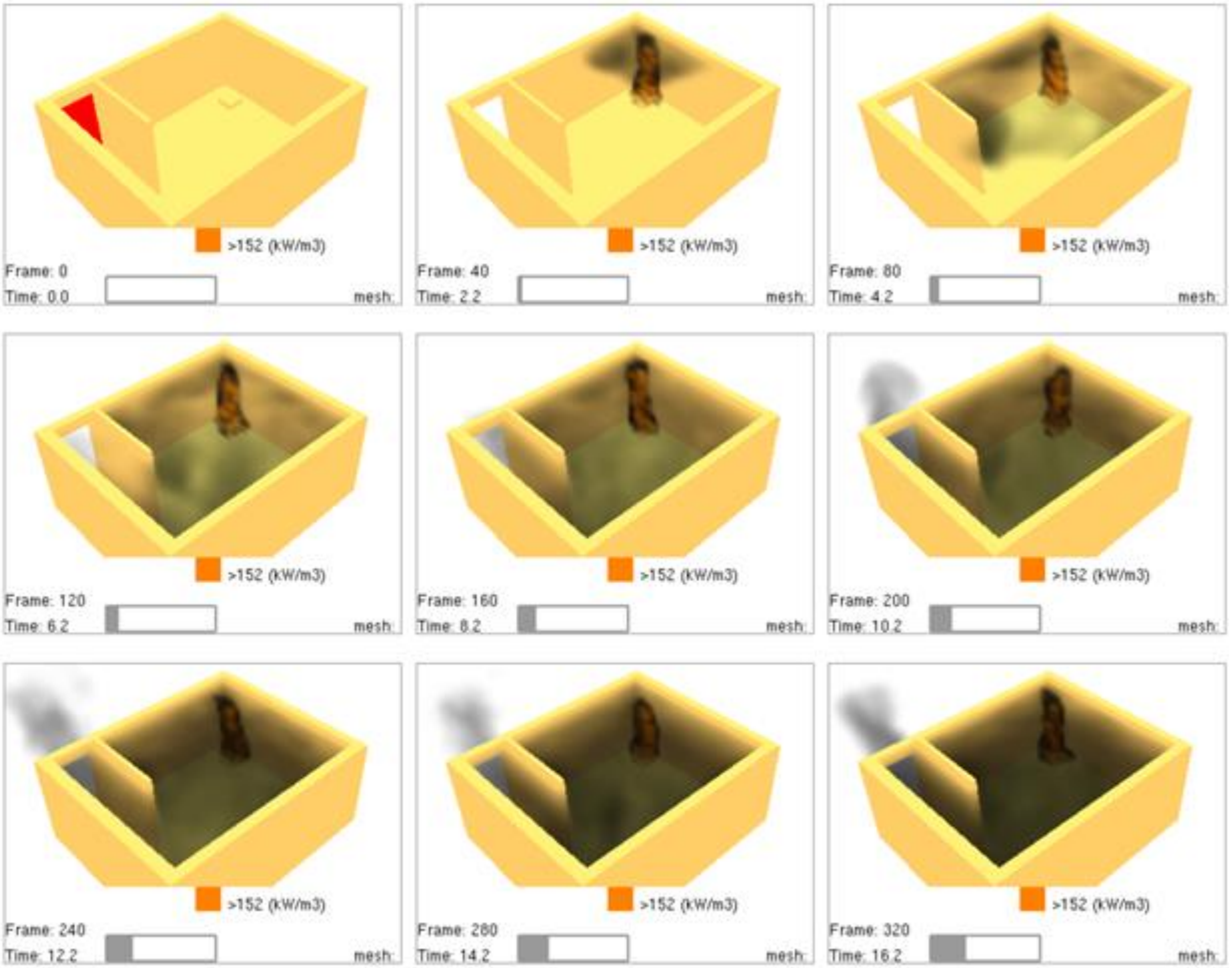


Fig. 5.3.7: FDS Fire model showing flame and smoke

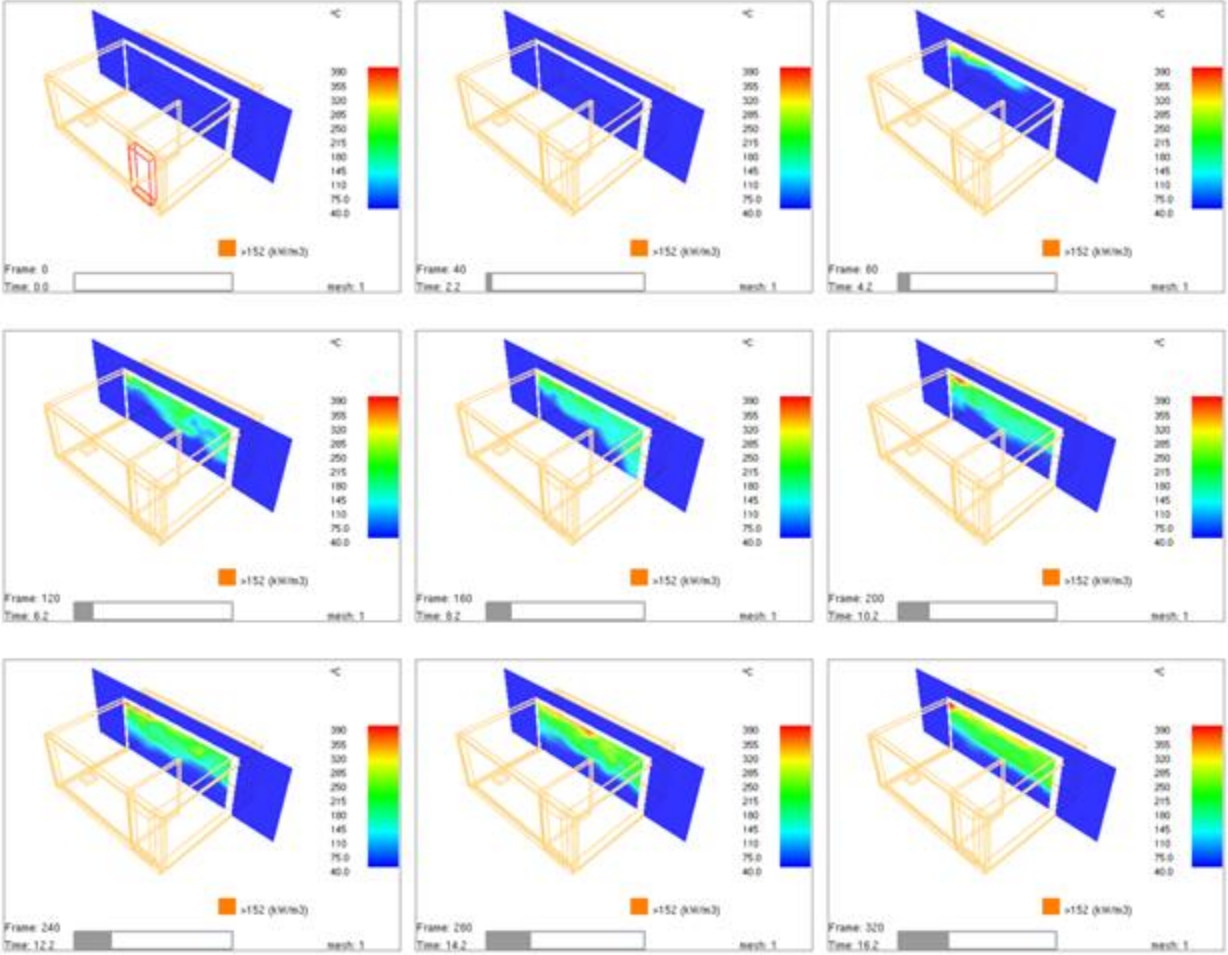


Fig. 5.3.8: FDS fire model showing slice temperatures

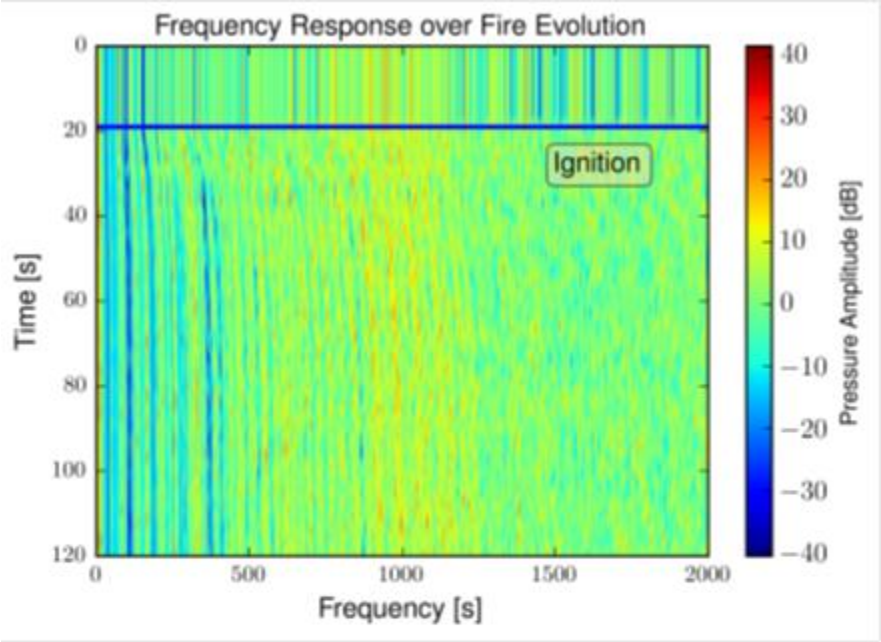


Fig. 5.3.9: COMSOL finite element acoustics model showing frequency response over fire evolution.

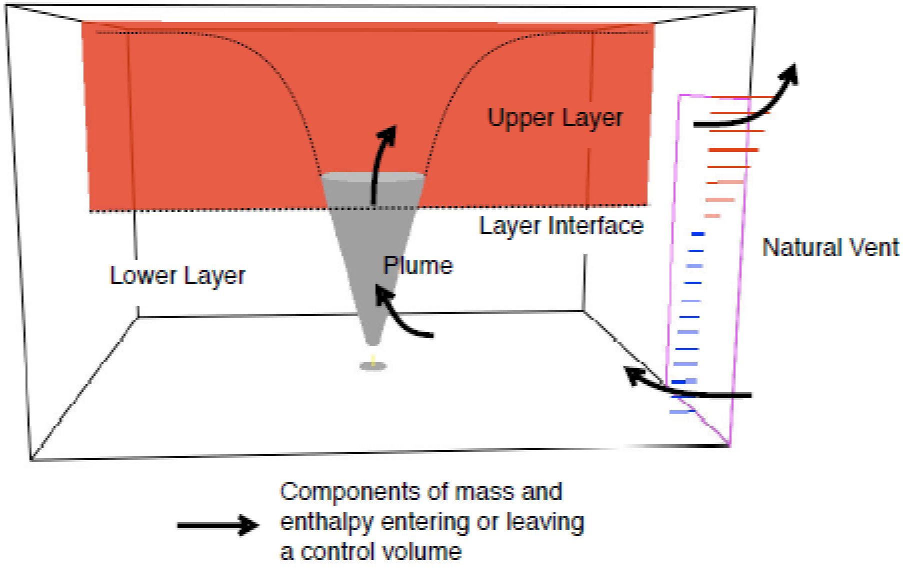


Fig. 5.3.10: Two Zone Schematic, NIST Technical Handbook, CFAST

In order to explain the change in the resonance frequency we rely on the analytic zone model for compartment fires. The zone model divided the compartment into a hot layer and cold layer. This is demonstration in Fig. 5.3.10, which is adapted from the NIST technical manual for the two zone model software, CFAST.

A compartment has certain acoustics resonances due to its geometry. Modeling the room as a purely rectangular geometry, we can use the wave equation to calculate the response of a room. By calculating an average sound speed in the room we can also calculate the change in the resonance frequencies. For a room with a hot layer at 500 C and cold layer at 25 C (as shown in Fig. 5.3.11) we will see a change in the resonance model based on the hot layer height as shown in Fig. 5.3.12.

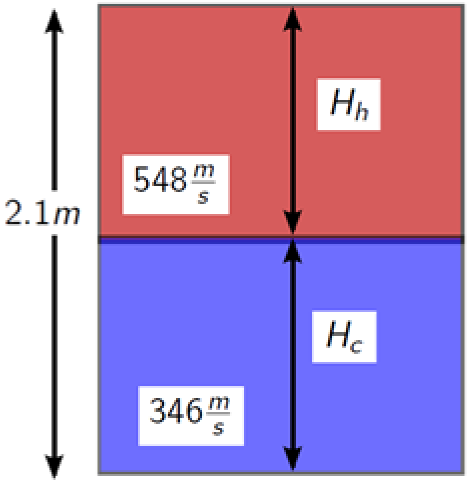


Fig. 5.3.11: Two zone model schematic

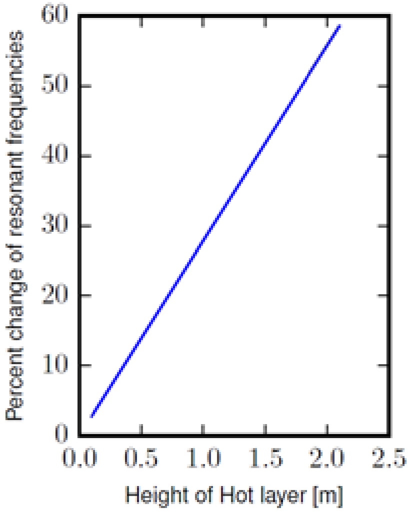


Fig. 5.3.12: Percent change in the resonance frequency as the hot layer develops

By using CFAST to calculate the layer heights and temperature we can calculate the predicted change in resonance frequency. We see the change in resonance frequency calculated by this model to be similar to that seen in both the experimental and CFD-acoustic finite element models.

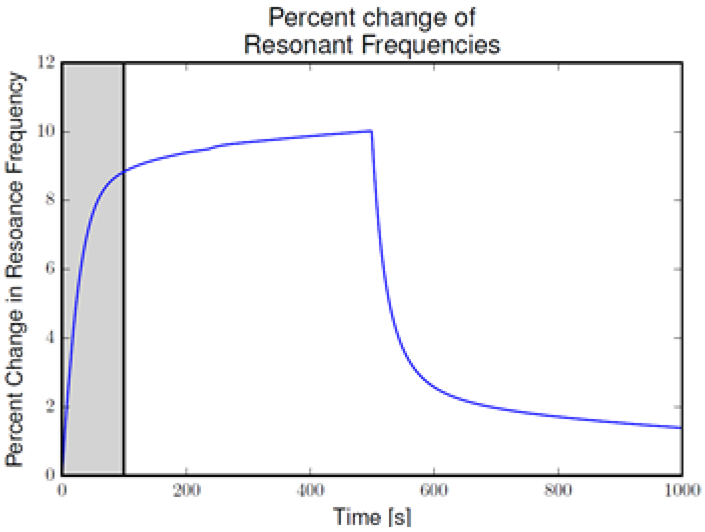


Fig. 5.3.13: Change in resonance frequency

The analytical model shows that the change in resonance frequency is governed primarily by the average temperature of the room. However, we not have an explanation for the attenuation of the higher frequency modes. We hypothesize that higher frequencies (>1500 Hz) attenuate because scattering from the hot gases in the environment prevents the formation of the standing waves to create the modes.

In order to test this hypothesis, we build a simple model of a 3D fire plume. As shown in Fig. 5.3.14, we place a source and a receiver on either side of a flame and calculate the acoustics response at the receiver.

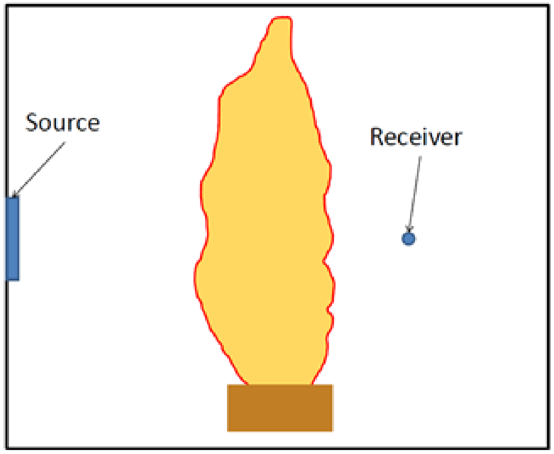


Fig. 5.3.14: Schematic of a fire plume scattering model

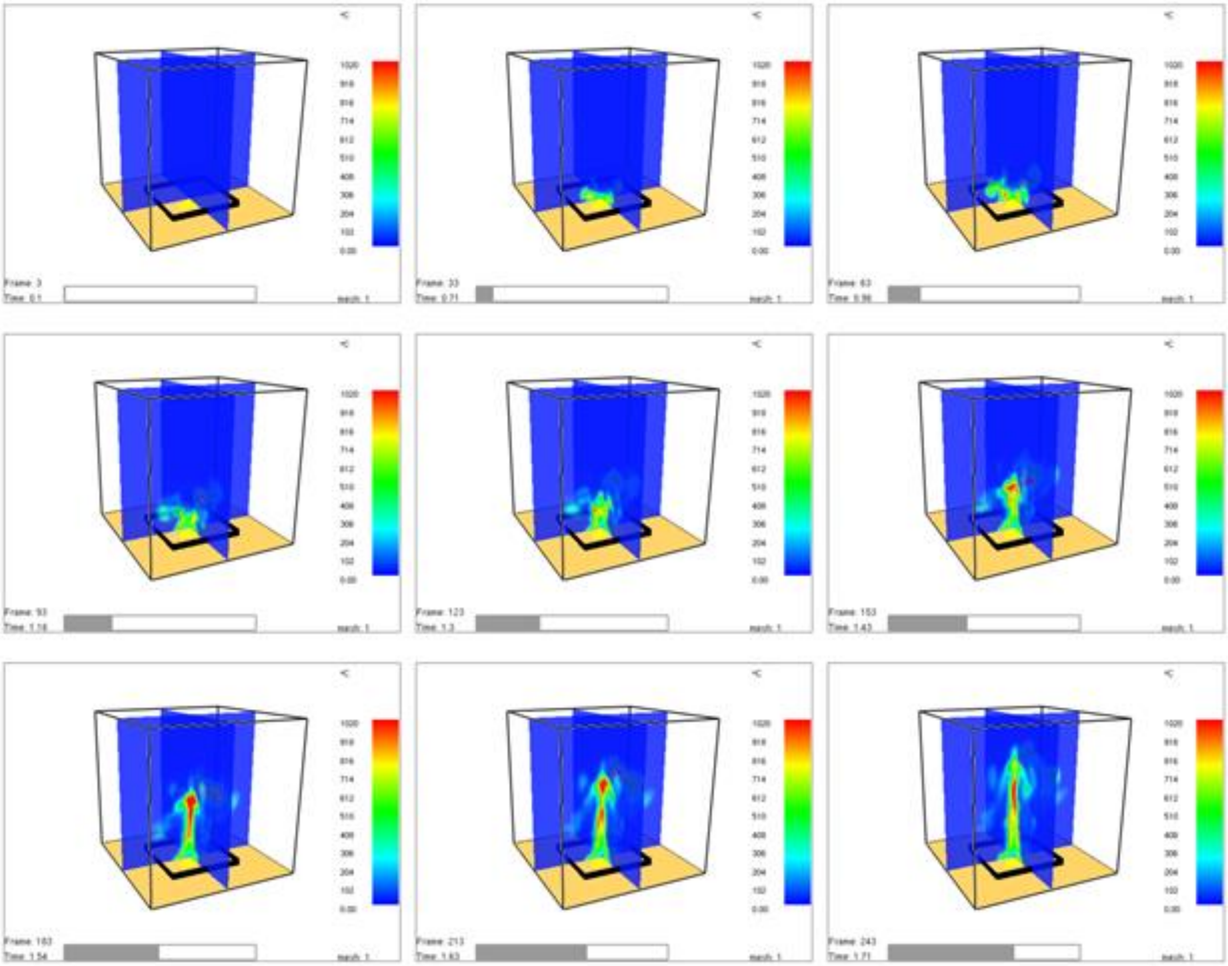


Fig. 5.3.15: Evolution of a flame calculated using FDS

Fig. 5.3.15 shows the evolution of a flame as calculated by a CFD model. The 3D Temperature distribution is used to create the finite element acoustics model of the fire using COMSOL Multiphysics for every 0.1 s step. Fig. 5.3.16 shows the acoustics pressure at the receiver over time as the flame evolves. We see very strong attenuation when the flame begins to impinge on the plane of the speaker and the receiver. Even frequencies as low as 200 Hz are significantly affected. This explains why the higher frequency modes attenuate in the room response measurement.

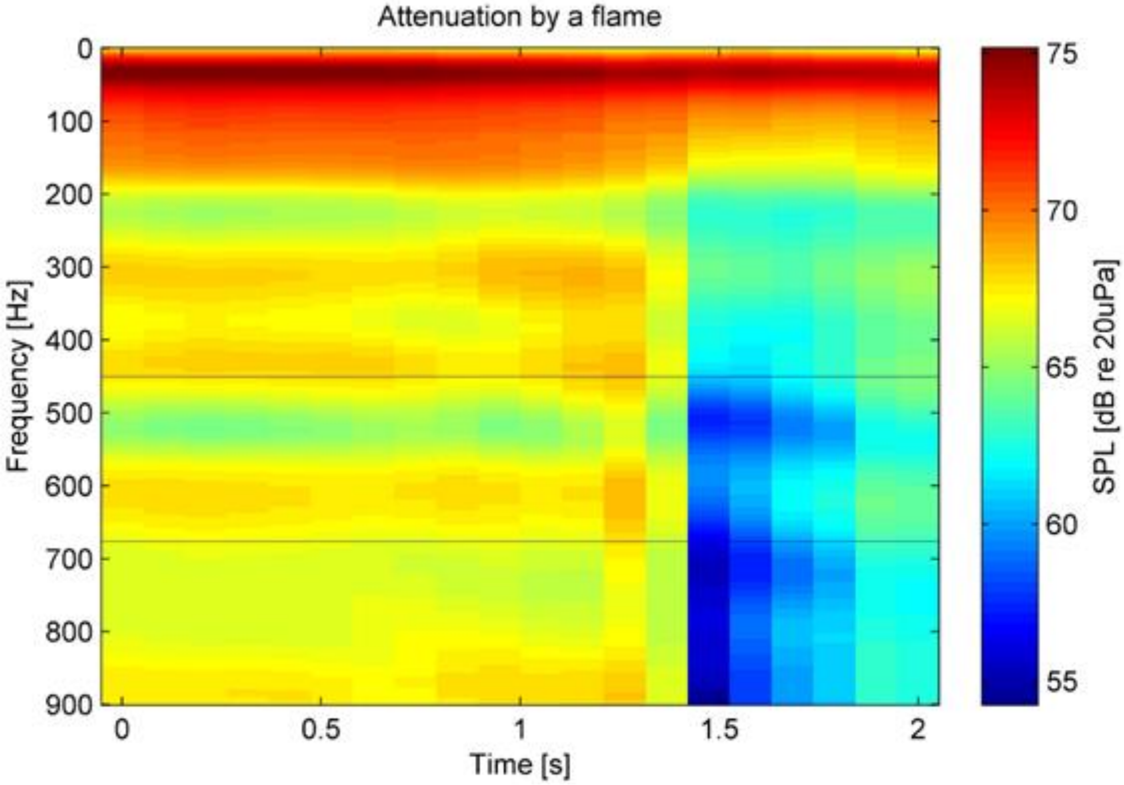


Fig. 5.3.16: Frequency response over time for a 3D flame

So far we have seen that the fire can change the acoustical response of the room, change certain frequencies, and attenuate others. The refraction caused by a fire could have another effect. The direction that sound arrives at the ears could be changed. This is demonstrated in Fig. 5.3.17 where we can we have plotted the eigenrays (rays that arrive at the receivers) for two receivers in a temperature field calculated by FDS. The red ray is the one that arrives without interaction with the boundaries and is the direct arrival. We can see that in an isothermal environment (1 second after ignition) the rays are straight, however they bend significantly as the fire develops. The two receivers placed in the model are 20 cm apart, which is the width of the human head. Therefore we can see that in a fire the temperature change can cause sound to appear to come from a different direction.

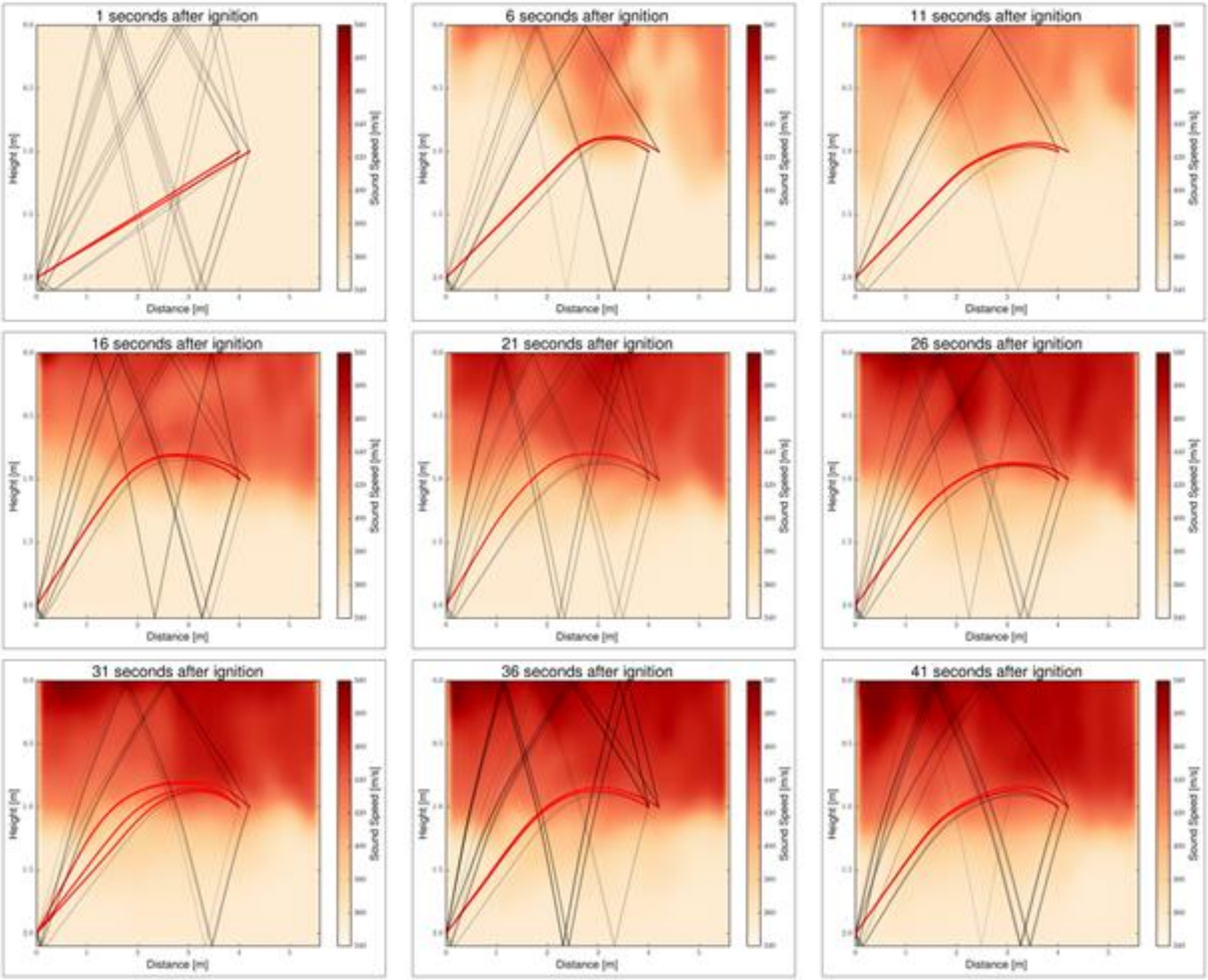


Fig. 5.3.17: Change in eigenray paths in a fire.

5.4 Measured acoustic response of a simulated two zone stratified acoustic environment in a hallway

The full explanation as to why a functioning PASS device that was active on the fireground, might remain undetected (and therefore unclassified and unlocalized by firefighters trying to find it) remains unknown. In this section we describe an experiment to test one hypothesis proposed to address this deficiency for cases when the acoustic path between the PASS device and the receivers includes a long hallway. We hypothesized that a temperature-stratified hallway could cause temporal and frequency domain distortion of a PASS signal severely enough that listeners who heard it might not be able to classify it as a PASS signal. In other words, such an environment might cause signal distortion to such an extent, that the PASS signal no longer sounds like the PASS signal, but instead sounds like something else. In such a case the firefighters might actually hear the PASS device, but not classify the sound as that of the PASS device, and hence not find the downed firefighter.

To test this hypothesis, we constructed a simulated two-zone fire environment in a hallway of a building on campus using helium balloons, as shown in Fig. 5.4.1 and 5.4.2. Room temperature helium balloons (oblate spheroid in shape, 61 cm length major axis by 40 cm length minor axis) were placed in a layer against the ceiling of the hallway to simulate the hot upper layer of the two-zone system. Room temperature air filled the lower layer. The speed of sound in helium is about 1000 m/s, which is equivalent to air at about 1100 °C. A pair of loudspeakers driven in parallel was placed at one end of the hallway and a pair of microphones was placed at the other end, and transfer functions between each microphone and the drive signal were measured. Human listeners at the far end of the hallway also evaluated a PASS signal played through the system. No other significant noise sources were present.

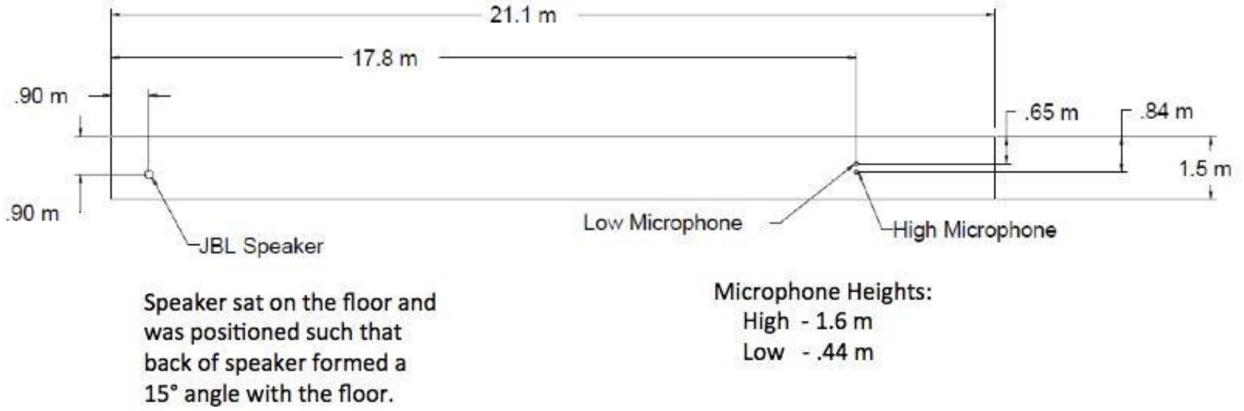


Fig. 5.4.1: A top down view of the hallway used for the experiment is shown. The ceiling height was 2.43 m. The layer of room-temperature helium balloons (not visible in this view) was 1.20 m thick, leaving 1.23 m of room temperature air beneath it. The length of the hallway was 21.1 m and its width was 1.5 m. Both ends of the hallway terminated into perpendicular hallways (not shown). A pair of loudspeakers was position at the left end, and two microphones were positioned at the right end, as shown (their heights above the floor are given in the figure). The high microphone was within the helium layer and the low microphone was below the layer.

Fig.5.4.2: Photographs of the hallway during the experiment are shown. On the left, the photo shows the pair of loudspeakers in the orientation used during the experiment. In the upper right, one of the microphones is shown prior to it being placed in the measurement position that was described in the previous figure. The helium balloons are visible in all of the photos. The lower-right photo shows some of the equipment before being placed in the positions actually used in the measurements.

5.4.1 Qualitative Results Reported by Human Listeners

Four human listeners ranging in age from about 25 to about 40 years of age, with self-reported normal hearing, reported no difficulty classifying the PASS signal after propagation down the hallway with the helium balloons. In other words, the hypothesis was found to be false. The presence of the simulated hot layer did not distort the PASS signal enough to cause it to be confused for something else. This is indeed a qualitative result. We did not attempt to quantify this perception.

5.4.2 Results of Transfer Function Measurements for Horizontal Stratification

Despite the qualitative results described above, measurements did reveal an acoustic effect associated with the presence of the helium layer as shown in Fig. 5.4.2.1. The baseline hallway acoustic response, with no helium layer present is shown (red curve), for the lower microphone. Acoustic received levels at the same mic location were higher (louder) than the baseline case when the helium layer was present (red curve), for frequencies above about 1.8 kHz. This is likely due to the confinement of sound within the hallway beneath the helium layer. In other words, since the helium layer is strongly reflective of sound, the energy delivered by the sound source ensonifies a smaller volume of hallway beneath the helium layer, hence the acoustic pressure is higher. For the upper microphone placed *inside* the helium layer (blue curve), received levels were significantly lower at all frequencies, which supports the notion that the sound was largely reflected from the layer.

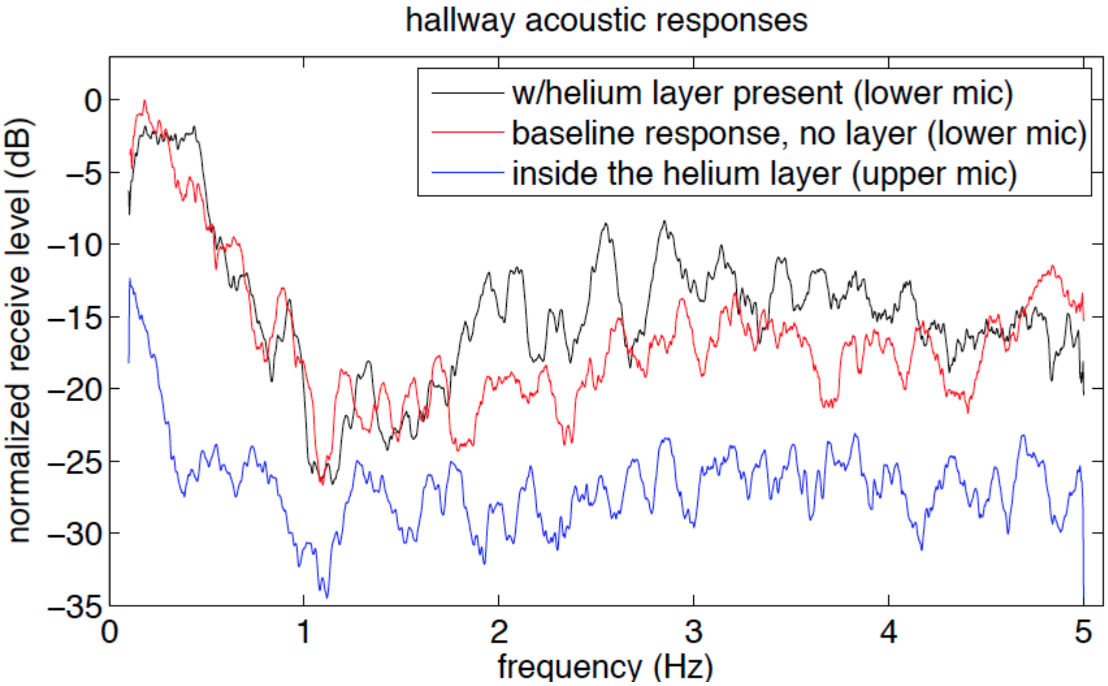


Fig. 5.4.2.1: Normalized acoustic received levels measured at the end of the hallway for a normal hallway filled just with room temperature air (red curve) and the stratified hallway with the helium balloon layer previously described (black curve). The presence of the helium layer increases the receive level in the layer below it, above about 1.8 kHz. In addition, the modal structure of the hallway shifts along the frequency axis, but this did not alter the classification of the PASS signal, as previously mentioned. The microphone positioned within the helium layer (blue curve) shows a reduced receive level.

Firefighters crawling on the ground beneath the simulated hot layer in this experiment would experience a PASS signal that was louder than that in the hallway without any fire present, but if their ears were in the hot layer, they would experience a lower level PASS signal, although it is unlikely that would ever happen in practice, because it represents a temperature much too hot for a human to endure, 1100 °C.

A second experiment was conducted quite similar to the first, except that the balloons where arranged as a barrier or wall spanning the entire height and width of the hallway. In other words, a collection of helium balloons were deployed that filled the hallway from floor to ceiling, and was either 1.2 m, 2.4 m or 3.6 m thick. Normal room temperature air filled the hallway on both sides of the helium balloon barrier. Acoustic transfer functions were measured for the baseline case, with no balloons present, and for the three wall thicknesses. These measurements represent the signal level received through the helium wall, simulating the signal level received through a section of a hall way filled floor to ceiling with hot gas. The results are shown in Fig. 5.4.2.2. Acoustic level received on the other side of the helium balloon wall was significantly lower than the baseline case with no balloons present. This indicates that a strong fire in a hallway could potentially significantly reduce the acoustic level transmitted from the other side.

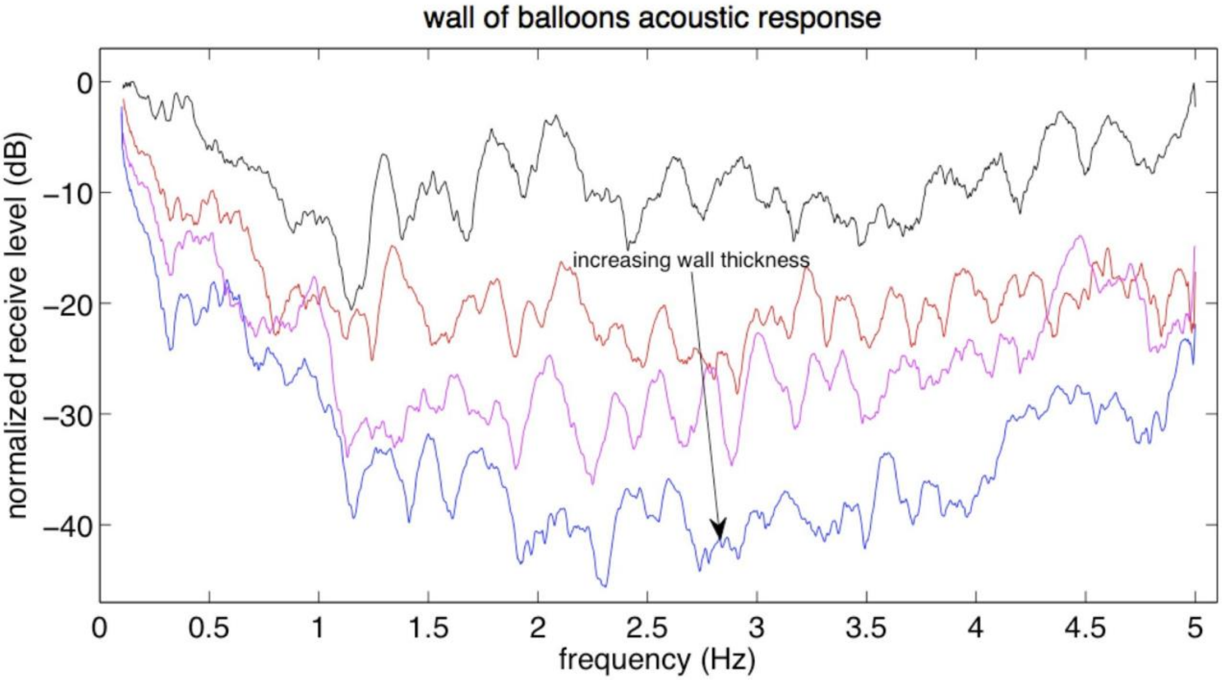


Fig. 5.4.2.2: Normalized acoustic received levels through a wall of helium balloons of various thicknesses. The baseline case (black curve) is for no balloons present. The red, magenta and blue curves are for 1.2 m, 2.4 m, and 3.6 m thick, respectively, walls of helium balloons. The received levels are significantly lower after propagation through the helium.

5.5 Gypsum Modeling

Part of the transmission loss suffered by a signal as it propagates through a building is due to acoustic interaction with the boundaries (walls, ceilings, and floors). In many cases, this involves gypsum wallboard. It has been documented that when gypsum is heated by a fire, it dehydrates causing a change in density and elastic modulus. (Cramer, et al. 2003) Since this change could potentially affect the acoustic properties of the gypsum, impedance tube measurements were conducted to investigate this issue.

5.5.1 Introduction

One would not traditionally measure the absorptivity of gypsum wallboard in an impedance tube; highly reflective materials cause problems because they cause standing waves to occur in the tube. Some tubes can be designed to combat this by applying a porous absorber coating or lining inside the impedance tube near the loudspeaker, but that is not possible with the construction of the ETS-Lindgren impedance tube used in this study.

Typically, gypsum wallboard is measured using reverberation time methods and is very rarely measured singularly. It is typically measured in an assembly, and sound transmission class (rather than acoustic impedance or absorption coefficient) is the provided metric for design.

Losso and Viveiros (2005) report that the density of gypsum wallboard is 960 kg/m^3 and the sound speed is 6800 m/s [13]. This leads to an acoustic impedance of 6.52x10^6 Rayls, which is closely comparable to brick (6.66x10^6 Rayls).

The primary difference between gypsum and brick regarding sound transmission, however, is density. Brick is much more dense than gypsum wallboard (1800 kg/m^3), and the additional mass prevents much sound transmission according to the acoustic mass law.

5.5.2 Impedance Tube Methods

An impedance tube is an acoustical instrument used to measure the specific acoustic impedance of materials (Blackstock 2000). Once the specific acoustic impedance of a material is determined, the absorption and reflection coefficients can be calculated using methods described below. This information can be used to increase the level of detail in existing fire models as described in the previous section.

ETS-Lindgren, a company specializing in third-party acoustic testing, has an out-of-commission impedance tube that was used in this experiment.

The tube was made of a rolled, square aluminum tube. The tube is approximately 1.93 meters long. The spacing between the microphones is approximately 0.0286 m. This is pictured in Fig. 5.5.2.1.

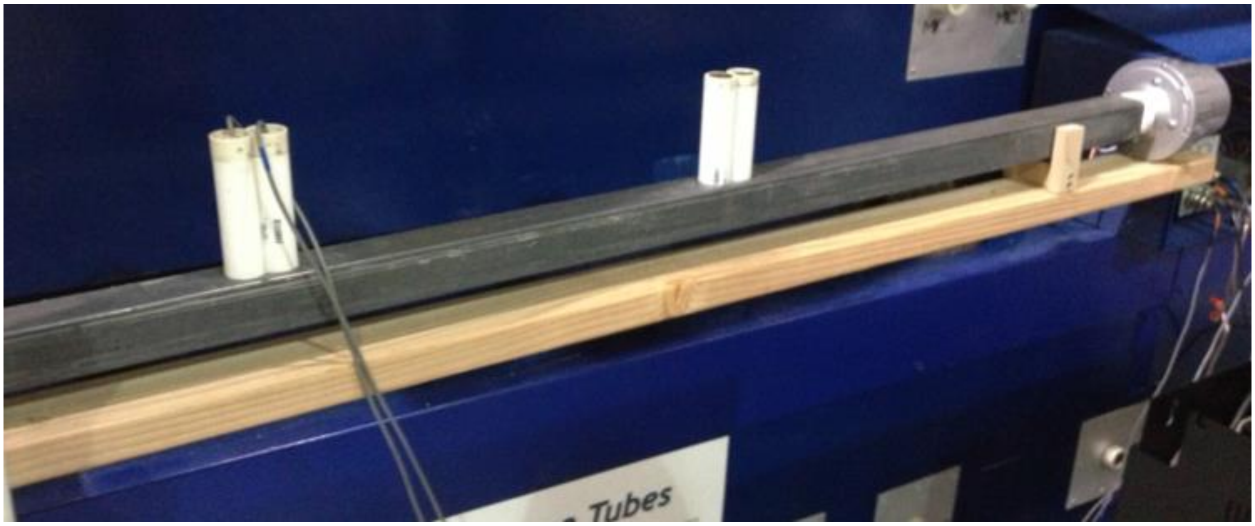


Fig. 5.5.2.1: A picture of the ETS-Lindgren impedence tube used in this study.

The tube was less than ideal for measuring gypsum wallboard because the backing plate for the test specimen was approximately 0.2413 m (9.5 in.) deep. The impedance tube was originally designed to measure the absorptivity of acoustic foam, which comes in thick wedges and is pliable to squeeze into such a space. Gypsum wallboard, on the other hand, is only 1.65 cm (0.65 in.) thick and very rigid, making it impossible to place against the backing plate of the tube. The backing plate is pictured in Fig. 5.5.2.2.

Fig. 5.5.2.2: A picture of the impedence tube backing plate.

The options were to place the gypsum at the edge of the tube and seal with vacuum grease, accounting for the air gap behind the gypsum in the calculations, or to make an alternate backing plate to better accommodate the sample. Both options were explored.

Additionally, there is no absorptive material in the tube near the speaker. Because the tube is so long and narrow, there were problems with standing waves in the tube that were not easily addressed.

5.5.3 Procedure

The procedure for taking measurements in the ETS-Lindgren impedance tube was as follows:

1. Calibrate the microphones into the Data Physics software (used for data acquisition in these experiments)
2. Place mics in original configuration, place anechoic foam in the sample holder and measure transfer function and coherence.
3. Switch the microphone configuration and measure the transfer function and coherence of anechoic foam sample.
4. Switch microphones back to original configuration.
5. Place gypsum in sample holder

5.5.4 Measurements

5.5.4.1 Impedance Tube Verification

First, two scenarios were used to test the fidelity of the impedance tube. The first was to determine the absorption coefficient of the anechoic foam, which one would expect to be very close to 1. The results are in Fig. 5.5.4.1.1. These tests used a pink noise generator to provide the input signal, as specified in ASTM E1050.

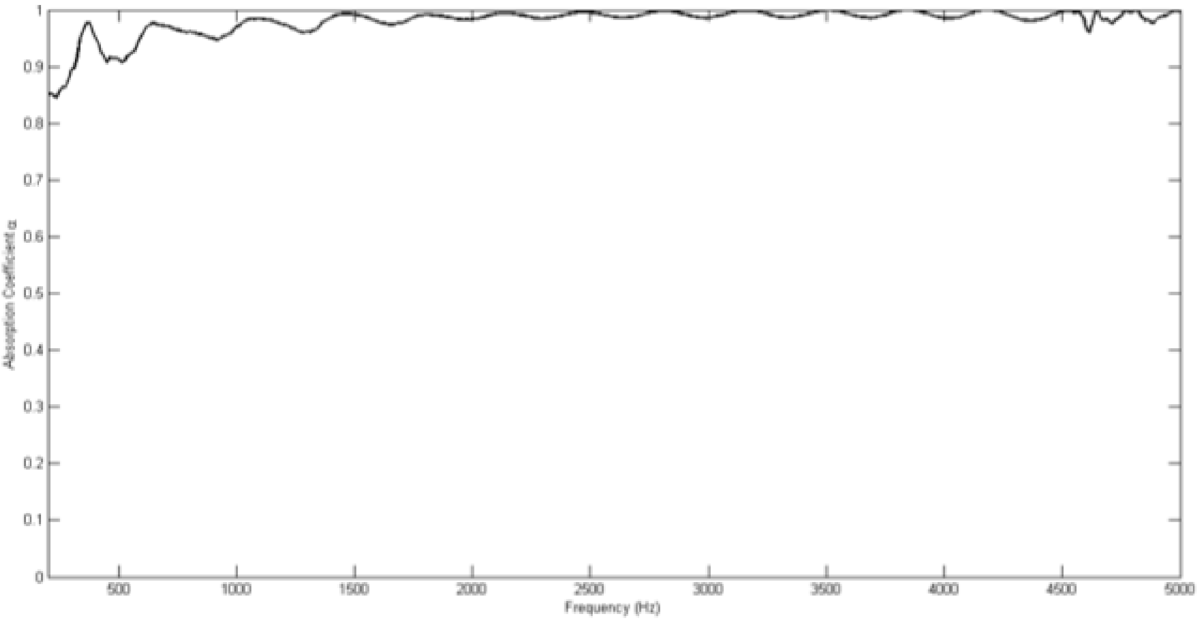


Fig. 5.5.4.1.1: Absorption coefficient of anechoic foam measured in the impedance tube as a validation measurement.

The coherence is also shown for each scenario. The coherence is a metric that measures the correlation between two signals that is often used to detect the presence of noise in digital signal processing. It is useful in impedance tube testing because it can prove the presence of disruptive standing waves (peaks and nulls within the tube).

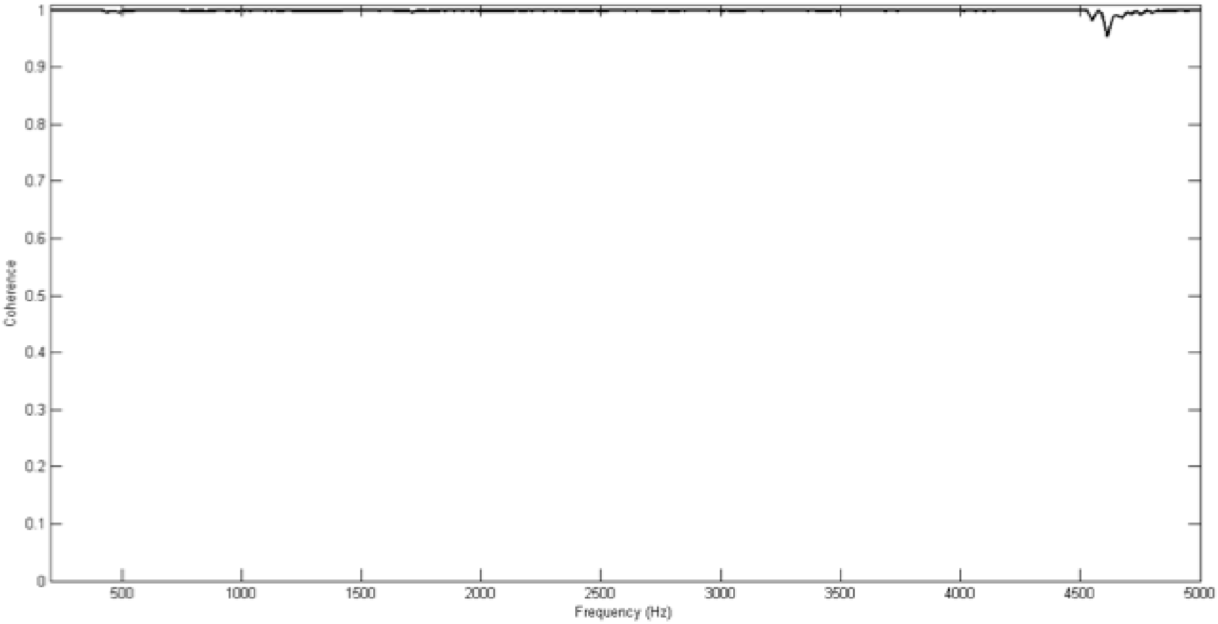


Fig. 5.5.4.1.2: The coherence of the anechoic foam measurement.

These results are encouraging. There is a small dip in coherence above 4500 Hz, but that is to be expected. Per the ASTM E1050 standard for impedance tube testing methods, the upper frequency limit of the tube is defined as

$$f_u < \frac{Kc}{d} \qquad \text{Eq. 5.5.4.1.1}$$

where f_u is the upper frequency limit (Hz), c is the speed of sound in the tube (m/s), d is the diameter (or largest section dimension) of the tube (m), and K is a constant, 0.5 (for rectangular tubes). Our tube is 0.038 m^2, and the speed of sound in the tube is 343 m/s. This puts the upper limit of the ETS-Lindgren tube at 4513 Hz. Above this frequency, cross-modes have started to affect the coherence between the two microphones.

Another test was performed with the sample holder with no sample inside (a rigid stop). We can compare the specific acoustic impedance measured to the expected specific acoustic impedance of a rigid stop.

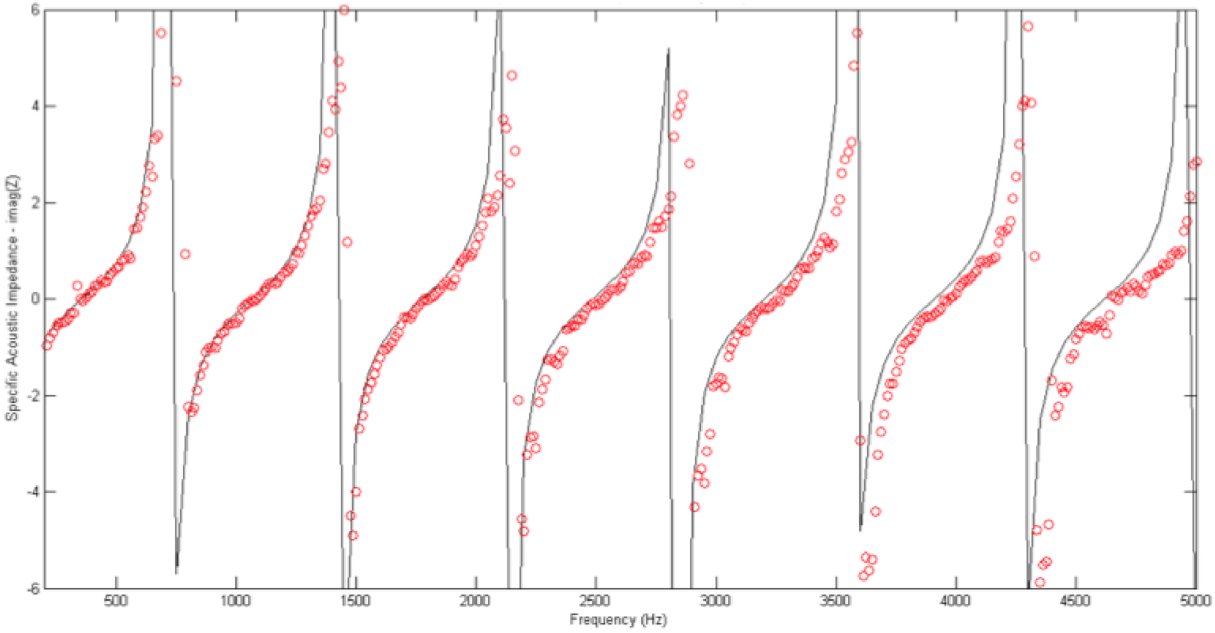


Fig. 5.5.4.1.3: The measured and calculated specific acoustic impedance for a rigid stop in the ETS-Lindgren impedance tube. The black line is the calculated impedance, and the red circles are the measured impedance.

The solid line represents the theoretical acoustic impedance for a rigid stop in a tube of this size calculated by

$$Z_t = -\cot(kd) \qquad \text{Eq. 5.5.4.1.2}$$

where k is the wavenumber and d is the distance from the rigid stop to the measurement point – in this case, the edge of the sample holder.

The data points represent the measured specific acoustic impedance in the tube. There is good agreement between the two, although it begins to deviate above 4500 Hz, as expected.

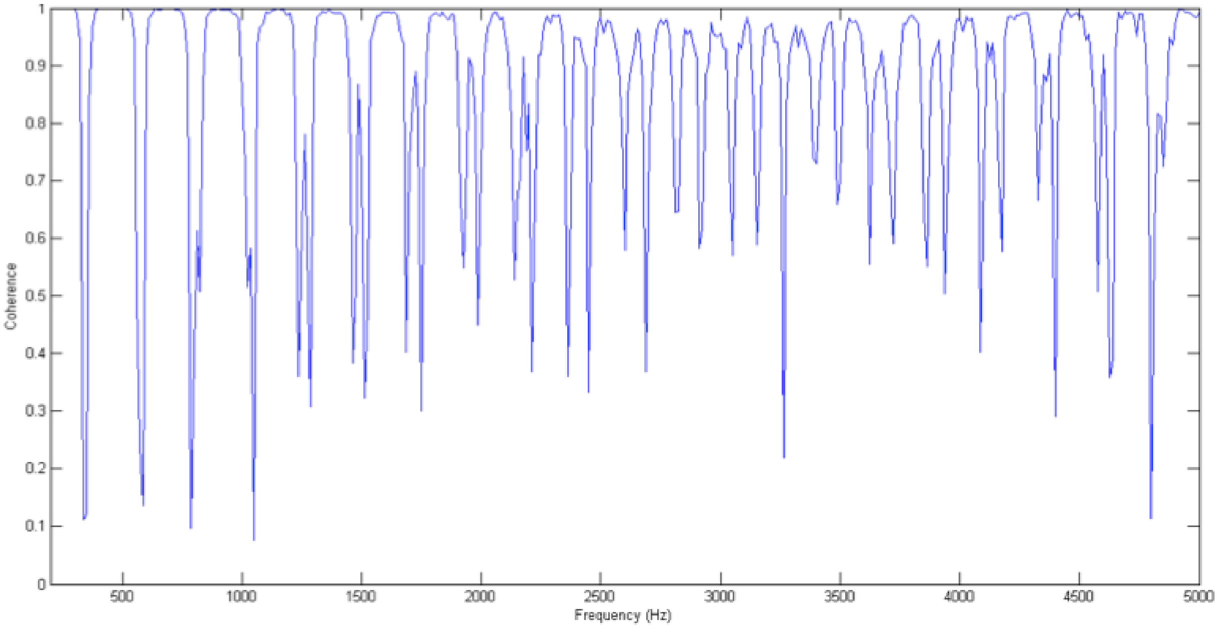


Fig. 5.5.4.1.4: Measured coherence for the rigid stop in the impedance tube.

Fig. 5.5.4.1.4 shows the coherence for the rigid stop measurements. The coherence plot is not clean. The first assumption was that this was caused by standing wave structures in the tube (if there is a null at or near one of the microphone locations, coherence would drop significantly). This is theoretically demonstrated in the coherence data, as towards higher frequencies, you get double dips (presumably due to the presence of more null locations) versus lower frequencies (fewer null locations).

However, this is not numerically verified. The full length of the tube (from rigid stop to speaker face) is 1.9336 m. For a pipe closed at both ends, the resonant frequencies should be

$$f_n = \frac{nc}{2L} \qquad \text{Eq. 5.5.4.1.3}$$

These frequencies are compared to the nulls in the coherence in the following table. There is little to no agreement, except at the fundamental frequency.

Table 5.5.4.1.1: Calculated and measured coherence nulls for a rigid stop in the impedance tube.

n	Closed-Closed (Hz)	Coherence Nulls (Hz)
1	331.6124	337
2	663.2248	587
3	994.8372	787
4	1326.4496	1050
5	1658.062	1238

5.5.4.2 Gypsum Measurements

After the impedance tube was verified, gypsum was placed in the sample holder and measured.

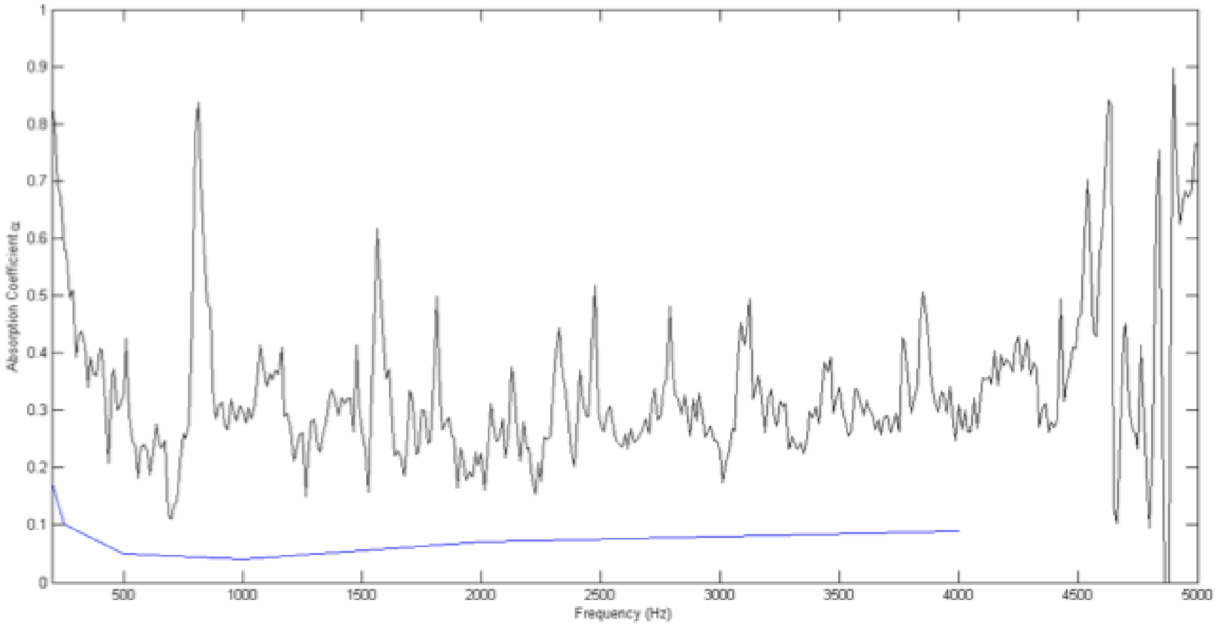


Fig. 5.5.4.2.1: The absorption coefficient of the gypsum wall board. The black line is the measured in the impedance tube. The blue line is the octave-band absorption (Acoustical Surfaces, Inc. 2014).

Fig. 5.5.4.2.1 presents the absorption coefficient of the gypsum wallboard. The data is not what should be expected – in comparison, the blue line represents the octave-band absorption coefficients presented in acoustic textbooks. The measured absorption presents more losses than one would expect from gypsum wallboard.

Fig. 5.5.4.2.2 shows the coherence of the gypsum wallboard measurement. The coherence in this measurement shows the same type of structure as seen in the rigid stop measurements. This points to the development of standing waves that was expected in the rigid stop.

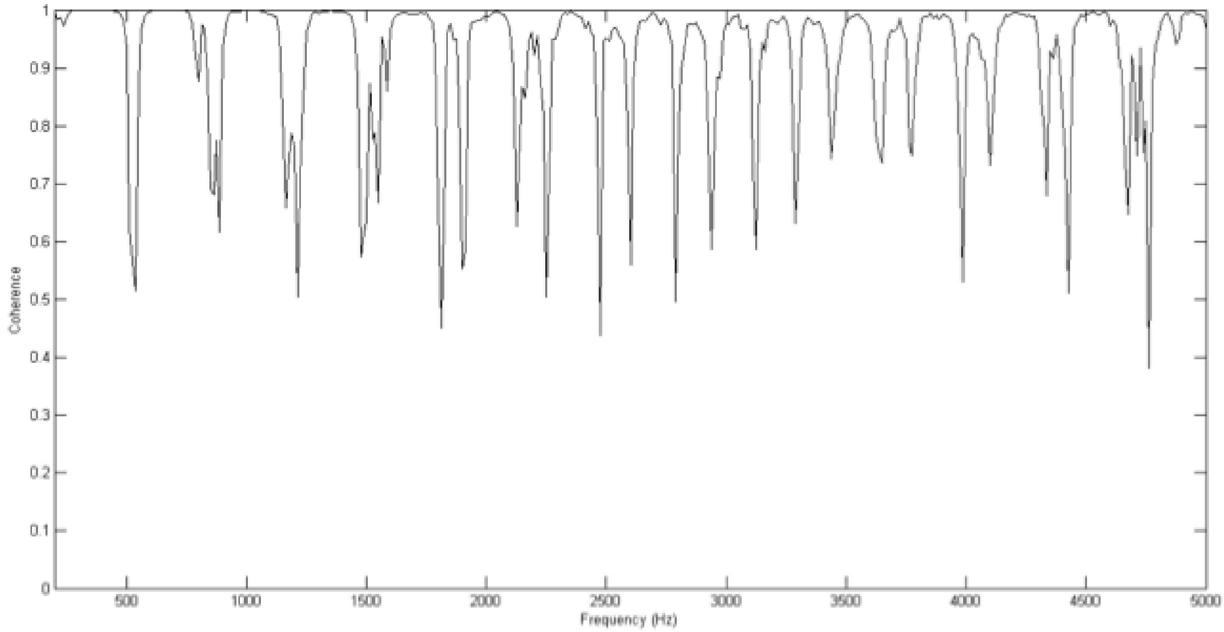


Fig. 5.5.4.2.2: Coherence of the gypsum wallboard measurement.

The next iteration used a new sample holder with less space between the sample and the rigid backing plate (4.365 cm). It still did not mount the gypsum wallboard flush against the rigid back, but the distance between the two decreased. It was not possible to create a stop short enough to place the gypsum flush against the rigid backing due to the geometry of the tube.

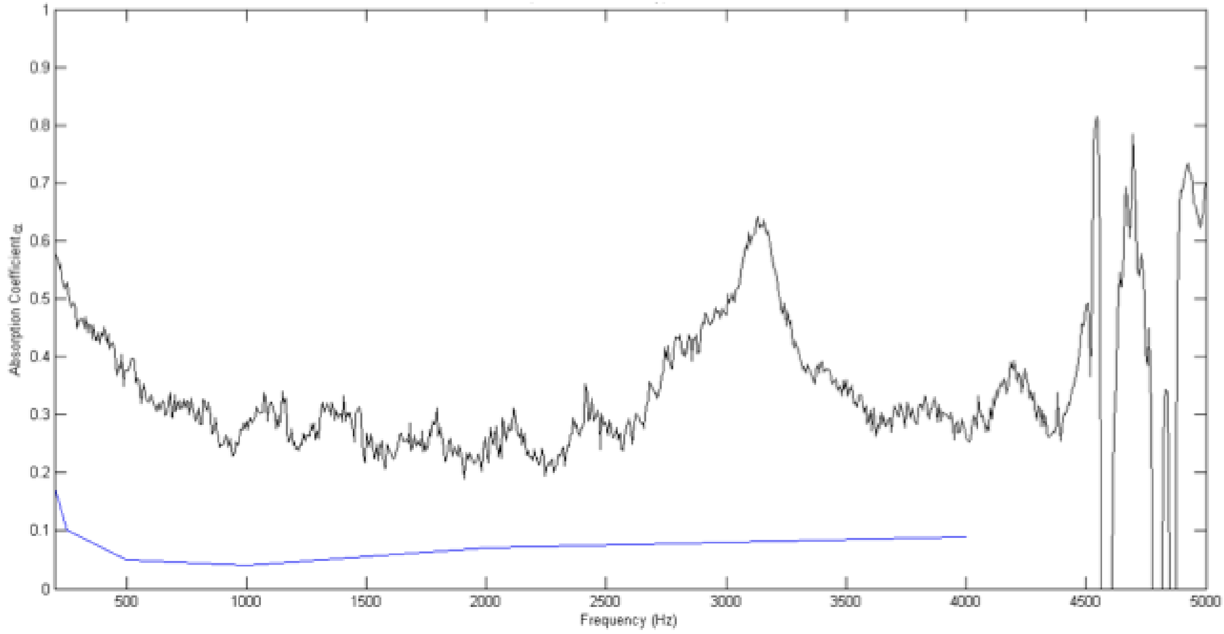


Fig. 5.5.4.2.3: The absorption coefficient of the gypsum wall board using the second position. The black line represents the measurements, and the blue line again shows the octave-band values.

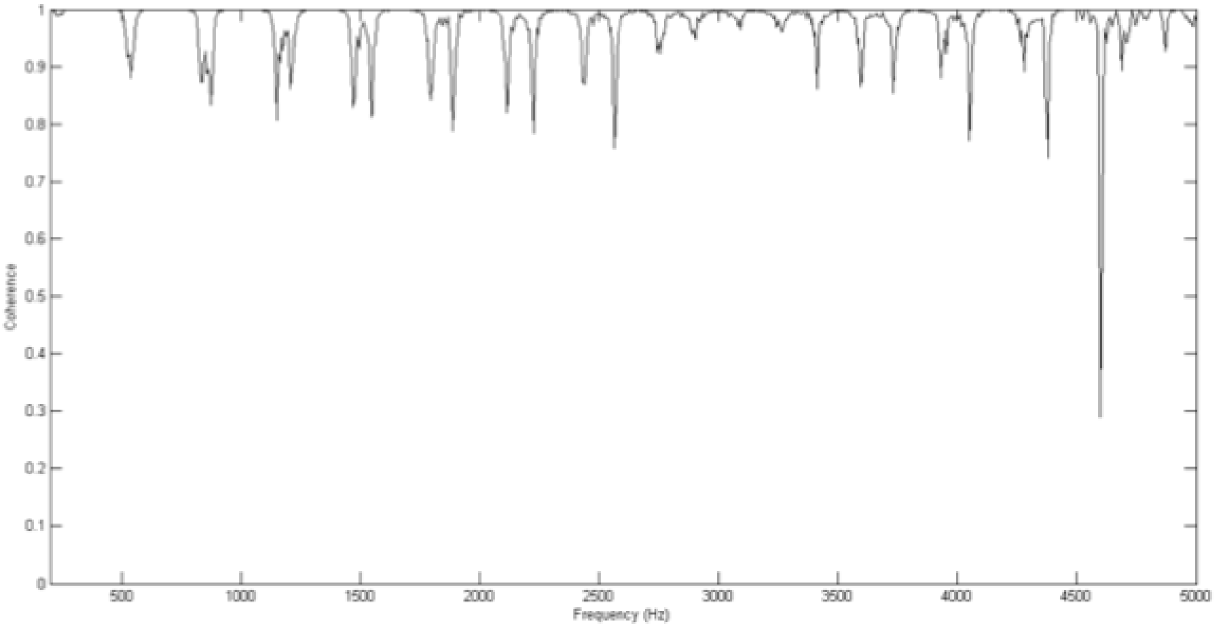


Fig. 5.5.4.2.4: The measured coherence from the second gypsum wallboard test.

Fig. 5.5.4.2.4 shows the coherence from this second test. The coherence improved, implying that something about the sample holder structure is causing the resonances in the first place. However, for all measurements taken with the new sample holder, the absorption coefficient shows a spike around 3000 Hz (up to an absorption coefficient of 0.7 – for reference, this is approximately equal to the absorption of acoustic drapery). This correlates with an improvement in coherence. The increased losses are due to the tube's design; the tube is not intended for rigid samples and is at best loosely adapted for the purpose.

5.5.4.3 Burned Gypsum Measurements

Although the data obtained for unburned gypsum was not near the range of expected values, a burned sample was measured for the purposes of a general comparison.

16% mass loss represents complete dehydration of the sample. However, gypsum will rehydrate by about 4% between time in the oven and a longer period of time after heat exposure. Because there was no oven at the impedance tube facility, rehydration was inevitable (but measurable).

The initial mass of the gypsum sample was 72.5 g. It was placed in a lab convection oven for 60 minutes at 200°C. After heat exposure, the gypsum sample measured 60.2 g, or approximately a 17% mass loss. After 2 hours of rehydration, the gypsum sample measured 62.9 g, or approximately a 13% mass loss.

In a fire, the ablation process would proceed in a very similar manner. One difference between the two is that the paper layer would probably ignite and burn away. However, this limits the structural integrity of the sample, and when this was attempted, the sample could not stand alone in the sample holder. The pressure to put it in place caused the dehydrated gypsum to crumble.

The burned sample used the same setup as the unburned sample presented immediately prior to this, and the results can be seen in Fig. 5.5.4.3.1.

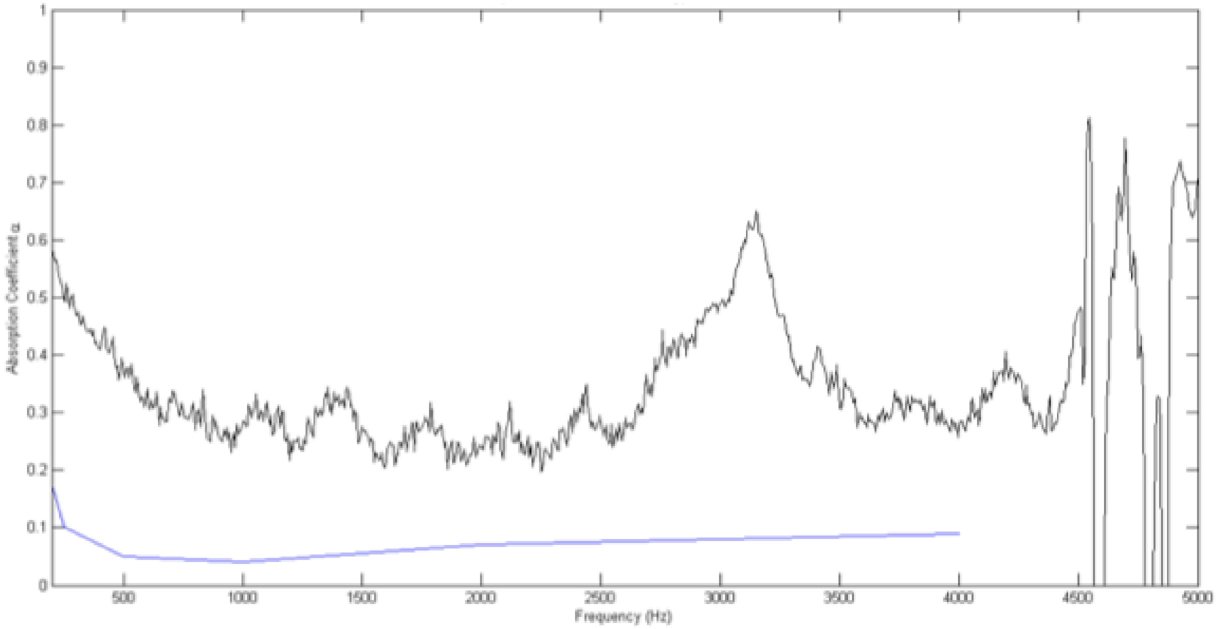


Fig. 5.5.4.3.1: The absorption coefficient for the burned gypsum sample. The black line is the measured absorption. The blue line is the octave-band absorption coefficient of gypsum.

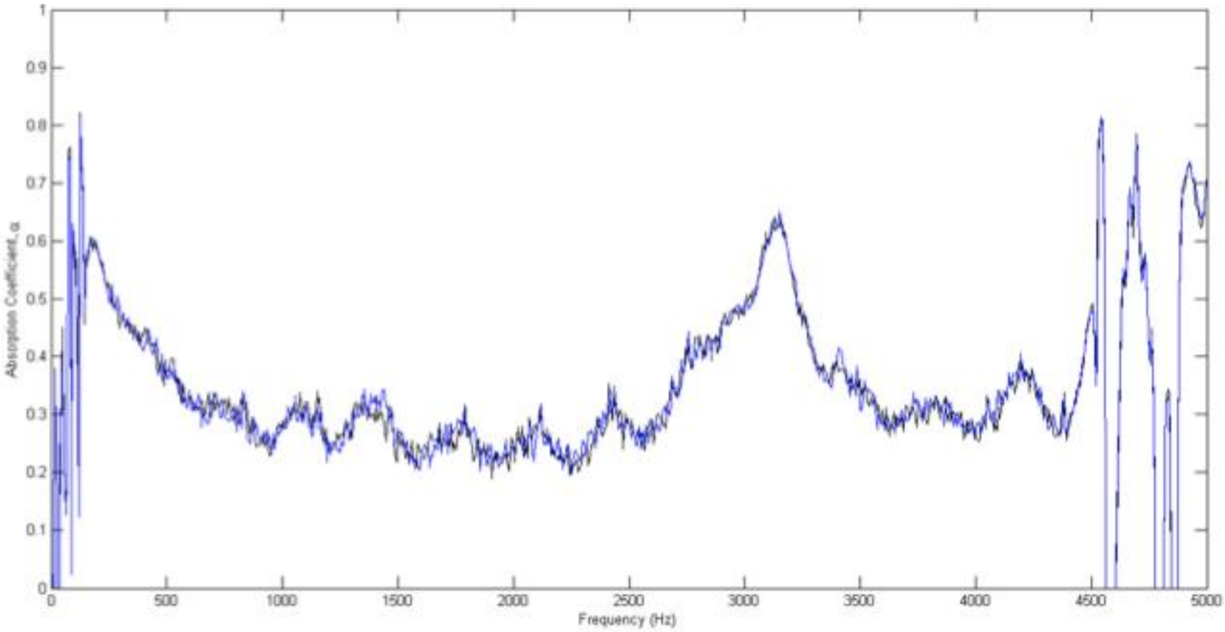


Fig.5.5.4.3.2: A comparison of the measured absorption coefficients for both the burned and unburned gypsum wallboard samples.

Fig. 5.5.4.3.2 shows a comparison of the burned gypsum wall board absorption coefficient to the unburned gypsum wallboard absorption coefficient. It is hard to see graphically, but there is less than 0.5% deviation between the two plots. Regardless of the unknown losses causing the absorption to be so high, there is negligible difference between an unburned sample and a fully dehydrated symbol. This implies that the change in acoustic properties between unburned and burned gypsum, prior to structural failure, is small.

5.6 Modeling and Validation Conclusions

In this section we detailed several tests to determine how acoustic transmission in a compartment could be affected by the presence of a fire. We showed that the hot gas layer affects the modal structure of the compartment and that the inhomogeneity of the environment causes attenuation of some frequencies. We showed that a combination of CFD and acoustic modeling was useful in identifying the physical causes of these observed acoustic effects. We also found that despite significant changes to the gypsum board strength after thermal degradation in a fire, there were relatively minor changes to the acoustical properties.

The received signal within a room is the convolution of the source signal with the room's acoustic response. The work reported in this section indicates that PASS may sound different to listeners within rooms as compared to outside, which is an expected result. The work reported in this section also shows that fire can change a room's acoustic response and cause fluctuations in the room response as the fire evolves, changing the modes of the room, and attenuating the higher frequencies (>1500 Hz). This means the PASS sound can change in real time as a firefighter is trying to detect, classify and localize the PASS signal. This could explain the anecdotes from firefighters that describe fluctuations in the PASS signal level and associated apparent distance changes perceived on active firegrounds.

5.7 Implications on Future Technological Enhancements

One consequence of fireground acoustic transmission fluctuation and its associated change in the received PASS signal is that automated detection systems based on correlation processing or matched filters will have to account for the continuously variable received signal. In other words, correlation processing relies on the received signal being similar to a predetermined model signal that must be known *a priori*. It is possible to do adaptive and/or model-based processing that accounts for transmission-induced received signal variation, but this is likely to increase the cost and complexity of the development of such systems, and the cost and complexity of the systems themselves. The degree to which the signal variation observed in this work might affect correlation processing was not investigated here, nor was a full range of fireground conditions studied here. Future work will be required to fully investigate the implications of variable acoustic transmission on automated detection and localization technologies.

6. Physical Acoustic and Audiology Testing with PPE

There are two major characteristics of the receiver that need to be investigated – the DI and the DT. Because the receiver of the PASS system is the unaided hearing of a firefighter, the DI is associated with the firefighter's ability to localize and DT is associated with the firefighter's ability to detect. A firefighters hood, helmet, and coat all change the sound that reaches the firefighter. To measure this change, and how it affects human hearing, two experiments were conducted. One used an acoustic manikin to measure the physical effects of the PPE on the signal. The second was an audiology study to measure how the PPE affected a human's auditory threshold.

6.1 Physical Acoustic Effects of PPE

6.1.1 Introduction

To measure the effects of the PPE, an acoustic manikin measured the head-related transfer function (HRTF) changes when the manikin was wearing the firefighting PPE and when it was not. A HRTF is a measurement of how the environment changes the acoustic signal as it travels from the sound source to the tympanic membrane. The changes in the signal can come from the room that the manikin is in or objects close to the manikin's head. HRTF have been used to measure the effect of everyday objects on the signal (Wersényi and Illényi 2005).

The acoustic manikin used for the physical acoustic experiment was a Knowles Electronic Manikin for Acoustic Research (KEMAR). This manikin is designed to simulate the physical characteristics of a person that are important to understand the signal reaching the tympanic membrane. These characteristics include the physiology of a human head and torso, as well as pinnae made of material that is acoustically matched to human pinnae. This manikin allows for consistent acoustic measurements of signals and how they change when the physical conditions around the manikin change. In this study, the change in the physical conditions was the addition of firefighting personal protective equipment (PPE) to the KEMAR.

6.1.2 Measurement Procedure

The KEMAR was placed in the University of Texas anechoic chamber to reduce changes caused by room effects and measure only the changes caused by the PPE. The KEMAR was placed in the middle of the chamber on an automated turntable that rotated 360° in 2° increments. The KEMAR was on a pole such that it was 1.8 m away from the source and tall enough to simulate an average human male. This can be seen in Fig. 6.1.2.1. The speaker produced 25 linear chirps from 500 Hz to 8000 Hz. The KEMAR's two ¼" microphones measured the signal and sent it to a computer where the amplitude and phase of the measured and produced signals were linearly averaged. The resulting measurements were then used to calculate head-related transfer functions (HRTF).

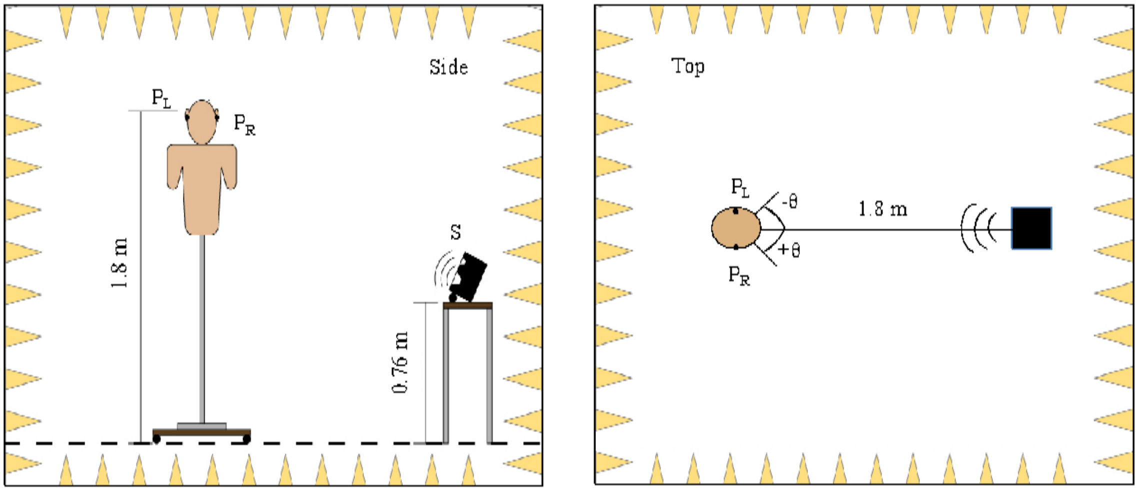


Fig. 6.1.2.1: A sketch of the KEMAR in the anechoic chamber. On the left is a side view. On the right is a top view.

The HRTF were calculated with fast Fourier transforms and the following:

$$P_i(f) = \mathrm{FFT}[p_i(t)] \qquad \text{Eq. 6.1.2.1}$$

where *i* is either left (L) or right (R) $p_i(\mathrm{t})$ is the time domain acoustic pressure output of the left or right microphone,

$$S(f) = \mathrm{FFT}[s(t)] \qquad \text{Eq. 6.2.1.2}$$

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

$$HRTF(\theta, f) = 20\log_{10}\left\lfloor \frac{P_i(\theta, f)}{X(\theta, f)} \right\rfloor \qquad \text{Eq. 6.2.1.3}$$

where $X(\theta, f)$ is either $S(\theta, f)$ or $P(\theta, f)$ of the opposite ear. This procedure was used to measure the HRTF for the bare KEMAR, KEMAR wearing individually a firefighting coat, hood, and helmet, and the whole ensemble of coat, hood, and helmet.

In order to compare multiple HRTF across all frequencies and angles, a single number metric D_{rms} was established. To calculate this, first D is calculated using:

$$D(\theta, f) = 20\log_{10}\left\lfloor \frac{P(\theta, f)_{R,BARE}}{P(\theta, f)_{R,HELMET}} \right\rfloor \qquad \text{Eq. 6.2.1.4}$$

This was adapted from Wersenyi, et al [15].

$$D_{RMS} = \frac{1}{2\pi N}\sum_i \sqrt{\sum_k D(\theta_k, f_i)^2} \qquad \text{Eq. 6.2.1.5}$$

where N is the number of frequencies of interest in the HRTF. Here, the D_{rms} was calculated for the frequencies between 0 Hz and 4000 Hz.

6.1.3 Effect on PPE on RL

The bare and gear HRTF measurements can be seen in Fig. 6.2.3.1. One thing to notice is that in the bare results, there is a monotonic transition from the left to right of the graph. This is how humans normally localize sound. There is a smooth change from where the sound is loudest in the ear closest to the sound source and it evenly changes to being low in the ear that is farther from the source. In the right colormap, there are many changes between the higher and lower sound pressure levels. These multiple changes could confound the localization of the PASS alarm signal.

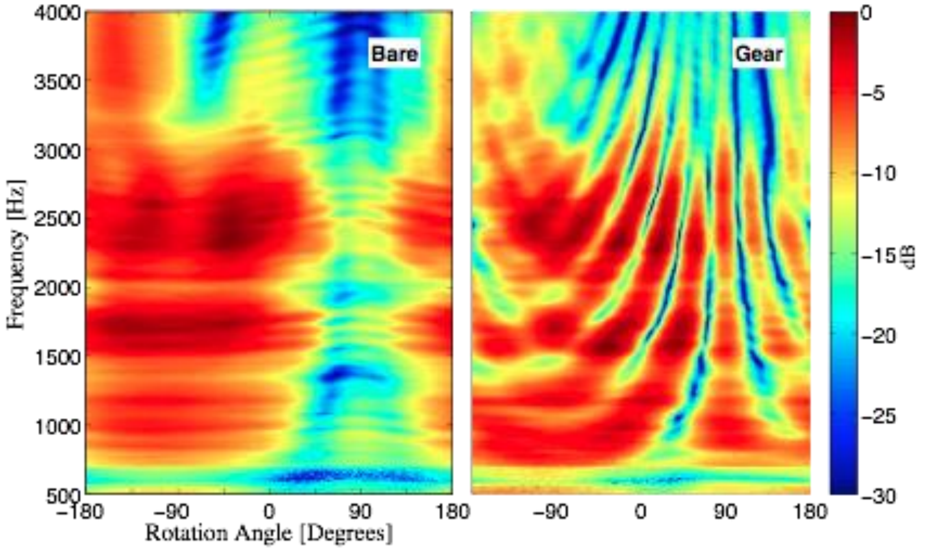


Fig. 6.2.3.1: The bare, left, and gear, right, results of the HRTF measurements with the KEMAR. The warmer colors denote higher sound pressure levels.

The other point of interest is that there is an average 3 dB reduction in level in the results of the KEMAR wearing the coat, hood, and helmet. This reduction is equal to lowering the detection radius by 1.4 m (4.6 ft). This is a reduction in all frequencies and signals, not just the PASS. However, this does not help the PASS either.

An anechoic chamber is a room with no reflections. This environment is ideal for measuring the HRTF changes, but it is not a normally occurring condition. To see how these effects would change in the presence of normal room reverberation, or extreme reverberation, the same measurements were conducted in an office on The University of Texas campus and a reverberation chamber on campus. These two HRTF measurements can be seen in Fig. 6.2.3.2 and Fig. 6.2.3.3 respectively.

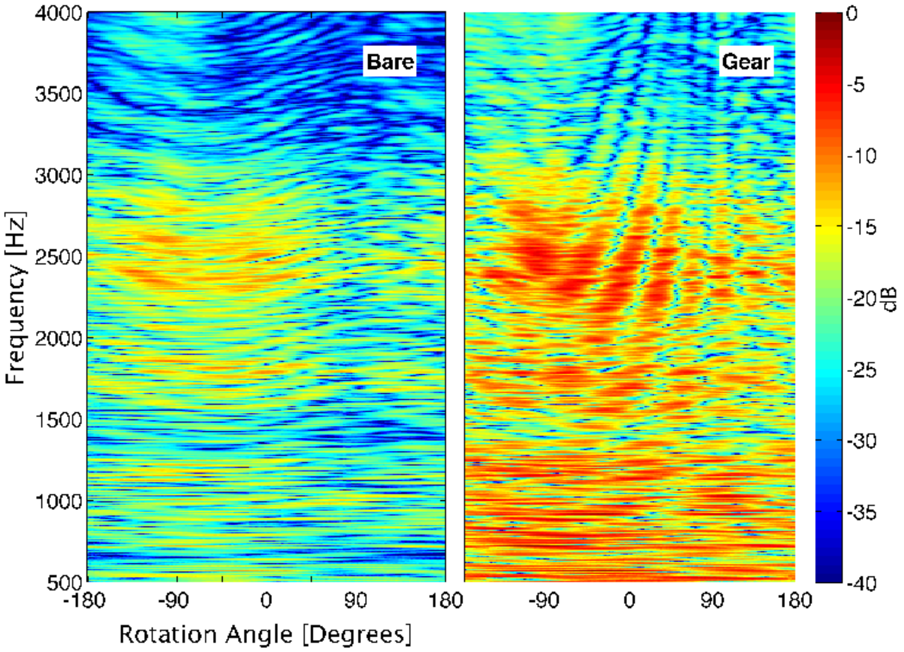


Fig. 6.2.3.2: The bare, left, and gear, right, results of the HRTF measurements with the KEMAR in the office. The warmer colors denote higher sound pressure levels.

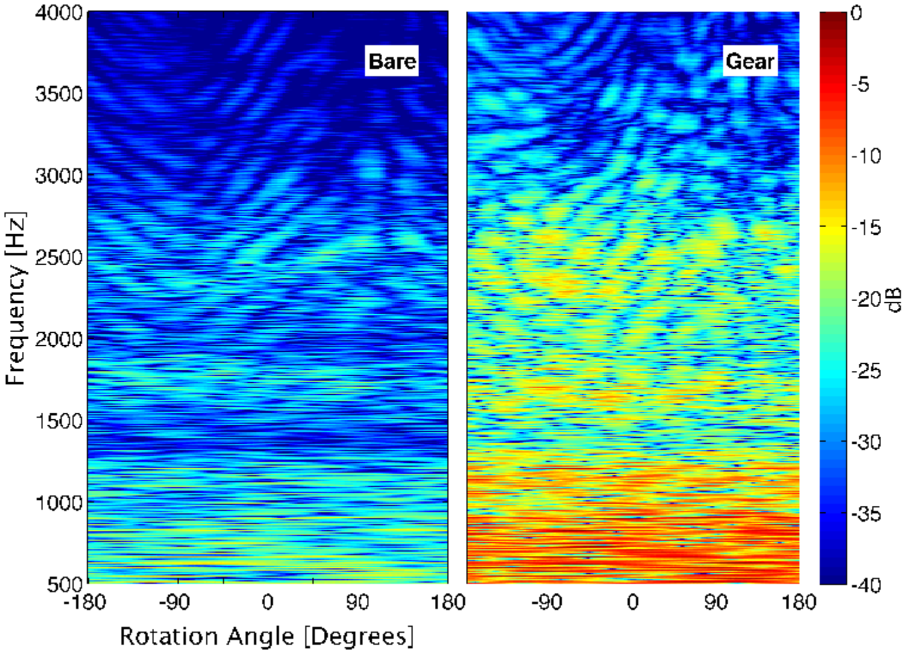


Fig. 6.2.3.3: The bare, left, and gear, right, results of the HRTF measurements with the KEMAR in the reverberation room. The warmer colors denote higher sound pressure levels.

The results from both measurements show the effect that reverberation has on localization cues. There is a smearing effect of the features that are prominent in both the bare and gear case. The change in received level seen in the reverberation results is a result of the size of the reverberation chamber.

6.1.4 Variation across Twelve Different Helmet Designs

During the original study of the effects of the PPE on human hearing, it was noticed that the firefighting helmet had the largest effect on the structure of the receive signal. To understand this change better, eleven other helmets were acquired and tested in the same manner. The result of this testing can be seen in Table 6.2.4.1. HRTFs for all twelve helmets can be seen in Appendix B.

The results of this study show that there are a varying effects caused by each helmet. Each helmet shows a deviation from the bare case with rapid changes between high and low receive levels instead of the monotonic shift. Two typical examples of this deviation can be seen in Fig. 6.2.4.1. These effects range in a D_{rms} from 2.65 to 4.03.

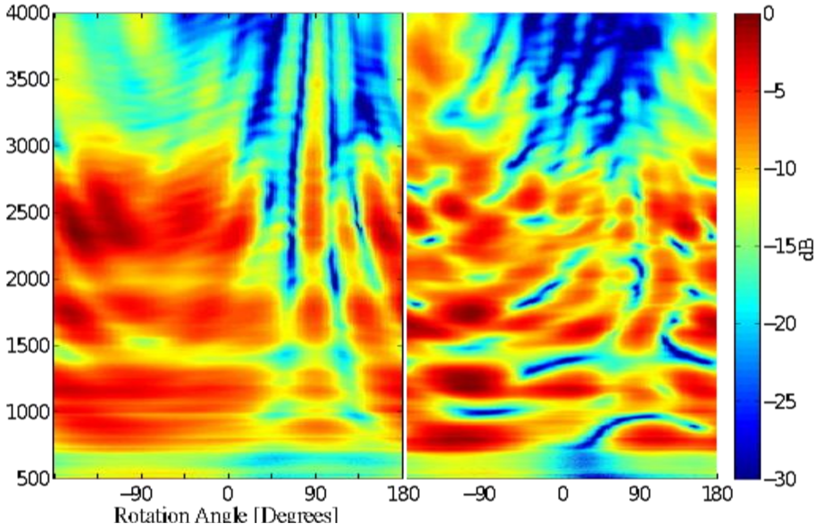


Fig. 6.2.4.1: The HRTFs of two helmets tested. The helmet on the left had a D_{rms} of 2.65. The helmet on the right had a D_{rms} of 4.03.

Table 6.2.4.1: The D_{rms}, style, and type of face protection for all helmets. M denotes a modern style. T is a traditional style. E is European. G is goggles. FS is face shield. FS* is the double face shield found with the European style helmet.

Helmet	Style	Face Protection	D_{rms}	Helmet	Style	Face Protection	D_{rms}
1	M	G	2.65	7	T	G	3.48
2	T	G	3.13	8	M	FS	3.68
3	M	FS	3.20	9	M	FS	3.85
4	T	G	3.29	10	M	FS	3.93
5	T	FS	3.33	11	T	FS	4.01
6	M	FS	3.36	12	E	FS*	4.03

6.2 Audiology Testing

A part of the sonar equation is the characteristics of the receiver. In the case of the PASS alarm, the receiver is the firefighter. Equipment worn by firefighters, like the personal protective equipment (PPE), could affect their ability to detect the PASS alarm. Two studies were used to begin to understand the effects of firefighter PPE on human hearing. The first was a physical acoustics study where an acoustic manikin was used to simulate how the coat, hood, and helmet typically worn by firefighters affected the signal as it travelled to a human's eardrums. The second was an audiology study to see how humans were truly affected by the absorption of the hood, coat, and helmet.

Studies have been conducted to see how military helmets affect auditory threshold, localization and speech intelligibility (Randall and Holland 1972). These studies showed little effect caused by the military helmets, but there are differences in the styles of these helmets and the firefighter helmets. Also, the addition of the hood and coat to the ensemble has shown to make a difference in the received levels as shown in the HRTF measurements.

6.2.1 Introduction

Auditory threshold is a measurement of the level of a sound that a person can just hear. To measure this, a method of limits (MOL) study was conducted. A MOL study measures this level by varying the level of an output signal from a speaker and the listener signals that they have heard it or not. If it is an ascending study, the signal starts at a level the listener cannot hear and is incrementally increased until the subject hears the signal. A descending study starts with the signal being easily heard and incrementally decreasing it until the listener can no longer hear it. This study used a modified study where the signal was easily heard and decreased until it could not be heard. Then it was increased again until it could be heard. After having gone back and forth across the auditory threshold several times, the results are averaged to obtain an auditory threshold for the signal.

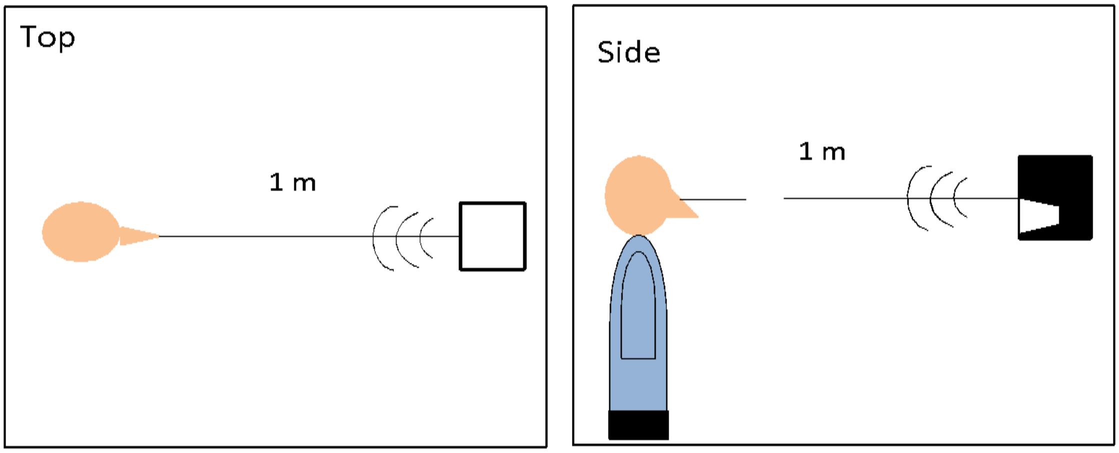


Fig. 6.2.1.1: A cartoon sketch of the listener's position relative to the speaker during the method of limits study.

For this study, ten listeners were recruited and paid for their participation in this study. The listeners had normal hearing within 20 dB. All listeners gave written informed consent in accordance with The University of Texas at Austin Institutional Review Board. These listeners were placed in a listening booth in the University of Texas Speech and Hearing Center for the duration of their testing. They were in the center of the booth 1 m away from a KRK Rokit 5 RPG powered loudspeaker that was adjusted to fit their height. This can be seen in Fig. 6.2.1.1.

6.2.2 Subject Test Results

The average change in auditory threshold, and associated standard deviation, can be seen in Fig. 6.2.2.1. The graph on the left shows the change in auditory threshold due to the helmet. The graph on the right shows the change in auditory threshold due to wearing the coat hood and helmet. Due to the limitations of the equipment used, anything under 5 dB is deemed insignificant. The helmet and hood, coat, and helmet cases show similar results. In both, the lower frequencies have no significant changes, while the higher frequencies and the PASS device show a positive change in auditory threshold. A positive change in auditory threshold means that the listener needed more sound pressure level in order to detect the signal. These results show that the listeners, on average, needed 7 dB more SPL to detect the signals.

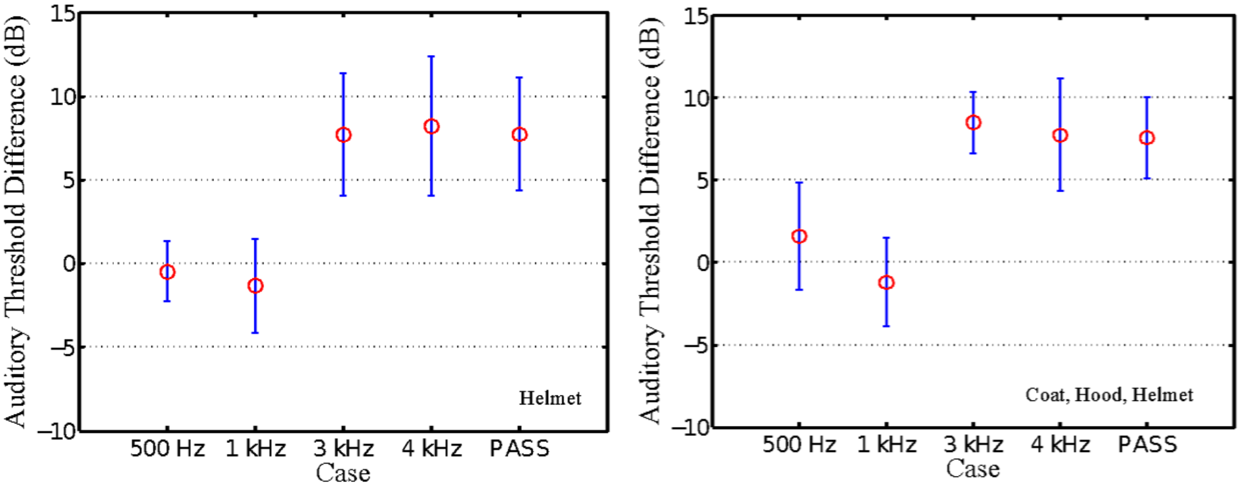


Fig. 6.2.2.1: The auditory threshold differences caused by wearing the firefighting helmet, left, and the coat, hood and helmet, right, calculated from the method of limits study. The average of the results is the circle symbol, and the error bars represent the standard deviation.

Also in Fig. 6.2.2.1, the error bars show the standard deviations of the results. These show that there was less spread in the coat-hood-helmet case than in the helmet case.

6.3 Conclusions

This section presents physical and audiology results associated with use of fire fighter PPE. In general, these results were consistent and both forms of testing revealed significant impact of PPE on human hearing. In the physical acoustics testing, received levels were measured as a function of direction relative to the source. The measurements revealed a mean received level reduction of 3 dB, averaged over direction and frequency. The significance of this reduction is due to its effect on detection range. According to the sonar equation, a 3 dB reduction in received level corresponds to a detection range reduction of about 1/3. In other words, a 3 dB reduction in received level would reduce a 100 ft detection range to about 70 ft. The measurements on fire helmets revealed that they had a major impact on the amplitude of signals received at the ear. The helmets caused frequency- and received-angle-dependence that deviate greatly from those measured on a bare head. A single number metric was devised to rank this deviation. Helmets tested showed that there were no apparent trends associated with the use of goggles or face shields, or between modern and traditional styles. The metric did show that the European style helmet caused the most deviation. One possible remedy for this is to train firefighters to repeatedly rotate their heads while attempting to localize the PASS, which has the effect of averaging out the helmet effect.

The results of the auditory testing indicated that fire fighter PPE caused a mean increase in the auditory detection threshold by 5 dB, which is statistically consistent with the physical acoustics results described above. This reduces detection range while wearing PPE and could result in longer locate times while searching for lost or injured firefighters. This could be overcome by making the PASS device louder. The PASS source level was originally chosen to correspond with safe hearing metrics associated with unprotected human ears. Since the PPE reduces the received level at the ear, and was also demonstrated to yield a similar perceptual change, increasing the PASS source level by 3 dB to 5 dB would offset the effect of the PPE and increase detection range.

6.4 Implications on Future Technological Enhancements

The results in this section are primarily related to the human detection of PASS signals in the presence of PPE, but any future PASS enhancement should consider the acoustic design of fire fighter helmets. It is likely that improved acoustic performance of fire helmets could be achieved. Using microphones located along the brim of the fire helmet would likely reduce the diffraction effects reported in this section and hence one possible technological enhancement would be to use such microphones to direct signals to the ears of firefighters by using earpieces, as one finds in aviation helmets and various other helmets, such as communications-equipped motorcycle helmets. This would remove the localization-related difficulties caused by the helmet and likely yield improved localization.

7. Evaluation of Firefighter Response to PASS Signal in Simulated Fireground Conditions

7.1 Introduction

To improve the PASS signal, the whole energy balance of the sonar equation must be considered in combination, including the human reaction to the observed physical effects. Towards this goal a study was conducted to see how the firefighters reacted to the effects previously analyzed. The goal of this study is to see how the combination of NL, DI, and TL affect firefighters. Four experiments were conducted at three fire departments – two at Austin Fire Department (AFD), one at Glendale Fire Department (GFD) and one at Oklahoma City Fire Department (OKCFD). To achieve this, scenarios were designed where firefighters were told to search for the location of a PASS signal in a structure while wearing full PPE. During the runs, the firefighters conducted a crawling search with obscured vision. This study combined the effects of the PPE, background noise, signal level, and basic transmission loss through a structure.

7.1.1 Subjects

Twelve to fourteen firefighters were recruited for each field test – twelve at the two field tests at AFD and fourteen for each field test at GFD and OKCFD. The firefighters were wearing full PPE (coat, hood, helmet, etc.) and using an SCBA. Each firefighter was given the same instructions: to use a crawling search to locate the PASS device while their vision was obscured. They were instructed to double tap their helmet when they first heard the PASS signal. This search was conducted in both a quiet condition and in a condition with added noise. Both the signal and the added noise were reproduced using speakers. A firefighting helmet was placed next to the speaker producing the signal to distinguish it from the speakers playing background noise. The tester would signal to the searcher the test was over either when the firefighter found the helmet or the speaker. All firefighters gave verbal consent in accordance with The University of Texas at Austin Institutional Review Board.

7.1.2 Scenarios

For each field test, the locations of the background speakers (four JBL LSR2328P), the PASS speaker (a KRK Rokit 5 G3), and the starting point were determined beforehand. Two locations for the PASS were chosen – one that created a longer path and one that created a shorter path. The background speaker locations were chosen with the intention of complicating the task of localization.

Four scenarios were used during each experiment. Two of the scenarios used the longer path, and two used the shorter path. The two scenarios for each path were with or without the added background noise. The testing matrix can be seen in Table 6.1.2.1.

Table 6.1.2.1: The testing matrix for the field tests showing the distribution of tests for each scenario

		Sound Scape	
		PASS and Noise	PASS only
Scenario	Long	7	7
	Short	7	7

The sounds used to provide the background noise were the previously recorded sounds analyzed in Section 3. They were Chainsaw 1, PPV 1, Chainsaw 2, and Engine with pump and generator. All of these sounds were reproduced at level.

7.1.3 Layouts

Each fire department was asked to provide the facility for the field tests. Once a location was agreed upon, a sketch of the building was used to design the scenarios that were discussed in Section 7.1.2. Waypoints were added to the layout to help track the firefighters. These waypoints also provided some information on average crawling speeds for firefighters under these conditions.

7.1.3.1 Austin, TX Facility

The AFD provided facility used in both tests was an out building at the AFD training center. The building had two hallways with linoleum floors, three offices with carpet, and four rooms of varying size with linoleum floors. The entire building was 1781 sq. ft. (165.5 m^2). The layout of the building can be seen in Fig. 7.1.3.1.1.

Four scenarios were set up in the building as described in Sec. 7.1.2. The location for the PASS device for the long scenario was at the end of the large long room farthest away from the entrance marked as PASS 1 in Fig. 7.1.3.1.1. The approximate path length for PASS 1 is 80 ft. (24.3 m). The location for the PASS device for the short scenario was along the back wall of the office at the end of the short hallway farthest from the entrance, approximately 24.4 ft. (7.43 m) from the start. The crosses note the locations of the background noise with labels underneath – CS is chainsaw 1, RS is chainsaw 2, Eng is the pumper truck with pump and onboard generator, and PPV is PPV 1.

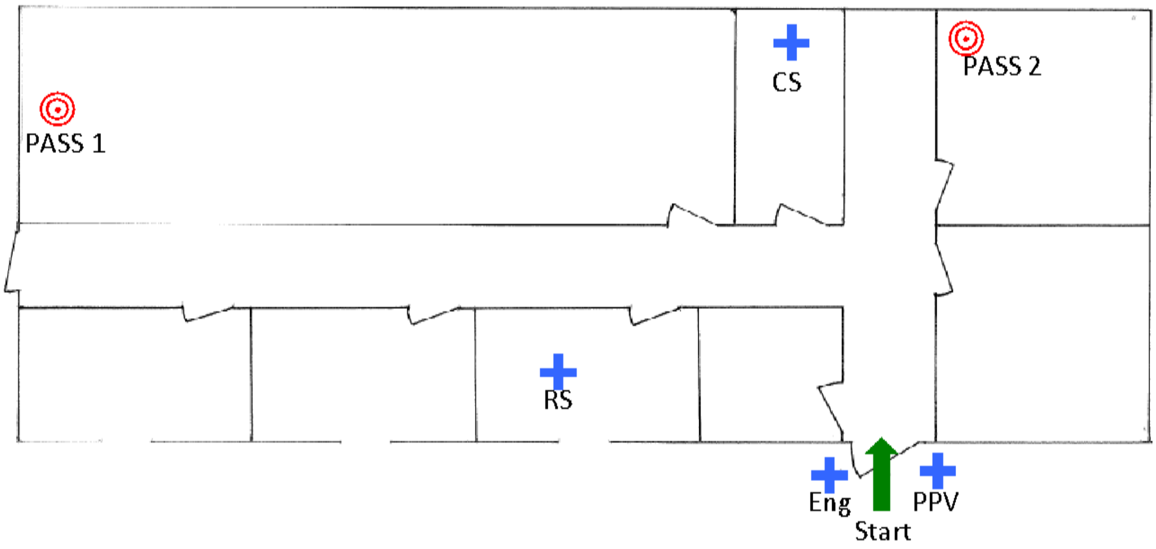


Fig. 7.1.3.1.1: The layout of the AFD scenario for both the long and short scenario. The red targets are the positions of the PASS devices for the long and short scenario. The blue crosses show the location of the speakers used to provide the background noise in each scenario.

7.1.3.2 Glendale, AZ Facility

The building provided by the Glendale Fire Department is a part of their training facility. The portion used was a warehouse type room, 9500 sq. ft. (882.6 m^2), with a 40 ft. (20.19 m) ceiling. Across half the ceiling there was a catwalk 25 ft. (7.62 m) above the floor. The walls and floors were made of acoustically reflective materials.

In the middle of the floor were two obstacles used in training. One was a steel frame. The other was several steel boxes about 3 ft. (0.91 m) high hooked together to form a u-shape. These are sketched in the layout in Fig. 7.1.3.2.1. Both PASS locations were past these obstacles. The first location was 79.5 ft. (24.23 m) from the start, and the second location was 62 ft. (18.83 m) from the start. CS was placed on the catwalk above the first PASS location with the speaker cone pointed down. The RS was placed in the middle of the right wall. Like the AFD layout, the PPV and Eng speakers were next to the start. All this can be seen in Fig. 7.1.3.2.1.

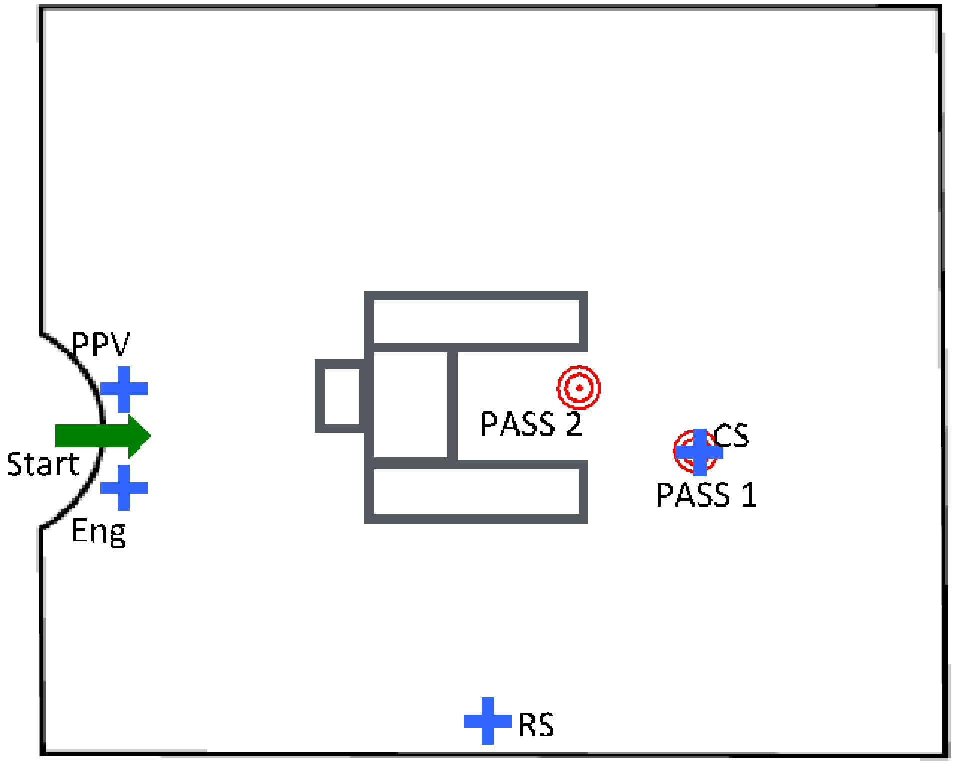


Fig. 7.1.3.2.1: The layout of the GFD scenario for both the long and short scenario. The red targets are the positions of the PASS devices for the long and short scenario. The blue crosses show the location of the speakers used to provide the background noise in each scenario.

7.1.3.3 Oklahoma City, OK Facility

The Oklahoma City fire department provided an offsite building in downtown Oklahoma City for the field test. This building was a warehouse with offices attached. The field test utilized the offices only, which covered 2548 sq. ft. (236.7 m^2). The building had concrete floors and cement block walls. In the long path scenario, the PASS was located in an office approximately 62.7 ft. (19.12 m) away from the starting point. The PASS in the short scenario was in the large room in the bottom right corner of the offices, approximately 54.5 ft. (16.6 m) away from the start. This can be seen in Fig. 7.1.3.3.1.

The two saws were placed relatively close to these positions. The CS was placed across the hall from the first PASS location, in a small bathroom. The RS was placed in the room next to the second PASS location. The Eng and PPV were again placed at the starting location.

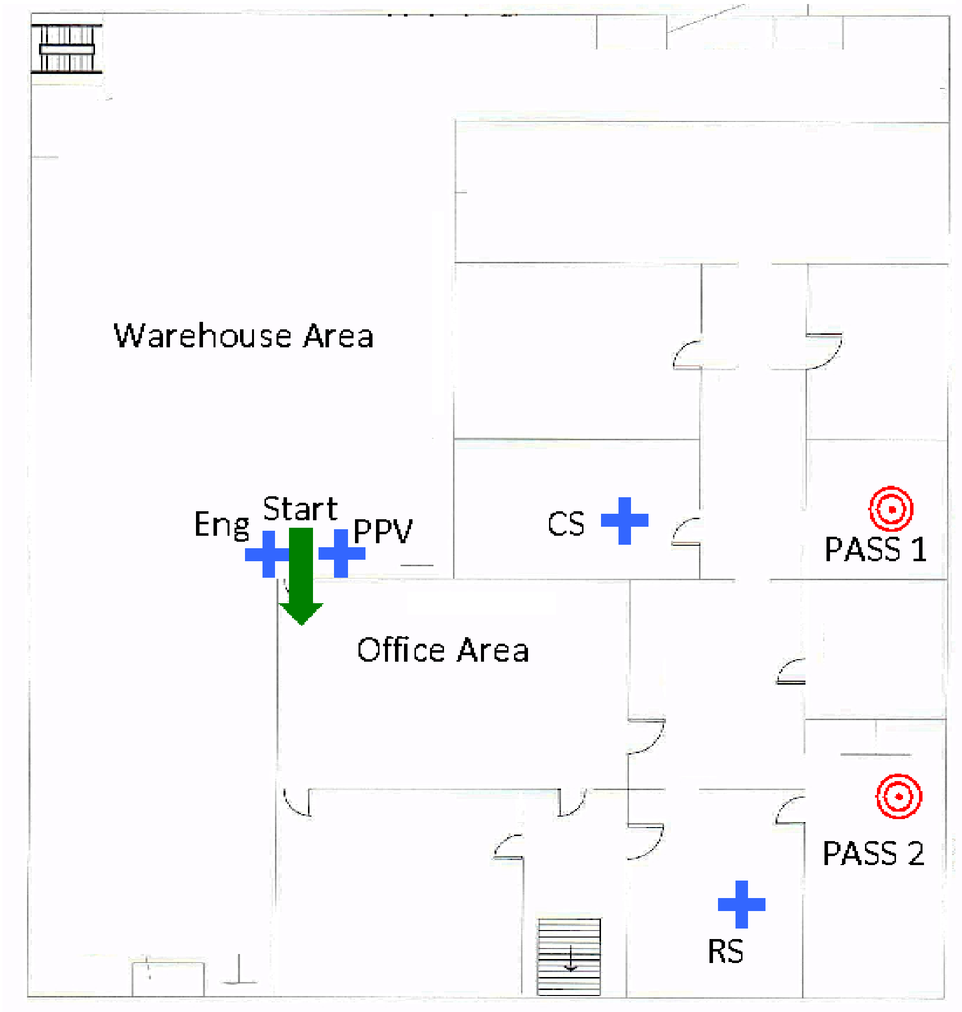


Fig. 7.1.3.3.1: The layout of the OKCFD scenario for both the long and short scenario. The red targets are the positions of the PASS devices for the long and short scenario. The blue crosses show the location of the speakers used to provide the background noise in each scenario.

7.2 Field Test Results

For each test, the time measurements were analyzed for the mean, standard deviation, skewness and kurtosis. The time measurements showed results that are predictable. The longer path took more time to find the PASS. The addition of noise also significantly increased the completion time of the task. This increase was seen in both scenarios, but there was a greater increase in the long scenario.

The results of the Austin scenarios can be seen in Fig. 7.2.1. During the long path with noise scenario, one firefighter’s low air alarm went off before finding the PASS. In normal operations, this would signal to the searcher to leave the building. Because of this the test was ended and his results are excluded from the analysis. The average find time for the short path was 29.5 s without noise and 37.83 s with noise with standard deviations of 12.5 and 21.7 respectively. The average find time for the long path was 58.2 s without added noise and 155.4 s with added noise with standard deviations of 13.7 and 64.2 respectively.

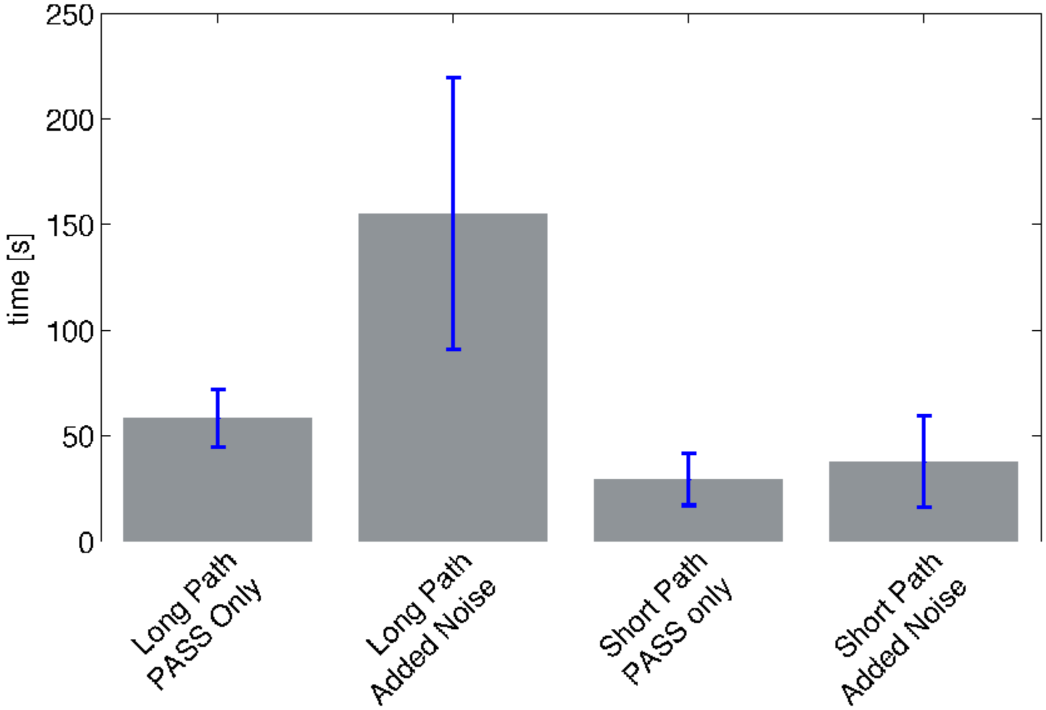


Fig. 7.2.1: The averaged find time results from the Austin Fire Department field tests. The error bars represent one standard deviation from the average.

The results show that there was not a significant change in find time between the PASS only and added noise short path scenarios. However, there was a significant change in find time when noise was introduced to the long path scenario.

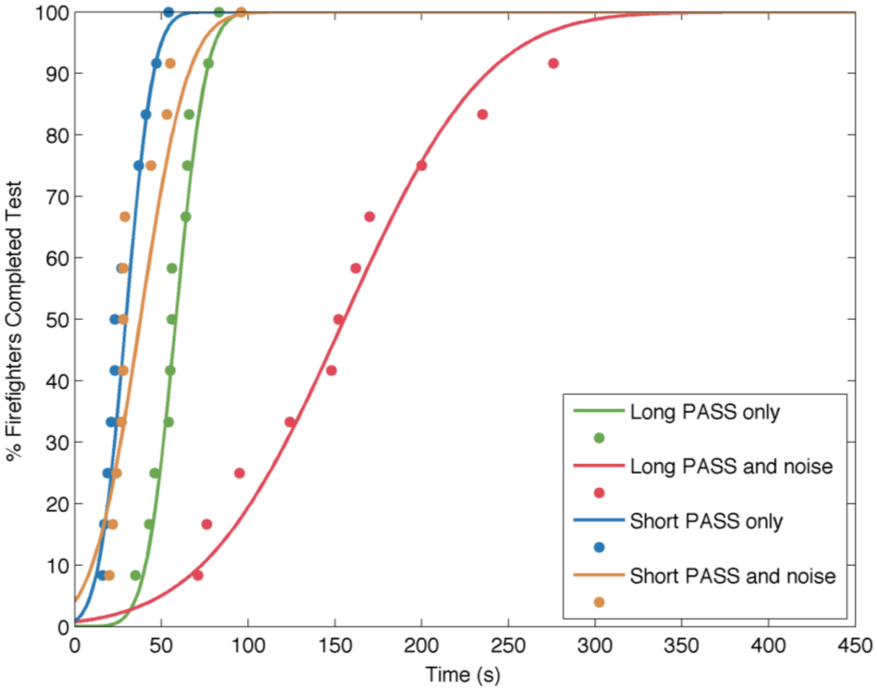


Fig. 7.2.2: Find time results from both Austin field tests. The data is represented by the dots, and the fitted cumulative distribution functions are the lines.

The results from the Glendale field test can be seen in Fig. 7.2.3. During the field test, it was decided to use the long path in noise scenario twice. This was to test the ability of the firefighters to learn a path in these conditions. The results showed no variation for the firefighters who went through the long path scenario twice. The average find time for the long path scenarios are 57.2 s with no noise and 123.4 s with noise. These had standard deviations of 28.4 and 64.57 respectively. The average find time for the short path was 61.9 s with a standard deviation of 20.5.

The average find time of both quiet scenarios are statistically the same. This is contrary to the other field tests. However, the addition of noise effects the find times the same in this test as it does in the other two.

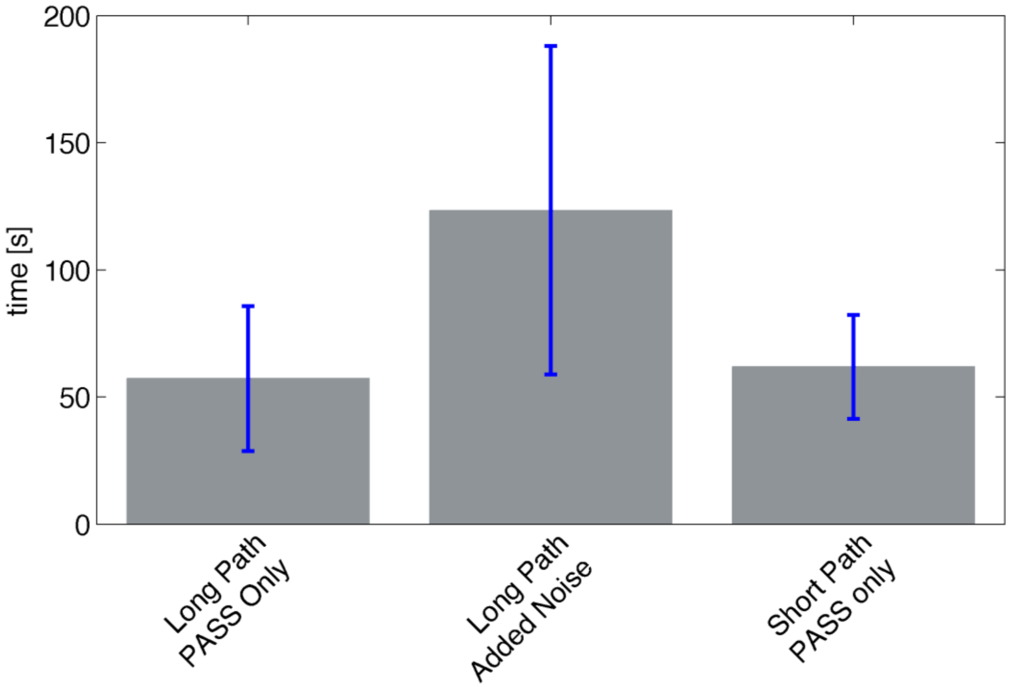


Fig. 7.2.3: The averaged find time results from the Glendale Fire Department field tests. The error bars represent one standard deviation from the average.

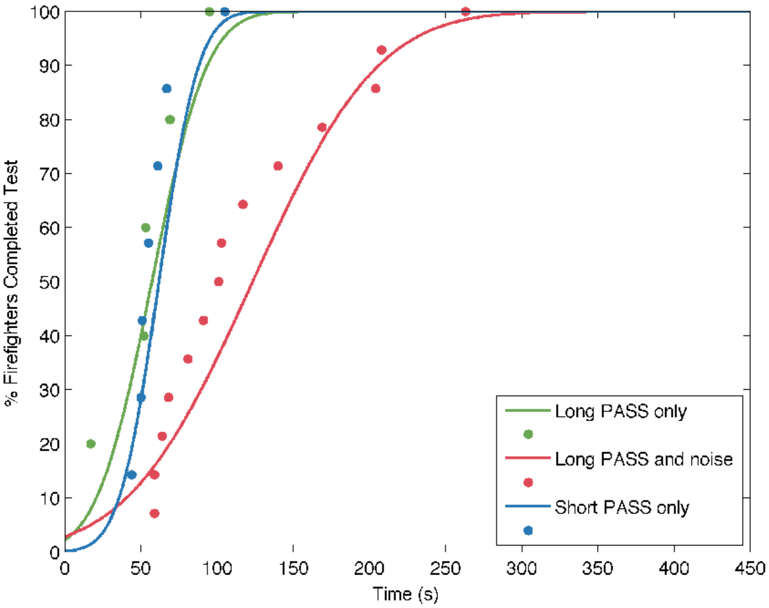


Fig. 7.2.4: Find time results from the Glendale field test. There is double the number of participants in the long PASS with noise scenario. The data is represented by the dots, and the fitted cumulative distribution functions are the lines.

The results of the OKC field tests can be seen in Fig. 7.2.5. The average find times of the long path scenarios are 85 s with no noise and 235.9 s with noise. The standard deviations are 35.6 and 139.9

respectively. The average find times of the short path scenarios are 56.86 s with no noise and 59.29 s with noise. The standard deviations are 37.39 and 31.13 respectively.

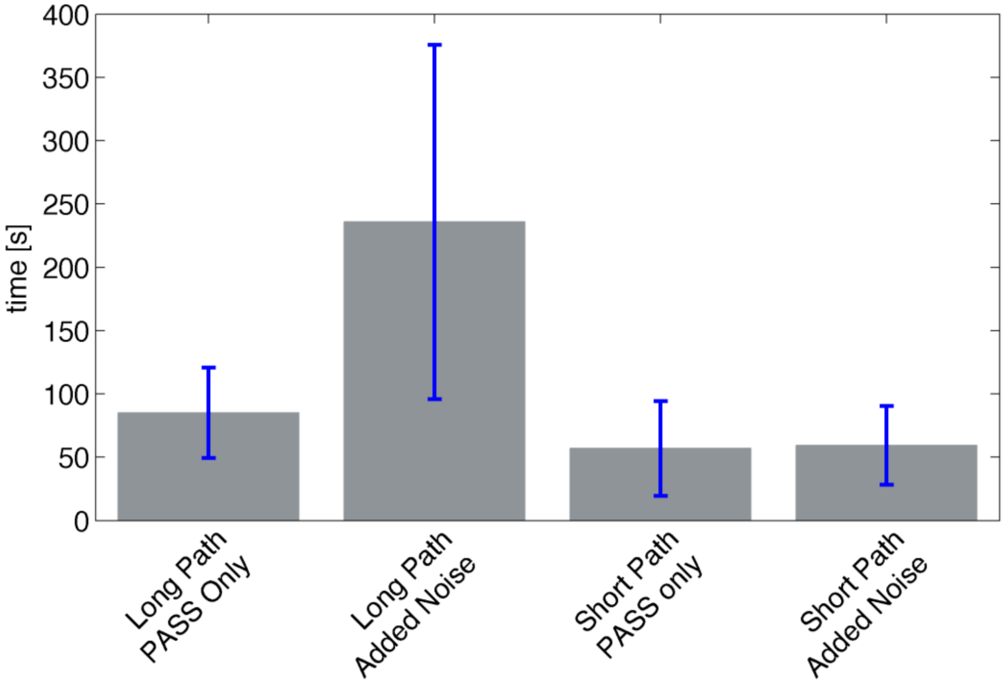


Fig. 7.2.5: The averaged find time results from the Oklahoma City Fire Department field tests. The error bars represent one standard deviation from the average.

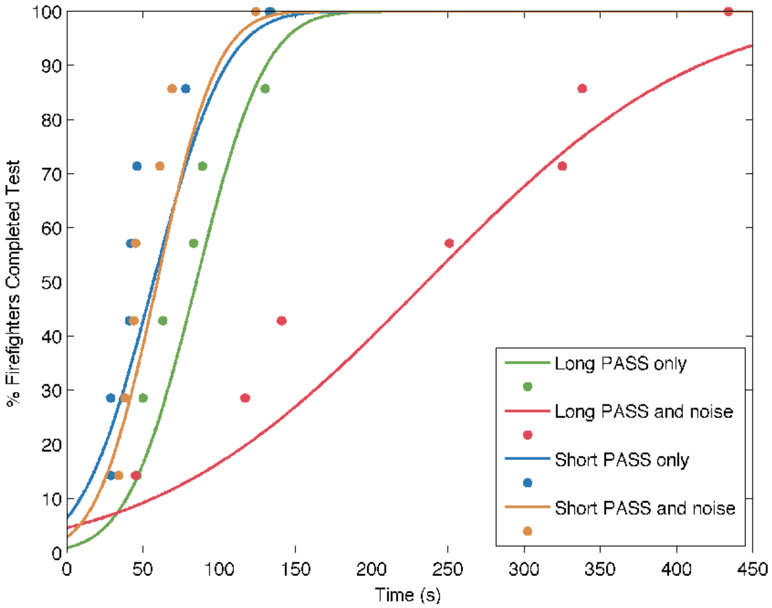


Fig. 7.2.3: The find times from the Oklahoma City field tests. The data is represented by the dots, and the fitted cumulative distribution functions are the lines.

The results from the Oklahoma City field test show similar results as the Austin field tests. There was not a significant change in find times when noise was introduced to the short path scenario. But, there was a change when noise was added to the long path scenario.

In all cases, the cumulative distribution curves were fitted using a normal distribution. As expected (since some data points do not match the curves), the skewness and kurtosis values indicate that a larger population is needed to verify that the normal distribution is appropriate.

Another result recorded during these tests was average firefighter obscured vision crawling speed. During both the Austin and Glendale test, there was a section of path that was straight enough to extract this information. In both tests it was found to be 1 ft/s (0.33 m/s) during quiet scenarios.

7.4 Field Testing Conclusions

The results of the field tests show a difference caused by both the length of the path and the added noise. The length of the path shifted the average find time. The noise increases the standard deviation of the find times.

The Glendale field test showed that the added noise did increase the average find time. However, in this field test, the long versus short path in quiet did not significantly change. The difference in length of the two paths was 17.5 ft. (5.3 m) which is significantly shorter than the Austin path lengths, 55.6 ft. (17 m), but longer than the Oklahoma City path lengths, 8.2 ft. (2.5 m). Both the Oklahoma City and Austin field tests showed a change due to path length. This suggests that there is another factor that needs to be considered. In the future, a test should be conducted with the same path length for each scenario, but more turns in one scenario than the other in order to evaluate how a more tortuous path affects the localization.

8. Conclusions

The Personal Alert Safety System (PASS) is the most widely accepted and used firefighter localization and rescue system in the U.S. There is increasing awareness that the evolution of this system should be directed by scientific principles and findings. Surprisingly little literature was available on fireground acoustics. This study represents the beginning of the characterization of the acoustical properties of the fireground. Another significant contribution of this study is the introduction of the sonar equation formalism as a way to organize the physics of sound detection, classification, and localization, and to formalize the analysis, design and optimization of future PASS devices and technological enhancements. In the following sections, we will present the major findings and conclusions of this study.

8.1 Summary of Observations

As previously noted, the study was organized using the sonar equation formalism and the conclusions will be discussed using this formalism. Detection of the PASS signal was affected by the overall source characteristics of the PASS device, the presence and characteristics of confounding sounds on the fireground, the physics of sound transmission within the structure/compartment and the PPE. Testing and analysis were used to understand the effects of these individual contributors to PASS signal detection. The overall effect of all of these factors on PASS detection and localization was evaluated using a field testing study that involved three fire departments. Results of the individual contributors to PASS signal detection are provided.

The source characteristics of the PASS signal were compared to other typical sound sources on the fireground. We found that many typical fireground equipment (e.g., saws and fans) have higher sound pressure levels than the PASS device when measured at the same distances from the sources. The larger bandwidth of the 2013 PASS signal standard is expected to be an improvement to the previous tonal signal. For any given source signal that might make up a PASS signal, transmission losses will ultimately affect the ability of a receiver to detect, classify, and localize the source. Transmission losses were characterized using experiments and computations. The contributors to transmission losses were determined to be both the temporally and spatially varying temperature field within the structure and the firefighter PPE. The temperature field induced transmission loss was found to depend on both the global temperature stratification and also on locally inhomogeneous spatial variations from plumes and other flow effects. These thermally induced transmission losses affected the modal structure in the compartment. The temporal variation of the modal structure of the compartment will affect the complexity of signal processing that could be used for auditory enhancement in fire scenarios. For PPE induced transmission losses, we found that the helmet design could be a significant contributor to sound signal detection and localization. Physical acoustics and audiology testing both showed significantly diminished receive levels associated with donning of the firefighting ensemble. Physical acoustics testing showed that there are strong directional artifacts that could mislead a human subject to misinterpret the true direction from which a source originates.

The field testing with partner fire departments was useful in better understanding how the time-to-task in locating a PASS beacon varied with the overall fireground noise level. This type of testing proved to be a useful training exercise and perhaps more importantly will be baseline for evaluating localization time-to-task for future PASS signals, modifications to PPE, and PASS localization tools.

8.2 Recommendations for Readily Implemented Alternative Technology

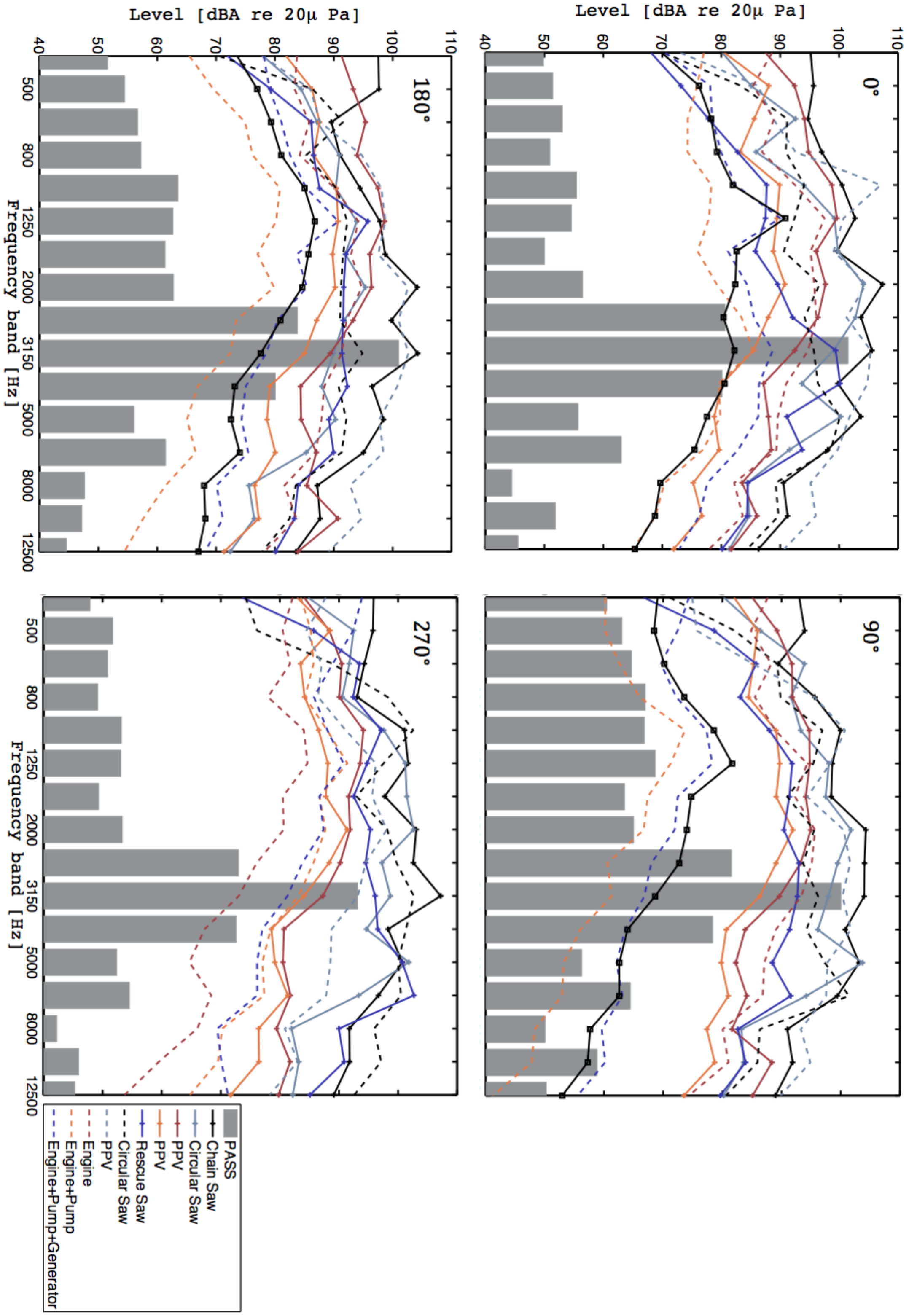
The sonar equation formalism can be used to guide future PASS technology developments. In order to maximize signal to noise ratio, noise attenuation headphones can be imagined that take advantage of advanced signal processing to reduce noise that the firefighter hears. There are commercially available headphones meant for construction workers that band pass filter audio (reduce noise levels outside the speech frequency band) and allow communication on a construction site without exposure to high noise levels.

Another technology that would be leverage would be PASS-based signal detectors. Correlation based processing has been suggested for this purpose, and while the authors believe that is a promising avenue, the change in the acoustic environment due to the fire could negatively affect the performance of such a device. Further research in this area is needed.

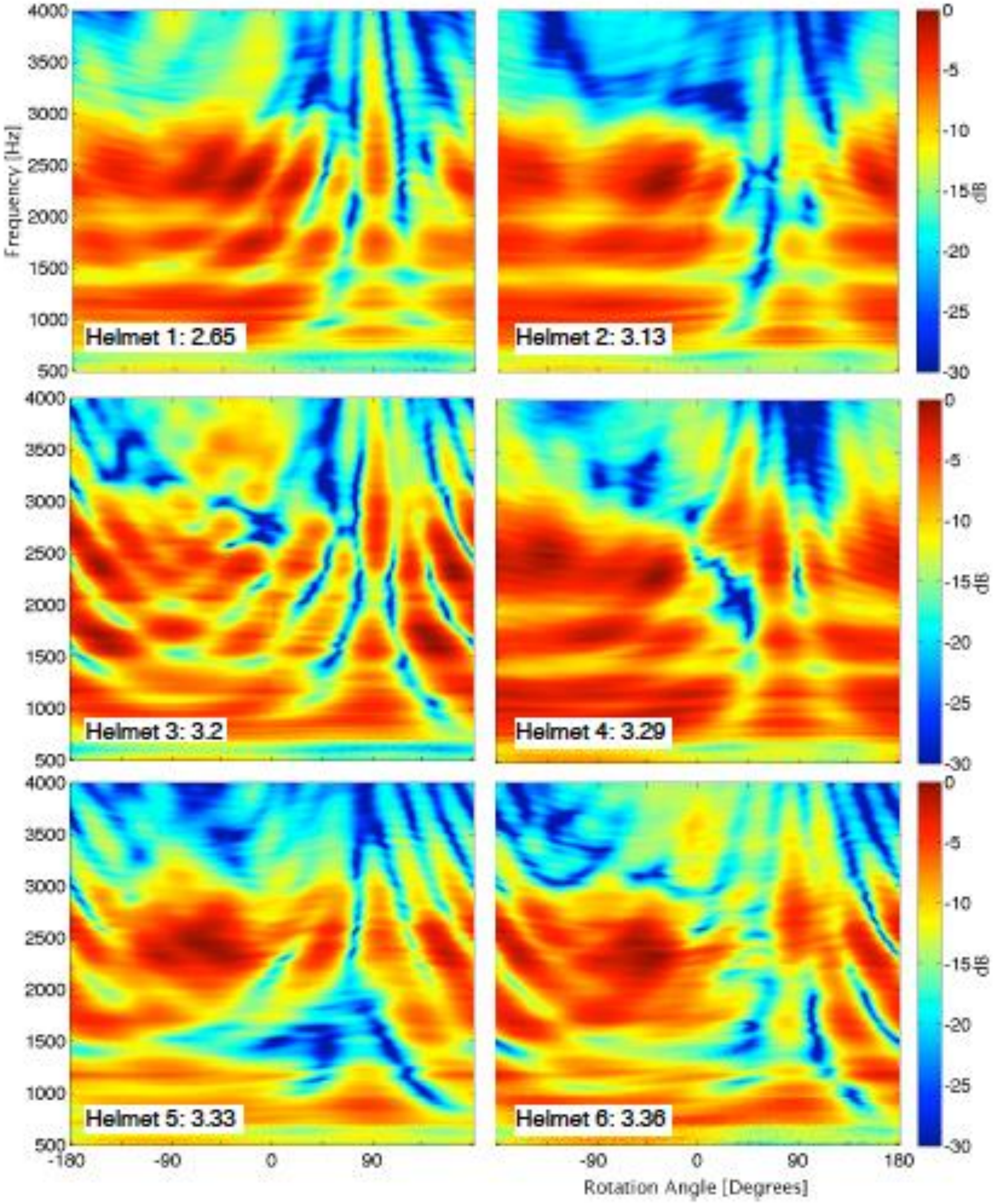
The change in the acoustic properties of the room can have positive implications as well. For example, one can imagine a device that keeps track of the average temperature of the room response around the firefighter (by using the PASS sweep as the source) and increases the PASS level based on temperature of the room.

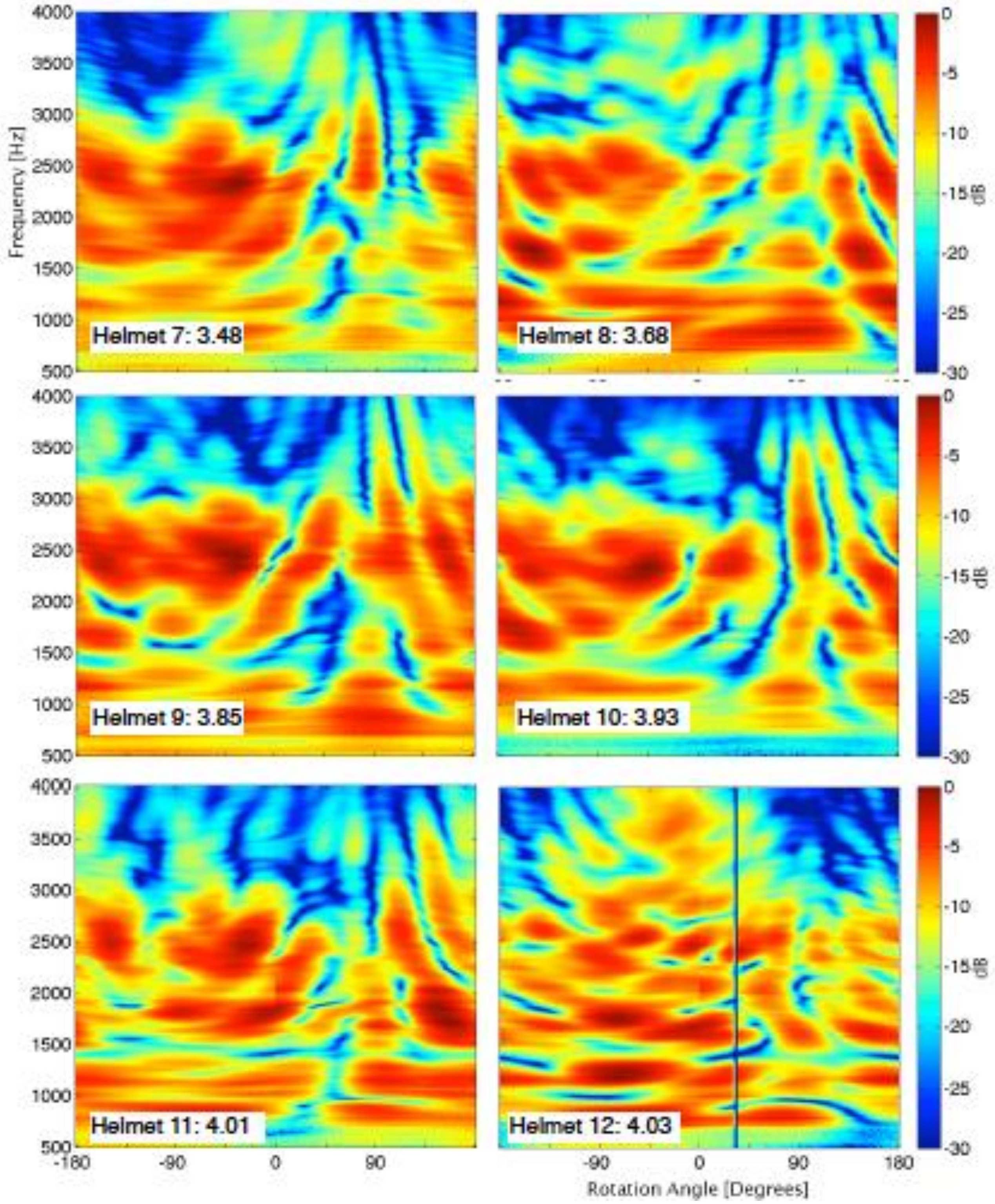
To increase the firefighter’s ability to localize, one can imagine using a directional microphone array to point towards the source of the sound. A microphone array would assist in detection by reducing the level of incoherent noise.

Appendix A: 1/3-Octave Band Analysis of All Recorded Equipment



Appendix B: HRTFs and D_{rms} for All Helmets




Helmet 7: 3.48
Helmet 8: 3.68
Helmet 9: 3.85
Helmet 10: 3.93
Helmet 11: 4.01
Helmet 12: 4.03
Frequency [Hz]
4000
3500
3000
2500
2000
1500
1000
500
Rotation Angle [Degrees]
-180
-90
0
90
180
dB
0
-5
-10
-15
-20
-25
-30

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